SOILS and ROCKS

An International Journal of Geotechnical and Geoenvironmental Engineering

Soils and Rocks publishes papers in English in the broad fields of Geotechnical Engineering, Engineering Geology, and Geoenvironmental Engineering. The Journal is published quarterly in March, June, September and December. The first issue was released in 1978, under the name *Solos e Rochas*, being originally published by the Graduate School of Engineering of the Federal University of Rio de Janeiro. In 1980, the Brazilian Association for Soil Mechanics and Geotechnical Engineering took over the editorial and publishing responsibilities of *Solos e Rochas*, increasing its reach. In 2007, the journal was renamed Soils and Rocks and acquired the status of an international journal, being published jointly by the Brazilian Association for Soil Mechanics and Geotechnical Engineering, by the Portuguese Geotechnical Society, and until 2010 by the Brazilian Association for Engineering Geology and the Environment.

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EDITORIAL

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Editorial overview for the themed issue on Geotechnical Engineering Education

Katia Vanessa Bicalho[1#]

Editorial

Keywords
Geotechnical engineering education
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Abstract

This special issue contains fifteen (15) peer-reviewed papers on geotechnical engineering education (Geo-engineering education). The themed issue includes the fundamental and interdisciplinary areas of geo-engineering: geomechanics (soil mechanics and rock mechanics), engineering geology, geotechnical engineering, and environmental engineering. This editorial presents a brief introduction of each article and highlights its key findings, main points, and conclusions. The papers in this issue cover a wide range of Geo-engineering topics in undergraduate curricula. This themed issue brings together articles from different universities and countries with inequalities in research funding for the current and future mutually beneficial exchange of ideas and experiences in Geo-engineering education. While this issue focuses especially on Geo-engineering education, some approaches or strategies presented here have applications to different topics in education and teaching.

1. Introduction

This themed issue included fifteen (15) peer-reviewed papers on geotechnical engineering education (Geo-engineering education). The issue includes the fundamental and interdisciplinary areas of Geo-engineering: geomechanics (soil mechanics and rock mechanics), engineering geology, geotechnical engineering, and environmental engineering.

Geotechnics are mainly represented by three international societies (i.e, the International Society for Soil Mechanics and Geotechnical Engineering, *ISSMGE*, the International Society for Rock Mechanics, *ISRM*, and the International Association for Engineering Geology and the Environment, *IAEG*), together with several other international societies, associations and groups (e.g, the International Geosynthetics Society, *IGS*). The international and regional associations have provided guidance and promotion for developing geo-engineering education and training at different levels (Pantazidou & Calvello, 2024, and Almeida et al., 2024).

The integration of technology and new tools in engineering education has created value and opportunities for advances in Geo-engineering education over the last decades. Normally, this useful information is dispersed and eventually published throughout journals and conference proceedings, and it is often difficult to identify suitable publication for research or professional purposes in Geo-engineering education. It is important therefore a themed issue dedicated solely to geotechnical engineering education in an open access international journal of geotechnical engineering and geoenvironmental engineering.

The papers in this issue cover the topics of computer-aided teaching-learning, education case studies, laboratory-to-field experiments, development of transferable educational material, and discussions of key concepts relevant to Geo-engineering education at undergraduate level. Some articles explore more than one topic. The wide range of topics and enthusiastic response illustrates that this theme is an important one for Geo-engineering (in its broad sense) and the wider society. A brief introduction of each article and highlights its key findings, main points, and conclusions are provided to hopefully stimulate further research. Together, the 15 articles that appear in this themed issue make contributions that help address solutions and challenges in Geotechnical Engineering Education. It is worthwhile to mention that all the published papers were submitted to revision by experts from the international geotechnical community.

2. The themed issue's articles

The themed issue's articles are grouped into three broadly linked categories as follows:

- development of transferable geo-engineering educational material and computer-aided teaching-learning;
- case studies and laboratory-to-field experiments relevant to geo-engineering education;
- discussion of key concepts in geo-engineering education.

The development of transferable geo-engineering educational materials and computer-aided teaching-learning used to guide learning and teaching processes is not a trivial

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task and requires the academia-industry collaboration to produce high-quality educational material. Thus, the papers grouped herein in the categories namely "case studies and laboratory-to-field experiments relevant to geo-engineering education" and "discussion of key concepts in geo-engineering education" provide resources for "development of transferable geo-engineering educational materials". Some papers could be fitted into one or more of the three considered categories.

2.1 Development of transferable geo-engineering educational material and computer-aided teaching-learning

The paper by Pantazidou & Calvello (2024) presents a survey project developed to find out the types of educational material (*EM*) geotechnical engineering instructors-Professors would like to have available. The study also collects information on existing *EM*, where do instructors search for them and how satisfied they are with available *EM*. The survey participants include members of the technical committee on Geo-engineering Education (*TC306*) of the *ISSMGE*, and geotechnical engineering educators who follow the *ISSMGE* activities. The results reveal that most of the instructors are not adequately satisfied with the *EM* they use, a significant percentage have searched for additional *EM*, and many of them are not satisfied with *EM* found. The study also notes that the major obstacle in developing *EM* is insufficient time (or indirectly lack of adequate funding) and technology competency.

The paper of Mendonça & De Bona Becker (2024) describes the conception of a didactic video that uses a reduced model to address the issue of slope stability, presenting the main anthropic aspects that may contribute to landslides, as well as their consequences. They also present how the video was used in different spaces of education and the evaluation by an undergraduate class in civil engineering at the Federal University of Rio de Janeiro in Southeastern Brazil. The detailed description of the didactic video and the results make the paper a valuable source for replicating the experiment. Similar instructional small-scale model can be developed for teaching other geotechnical engineering concepts.

Chrusciak et al. (2024) discuss the potential of gamification as a tool for teaching and learning in geotechnical engineering. The paper describes background information for developing and implementing game-based learning in Geo-engineering education, specifically on basic soil characterization. The results suggest that gamification has the potential to make geotechnical engineering education more interactive and engaging. The approach is relatively easy to apply to traditional geotechnical engineering coursework and requires only a modest effort to adopt. Exploring the effectiveness of the game in various contexts and with diverse student populations constitutes a key direction for future research.

Lemos et al. (2024) investigate the incorporation of information and communication technologies on the teaching-learning process of various themes of geotechnical engineering, from laboratory tests data handling and processing to slope stability and rock mass stability numerical analysis. It is illustrated with several practical examples developed by the authors. The activities were conducted in geotechnical disciplines of a civil engineering course in southeast Brazil aiming to promote active learning and improve teaching quality. Based on the results of an applied feedback questionnaire, it was observed that most students were satisfied with the resources used in the classroom, suggesting that the implemented didactic digital tool facilitate learning and comprehension of the practice of geo-engineering, in addition to enabling the investigation of geotechnical engineering problems more efficiently considering the variability of different input parameters based on descriptions from observations.

2.2 Case studies and laboratory-to-field experiments relevant to geo-engineering education

Almeida et al. (2024) describe an international educational initiative of *IGS* to facilitate the exposure of geosynthetics and associated technologies to undergraduate civil engineering students for over a decade. Emphasis is given on the experience of the Brazilian Chapter of *IGS*, which has already conducted programs. The educational outcomes of the programs currently offered are being evaluated and they suggest excellent acceptance of the course by participants and undergraduate students at various universities.

Mascarenha et al. (2024) draw attention to the need of geotechnical interaction with society through extension activities, teaching, and research, in some cases using social networks that are part of the reality of modern engineering practice. The article highlights that the effectiveness of the extension activities requires a broader participation and engagement of professional associations, funding and evaluation agencies, education departments schools, and education, science, technology and innovation government sections.

Ferreira (2024) analyzes methodological experiments from the teaching-learning process carried out in the geotechnical area of the civil engineering program at three universities in Northeast Brazil for more than 40 years. Three integrated experiments are presented and discussed. In the first experiment, collaborations between industry and academia in the Geo-engineering area are discussed. The second experiment integrated students and educators from different areas of the civil engineering program around a multidisciplinary project, while the third brought together undergraduate and graduate (master and doctoral) student research activities into a single Geo-engineering project. The study shows the use of teaching-learning experiences carried out in geotechnical engineering, contributing to the development of technical skills and professional competencies of civil engineers. The interaction between the university, society and government institutions in problem solving also contributed.

Ribeiro et al. (2024a) discuss some points of the evolution of engineering geology based on a structured and comprehensive research of historical facts in engineering schools. The study included the main topics considered in the teaching of engineering geology and challenges and solutions of the teaching experience at undergraduate and graduate levels. Engineering geology teaching has undergone different phases and adaptations to the evolution of knowledge and research procedures. According to the study, it focuses on four large groups of didactic activities for the current decade and, perhaps, for the next one in several countries. The first group refers to access to materials of each topic and the second includes face-to-face activities on the solution of practical problems related to a specific topic. The third group focuses on field and laboratory works, whereas the fourth explores comprehends development and analyses of specific civil work projects, mineral exploration, and environmental problems. The paper demonstrates the wide relevance of engineering geology education across a range of research opportunities and applications.

França et al. (2024) present a case study of implementing an in-class/ex-class activity conducted in the introductory Soil Mechanics course at a public university in North Brazil. Additionally, the study discusses students' perception regarding development of the proposed activity. The activity comprised three phases: selection of Geotechnical Engineering problems on university campus, documentation and analysis of each situation, and presentation of solutions considering technical, environmental, and social aspects. The article reports encouraging results. The community-based approach in dealing with real problems and work in groups appears to be a successful approach for teaching-learning Geo-engineering courses.

MacRobert (2024) presents three geotechnical design projects set by the author, along with three interventions used to scaffold student progress. Projects included the design of an industrial waste facility for dry filtered residue, design of remedial works for a clay river embankment subject to undercutting, and design of a remining method for mine slimes contained behind a sand embankment. Interventions included requiring students to prepare, present and critique presentations based on weekly stage gates, collaboratively brainstorming, and ranking high level implications of a design, and collaboratively brainstorming specific implications of a design. It is observed that care must be taken when implementing such interventions to ensure they remain student driven, or the learning benefits of a capstone design course may be lost.

The paper by Macedo & Oliveira (2024) discusses the application of information and communication technologies to promote learning in soil mechanics courses at undergraduate level. It was presented and discussed an experience in implementing an active learning strategy called "Guided Exercises" in two consecutive soil mechanics courses of the civil engineering undergraduate study programme at the University of Aveiro, Portugal. The results of the study showed that students considered the strategy useful for the understanding of the concepts covered in the courses and those who used the methodology had a better approval ratio.

Ribeiro et al. (2024b) describe a study undertaken to mitigate climate change effects or adapt cities to them during an undergraduate course of Study and Behaviour of Soils in Sustainable City Management. Students are faced with the need to present solutions to solve an urban problem by implementing a green solution. It is called a co-creation academic activity. This project-based learning methodology is seen as an active learning process, and three cases of the academic activities are described in the paper. Students' perceptions, academic results and assiduity are compared to enhance the benefits of the adopted approach in geotechnical education. Preliminary results are presented that illustrate better students' performance.

2.3 Discussions of key concepts in Geo-engineering education

Three papers by research-active geotechnical Professors (Maranha das Neves, 2024, Salgado, 2024, Ledesma, 2024) revisit and discuss key concepts in Geo-engineering education. The papers raise several important insights that are not analyzed in detail in many textbooks, and the authors illustrate the importance and relevance of consider them in a modern Soil Mechanics course.

The paper by Maranha das Neves (2024) addresses the importance of the critical state theory (*CST*) as the foundation of modern soil mechanics teaching. Some ideas concerning where and how soil mechanics has been taught are also introduced and discussed. The fundamentals about plastic design of geotechnical structures are highlighted. The article ends calling attention to the outstanding contribution of the *CST* for a unified understanding of the soil behavior. Its pedagogic benefits are of great worth.

Salgado (2024) focuses on mechanics-based geotechnical engineering applications. The paper reviews some of the major decisions that were made by the engineers and researchers who developed geotechnical engineering to the point at which it was an identifiable separate discipline and the consequences that these decisions have had on the development of the discipline and on its teaching. The paper identifies some key modelling choices that were made that have had an undeservedly disproportionate impact on the teaching and practice of geotechnical engineering. The focus of the paper is therefore on these decisions and choices, and what should be taught in their place today. Challenges that future geotechnical engineers may face, as well tools that will be available to them, are also discussed in the context of what should be taught in undergraduate and graduate courses.

The technical note by Ledesma (2024) presents valuable insights into the difficulties that arise when teaching shear strength of soils, and the limitations of the Mohr-Coulomb strength criterion. The author suggests that in an undergraduate Soil Mechanics course it would seem more convenient to consider a strength envelope and some fitting parameters useful for computations, but without a specific physical meaning. Those difficulties are related to the drained/ undrained behavior of soils, but also to the fact that cohesion is a tricky parameter, with a misleading physical meaning, depending not only on the properties of the contacts between particles, but also on external conditions (i.e., saturation or unsaturation).

3. Closing comments

In general, papers published in this themed issue present comprehensive work on some of the Geo-engineering education solutions and challenges. It is clear from the contributions submitted for this special issue and other recent work that education and training is a wide important theme to Geo-engineering, which until recently had little comprehensive attention.

Many solutions and challenges are currently being investigated and debated and this themed issue is a good overview of the current research topics and teaching-learning innovative methodologies used for shaping and developing students' broad critical thinking skills and providing global context for Geo-engineering problems. Guidance is giving for successful implementation of such initiatives and experiences in different contexts. There remain several outstanding issues, including more case studies of academia and industry collaborations for sharing of ideas, expertise, and best practices in Geo-engineering education.

It is hoped that the papers published in this themed issue are useful to the researchers, academicians and professionals working in Geo-engineering education.

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I dedicate this themed issue to Professor Waldemar C. Hachich (1950–2022) for his significant contributions to geotechnical engineering, with a particular emphasis on Geo-engineering Education. Professor Hachich was always a very actively engaged member (Chairman 2013-2017) of the technical committee on Geo-engineering Education (*TC306*) of the ISSMGE. For *TC306*, his legacy includes establishing the prestigious John Burland Honor Lecture and creating an alternative model for *TC306*'s international conferences. I am truly grateful to Waldemar for his support and enthusiasm to the idea of preparing a special issue dedicated to Geo-engineering education. I thank all the authors of the published papers for their contributions, as well as manuscript reviewers for contributing their valuable time and input. A special thanks goes to "Soils and Rocks" an international journal published by the Brazilian Association for Soil Mechanics and Geotechnical Engineering and Portuguese Geotechnical Society (National associations under the umbrella of the *ISSMGE*) for accepting to publish this first special issue focusing on Geo-engineering education. I also thank to Professor Renato Pinto da Cunha, Professor Gilson de F.N. Gitirana Jr. and Dr. Fernando F. Monteiro members of the editorial team of the Soils and Rocks journal for technical and administrative assistance throughout the planning and conduct of the themed issue. Thank you for proving support during all the editorial process. I am also grateful to the financial support from the Brazilian agency CNPq (Research Productivity grant).

Declaration of interest

The author has no conflicts of interest to declare.

Data availability

No dataset was generated or evaluated in the course of the current study; therefore, data sharing is not applicable.

List of symbols and abbreviations

CST	Critical state theory
EM	Educational Material
ISSMGE	International Society for Soil Mechanics and Geotechnical Engineering for Rock Mechanics
ISRM	International Society for Rock Mechanics
IAEG	International Association for Engineering Geology and the Environment
IGS	International Geosynthetics Society
TC 306	Technical committee on Geo-engineering Education of the ISSMGE

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ARTICLES

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What kinds of educational material are useful for and desired by university instructors? The case of Geotechnical Engineering

Marina Pantazidou[1#], Michele Calvello[2]

Article

Keywords
Geotechnical engineering education
Teaching needs assessment
Educational material development

Abstract

An online questionnaire was developed to find out (i) whether geotechnical engineering instructors have available a variety of satisfactory educational material and (ii) the types of educational material they desire. The title of the questionnaire was phrased as "What Geotechnical Engineering Educational Material can we dream of?", in order to convey that the main purpose of the survey project reported herein is to learn about these desired educational materials. In doing so, the survey also aims to assemble information on related issues, such as: existing educational materials, where do instructors search for them and how satisfied they are with available material. The questionnaire has 12 close-ended (four yes/no and eight multiple choice) and four open-ended questions. Of the 94 completed questionnaires received, 63 were deemed to be conscientious attempts to answer its questions and were analyzed in detail. The most revealing findings from the close-ended questions include the following. The majority of the instructors (52%) are not adequately satisfied with the material they use. Likewise, whereas a significant percentage have searched for additional material, a little less than half of them (45%) are not satisfied with material found. Respondents need materials for their lectures, materials to engage students outside lecture time and, to a lesser extent, materials to assess students. In terms of topics of interest, case studies and laboratory-related educational materials are the most popular. The online supplement of the paper includes broad-stroke and fine-stroke descriptions of desirable educational materials that provide directions for developing them.

1. Introduction

In the internet era, a common assumption is that instructors –university instructors included– have available a variety of satisfactory educational material to choose from for their lectures. However, having many sources available is akin to having the phonebooks for businesses of previous decades, known as "yellow pages", which are not helpful if the goal is to identify quality professionals. The starting point of the work presented herein is using a questionnaire to test this abundance assumption for instruction in geotechnical engineering, one of the disciplines of civil engineering, in particular for its accuracy for undergraduate instruction.

Educational material is a common research topic in the literature for lower levels of education, since it is anticipated that teachers may have some knowledge gaps (Davis et al., 2016). In contrast, the high content expertise of university instructors often leads to the conclusion –questioned herein– that this literature is irrelevant to tertiary education. However, since teaching at all levels has some common elements, even the literature for primary-secondary education can yield some useful overarching guidelines for desired educational material. For instance, teachers appreciate the educational materials that are *educational* for themselves as well, i.e. not only for students (Ball & Cohen, 1996). Such guidelines offer domain-general criteria for the usefulness of educational material. For tertiary education, efforts for "educating educators" essentially target: (i) content outside their main area of expertise but within their broader field, e.g. geosynthetics within geotechnical engineering (Zornberg et al., 2020); and (ii) educational topics, by means of various domain-general short courses or certificate-granting programs attended by instructors from all disciplines, such as those offered in the UK by universities and accredited by the organization Advance Higher Education –formerly Higher Education Academy. To the authors' best knowledge there has been no effort to re-educate educators for teaching in their discipline.

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If there were, most probably the standard would be quite high, even for undergraduate topics. That's why the goals of the questionnaire described herein aim very high, beyond the merely doable and all the way to the dream-able. The existing literature provides useful examples of questions asked (Skoumios & Skoumpourdi, 2018), and also the questions left out provided food for thought. Specifically, primary and secondary education teachers are rarely asked what materials they want; instead, education researchers create material and study how they are received by teachers (Ball & Cohen, 1996; Davis et al., 2016).

The main purpose of the survey project reported herein is to find out the types of educational material geotechnical engineering instructors would like to have available. To provide a broader context for the collected information, the online questionnaire developed also aimed to collect information on related issues, such as: existing educational materials, where do instructors search for them and how satisfied they are with available material. The ultimate goal of the project is to facilitate dissemination and production of shareable educational material deemed by geotechnical engineering instructors to be useful and desirable.

2. Methods

2.1 The questionnaire

The overall question asked in order to achieve the main research purpose was phrased as: "What Geotechnical Engineering Educational Material can we dream of?". This question served as the questionnaire title. The phrasing was meant to free respondents from the constraints imposed by their own available time and knowledge. The main question was framed with ancillary questions arranged in the four sections shown in Table 1: Section A – material used in instruction (phrased as "Your Educational Material"), Section B – searching for educational material and Section C – dream educational material. There is a final Section D, which asks for demographic data, including instructional experience. In total, the questionnaire consists of 16 questions, 12 close-ended (four yes/no and eight multiple choice) and four open-ended. The complete questionnaire with the possible answers to close-ended questions and their percentages is included in online Supplement A (Pantazidou & Calvello, 2023a: Table S1).

To guide respondents, the questionnaire starts with an introductory page stating the ultimate goal of the project, which is the use of the survey results for the development of shareable educational material for geotechnical engineering at undergraduate level. The introduction also includes a definition of educational material, adapted by Skoumios & Skoumpourdi (2018). Respondents are guided to think of educational material as anything they use in their teaching that (i) is specifically designed and produced to be used in instruction or (ii) can be used in instruction with minimal adaptation. It includes textbooks in printed or electronic format, published papers, online material, such as videos of any kind, and educational software of any kind (including educational versions of commercial software). For the purposes of this questionnaire, educational material excludes demonstrations involving physical objects or testing equipment but includes the results produced by such demonstrations, provided they are well documented so that they have educational value independently of the actual physical demonstration.

Section A has four questions. Question 1 asks respondents whether they have developed any shareable educational material themselves and, if the answer is yes, to provide examples (Question 2). Question 3 is a central question that asks how much or little satisfied are the respondents with the educational material they use and, if they are fully satisfied, to provide examples (Question 4). The wording "fully satisfied" was purposefully selected in order to guide instructors to select the very best from the material they use in order to ensure usefulness for other instructors.

Section B has six questions asking respondents if and where they search for educational material (Questions 5 and 7) and for which geotechnical engineering topics they search (Question 6). Question 8 is another central question asking respondents how satisfied they are with some of the material found and, if they are satisfied, to provide examples (Question 9). For material found the standard for examples was lowered to just "satisfied" (compared to "fully satisfied" for material used), in order to get a picture of what instructors would be happy –but not necessarily delighted– discovering without doing work themselves. The final question in Section B, Question 10, is also key for the project's aim and asks for reasons why any unsatisfactory material found was inappropriate, in order to collect usefulness criteria for the production of future educational material.

The core of the questionnaire, Section C, has two questions, 11 and 12. Question 11 is open-ended and asks respondents to imagine and describe a "wish list of Educational Materials" also expressed as "the educational material of our dreams". This is the only obligatory question of the questionnaire, i.e. respondents have to type something in order to proceed. Question 12 is multiple choice and asks respondents to select possible obstacles for developing themselves their dream material.

Lastly, Section D asks for demographic data, such as country (Question 13), instructional and professional experience (Questions 14 and 15), and whether respondents have had any formal training in Education (Question 16). The questionnaire was made available to respondents through the platform Survey Monkey.

Table 1. Questionnaire: phrasing and type of questions and numbers of responses analyzed.

ID	Question	Type	Replies (ISSMGE + TC306)
	Section A – Your Educational Material		
Q1	Have you ever developed shareable educational material yourself?	yes/no	62 (42+20)
Q2	If you answered “yes” to Question 1, please give examples and sources if you have made this material publicly available (e.g. give URLs, references of papers)	open ended	24 (13+11)
Q3	Are you satisfied with the educational material you currently use in your teaching?	likert: 4	62 (42+20)
Q4	If you answered “Fully” to Question 3, please provide sources (e.g. books, URLs, references of papers) of the material used in your teaching, including subject and course/module.	open ended	1 (1+0)
	Section B – Searching for Educational Material		
Q5	Have you ever searched for educational material to augment what you have/use?	yes/no	61 (40+21)
Q6	If you answered “yes” to Question 5 (= have you searched), for which geotechnical engineering topic(s) have you searched?	choices: 9+other	53 (37+16)
Q7	If you answered “yes” to Question 5 (= have you searched), where/how have you searched?	choices: 5+other	53 (37+16)
Q8	Were you satisfied with any material found?	yes/no	53 (37+16)
Q9	If you were satisfied with some of the material found (“yes” in 8), please give examples, sources (e.g. URLs, references of papers) and a brief description of how you incorporated the material in your teaching, including subject and course/module.	open ended	24 (17+7)
Q10	If you were not satisfied with some of the material found (answered either “yes” or “no” to Question 8), in what way was the material inappropriate?	choices: 4+other	39 (28+11)
	Section C – Dream Educational Material		
Q11	Please imagine and describe the “educational material of your dreams”, regardless of whether you believe there exists or that someone might produce it. Assume that there is a “Santa Claus for Geotechnical Engineering Instructors” who delivers all year round. Please describe what you would ask Santa, including subject and course/module where you would use the material. NOTE This “dream material” could be the same as the material you described in the answers to Questions 2, 4 or 9.	open ended	47 (28+19)
Q12	What might make it difficult for you to develop the “educational material of your dreams”?	choices: 8+other	61 (41+20)
	Section D – Demographic Data		
Q13	Country of the University where you teach	choices: country	61 (40+21)
Q14	Instructional experience	categories: 5	61 (40+21)
Q15	Professional experience	choices: 6+other	61 (41+20)
Q16	Have you had any formal training in Education? NOTE Formal training may range from one short course to certificate-granting programs offered by a university teaching and learning center or a state agency.	yes/no	63 (42+21)
Q17	Please write your name and e-mail if we have your permission to contact you and ask further elaboration on your answers to Questions 2 (material developed), 9 (material found) and 11 (dream material). You may also leave us comments in the same box.	open ended	25 (25+0)

2.2 Two groups of respondents

Respondents to the questionnaire belong to two groups. The first group is the technical committee on Geo-engineering Education (TC306) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) (TC306 group). This is a group of members of the ISSMGE who are nominated by national societies for Soil Mechanics and Geotechnical Engineering to represent them in the technical committee for education. The first author of the paper is the TC306 chair and the second author is the TC306 secretary. The questionnaire was made available in the summer of 2019 for the TC306 group, which at the time had 34 members. Members were informed about the questionnaire through e-mail. A total of 23 responses were received from the TC306 group.

The second group is the wider community of geotechnical engineering educators who follow the ISSMGE activities (ISSMGE group), i.e. it is a superset of the first. The questionnaire was made available to the wider community in the fall of 2019, after being disseminated as follows. The results from the responses of the TC306 members were presented at a special session on education during the 17th European Conf. on Soil Mechanics and Geotechnical Engineering that took place in Reykjavik, Iceland. Attendees of the special session were invited to respond. In addition, the questionnaire was announced in a news item of the September 2019 News & Information Circular, which is sent by the ISSMGE to the officers of all the national societies and the ISSMGE technical committees for further distribution. A total of 71 responses were received from the ISSMGE group between September 2019 and January 2020. In the version of the questionnaire for the wider community there was an extra optional question in Section D asking for the respondent's name, e-mail and permission to be contacted for further elaboration on answers.

2.3 Screening of the answers

It takes 10 minutes to read carefully all questions and complete the 12 yes/no and multiple choice questions of the questionnaire. Depending on how seriously the respondents treat the exercise, extra time is needed to write responses for the "other" option of four multiple choice questions and, mainly, for the open-ended questions. Because several completed questionnaires contained only a few answers (mostly to the easy close-ended questions) and were missing demographic data (ISSMGE group), it was decided to take into account only the more conscientious attempts to complete the questionnaire.

This "conscientiousness filter" left 21 responses in the TC306 group and 42 responses in the ISSMGE group. Of the latter 42 responses, 25 were signed. Only the answers from those 63 questionnaires have been compiled for perusal or analysis by anyone interested, see EXCEL file in online Supplement B (Pantazidou & Calvello, 2023b). Likewise, only these answers were taken into account in preparing the tables and figures of this paper, with the exception of any useful answers to the open-ended questions: one such answer was found, see Section 3.3 and Table S3 in online Supplement A (Pantazidou & Calvello, 2023a). The survey platform used to collect and analyze the results provides typical time spent on the questionnaire, taking all the responses together. Typical time was 12:26 for the TC306 group and 9:27 for the ISSMGE group. When taking into account only the more conscientious attempts, and excluding data for five respondents that suggest they took a break while working on the questionnaire (e.g. time spent from 51 to 98 minutes), the mean time spent was about 12.5 minutes for the TC306 group (min: ~3′, max: ~23′) and 11 minutes (min: ~4′, max: ~30′) for the ISSMGE group.

3. Results

When comparing the answers from the two groups, three sizeable differences stand out. As expected, instructional experience (Question 14) is significantly higher for the TC306 group compared to the ISSMGE group: the percentages of the Instructors-Professors with experience more than 15 years are 67% and 35%, respectively. The percentages for the various cohorts defined on the basis of experience is shown in Figure 1. The second sizeable difference is that a higher percentage of the TC306 respondents answer to Question 1 that they have developed shareable educational material (55%) compared to the ISSMGE respondents (33%) (Figure 2). The third sizeable difference is the lower percentage of the respondents from the TC306 group searching for additional educational material (Question 5), 76% vs 92% (Figure 3). It is probable that the last two differences are complementary. In the remainder of this section, the presentation of the answers is arranged in terms of the intention of the questions. When the percentages from the two groups did not differ significantly, the answers from the two groups were merged.

3.1 Testing the abundance hypothesis for education materials

The answers to Questions 3 and 8 reveal that a large percentage of instructors would like to have better teaching materials. As shown in Figure 4a, the majority of the instructors (52%) are not adequately satisfied with the material they use (55% of the TC306 group and 50% of the ISSMGE group). Similarly, as shown in Figure 4b, a little less than half (45%) are not satisfied with material found after searching (56%

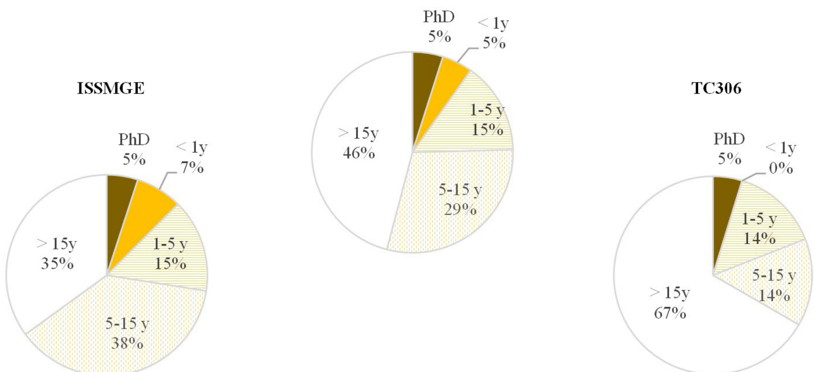


Figure 1. Instructional experience of respondents (Question 14).

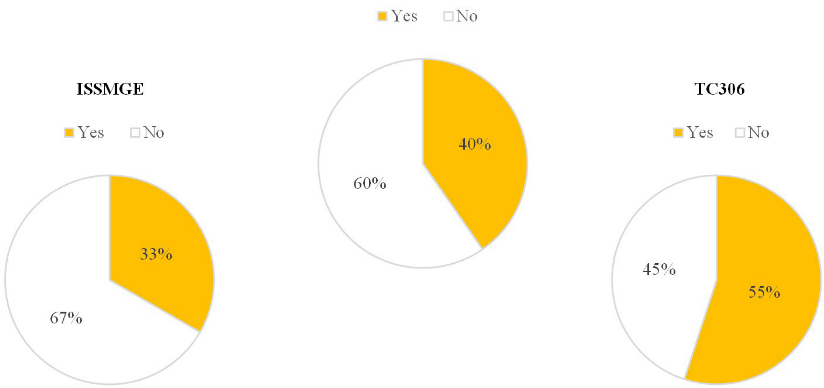


Figure 2. Answers to Question 1 "Have you ever developed shareable educational material yourself?".

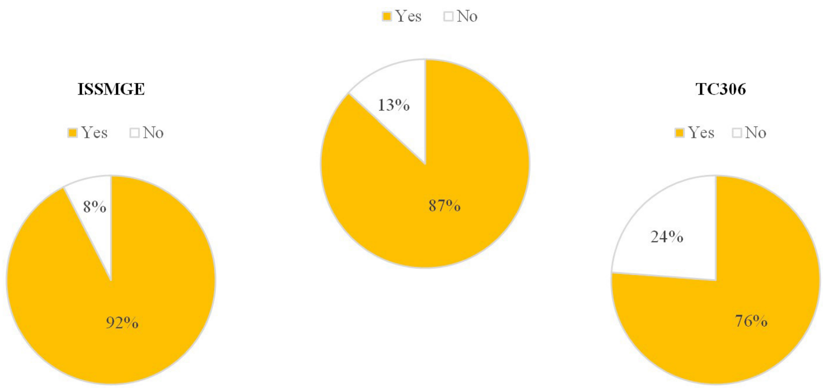


Figure 3. Answers to Question 5 "Have you ever searched for educational material to augment what you have/use?".

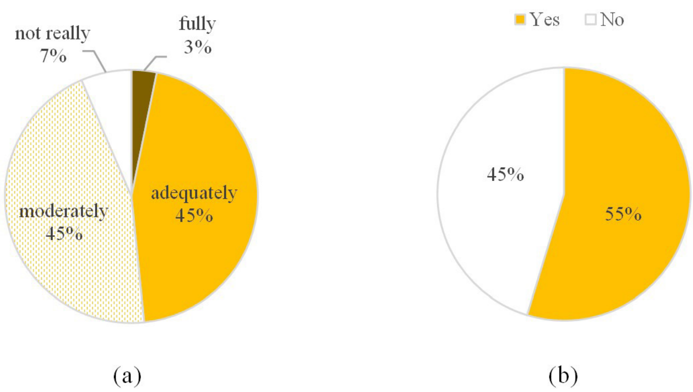


Figure 4. (a) Answers to Question 3 "Are you satisfied with the educational material you currently use in your teaching?" (b) Answers to Question 8 "Were you satisfied with any material found (after searching)?".

of the TC306 group and 40.5% of the ISSMGE group). Similar percentages are found when the larger groups, i.e. all submitted answers, are taken into account: 54.5% of the TC306 group and 54% of the ISSMGE group are not adequately satisfied with the material they use, while 53% of the TC306 group and 46% of the ISSMGE group are not satisfied with the material they have found after searching. In other words, the decision to exclude the less conscientious responses did not alter the gist of the findings: the abundance assumption mentioned in the introduction does not represent the majority of geotechnical engineering instructors when the criterion of satisfaction is used as filter.

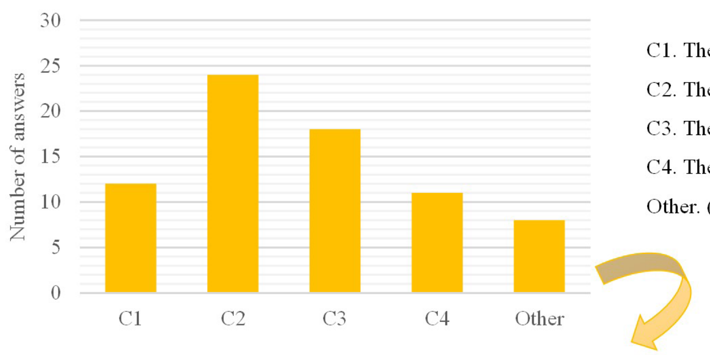
3.2 Instructors' searches for educational materials

A large majority of the respondents (87%) answered to Question 5 that they search for material to augment their own (Figure 3). Question 6 asks for topics searched and admitted as answers eight typical subjects in introductory geotechnical engineering courses (e.g. consolidation, foundations), one potentially –depending on interpretation– more advanced topic (soil constitutive modeling, e.g. stress distribution, shear strength) and the option "other". This question ended up being of relatively low value because of the low variety of answers. As shown in Figure S1 in Supplement A (Pantazidou & Calvello, 2023a), no topic stands out, with either a sizably low percentage (suggesting that instructors do not need to search for it), or high percentage (suggesting a significant need of instructors for additional material to teach it). The highest numbers in a total of 53 answers were for Laboratory Testing (32 answers, 60%), Field Testing and Foundations (31 answers each, 58%). The answers to the "other" option mainly included advanced topics or referred to type of material ("look for exam questions, books and papers") rather than topic. The most popular sources where respondents search (Question 7) are scholarly journal papers (41%) and additional textbooks (38%) (see Figure S2 in Supplement A), while in the "other" category, by far the most popular category is general internet searches for videos.

Question 10 illuminates the reasons why some material found may not be useful for teaching purposes. This question was answered by 39 respondents, from both subsets (either satisfied with some of the material found or not satisfied with any material found). The primary reason for dissatisfaction is when the material found requires a lot of time to adapt it (62%), while 46% of the respondents further note the lack of adequate documentation (see Figure 5). The other two options for dissatisfaction, "material was not adaptable" and "material did not come with reuse permit" were true for 31% and 28% of the respondents, respectively. There were eight "other" answers (21%), further elaborated as follows: 1) lack of videos (which were deemed to be more suitable for undergraduates) or 2) videos not being appropriate, 3) the preponderance of solutions for idealized problems and the lack of real problems that lack simple solutions or 4) complexity of material unsuitable for undergraduate instruction, 5) broken links no longer available, 6) lack of good textbooks in spoken language, 7) time needed for adaptation mentioned again and 8) testing for demonstration purposes performed non-rigorously, without satisfying standards.

3.3 Questions with answers intended for the dissemination of educational materials

The questionnaire includes three open-ended questions (Questions 2, 4 and 9) aiming to collect examples of useful educational material for dissemination purposes; each question is addressed to the subset of the respondents who answered affirmatively to a previous question. As already mentioned, a good number of respondents, 11 of the TC306 group (55%) and 14 of the ISSMGE group (33%) replied to Question 1 that they have developed shareable educational material (Figure 2). The authors visited all websites included in the answers in order to review the material and simulate the experience of an instructor searching for educational material. When the information provided was incomplete, they made an effort to locate the missing information in order to provide both a description and a full reference. Unfortunately, even with this extra effort, only a small percentage of the answers can be used for the intended purpose of dissemination. Out of the 11 answers to Question 2 provided by the TC306 group, only four were valid, i.e. usable, and out of the 13 answers provided by the ISSMGE group, only one was valid (see Table S2 in Supplement A). For the remaining answers, documentation provided was too general (e.g. reference



C1. The material was not adaptable

C2. The material would take a lot of time to adapt it

C3. The material did not have adequate documentation

C4. The material did not come with a reuse permit

Other. (specified below)

1) lack of videos (which were deemed to be more suitable for undergraduates) or 2) videos not being appropriate, 3) preponderance of solutions for idealized problems and the lack of real problems that lack simple solutions or 4) complexity of material unsuitable for undergraduate instruction, 5) broken links no longer available, 6) lack of good textbooks in spoken language, 7) time needed for adaptation mentioned again and 8) testing for demonstration purposes performed non-rigorously, without satisfying standards.

Figure 5. Answers to Question 10 "If you were not satisfied with some of the material found, in what way was the material inappropriate?".

to a software used), vague (e.g. "journals and papers"), "shareable" was interpreted in a narrow sense (e.g. only for the students at the institution of the respondent) or consisted of brief descriptions without links or links of sites in languages other than English, with content that could not be reviewed. Question 4 asking instructors for fully satisfactory teaching materials they use yielded only one answer from the ISSMGE group, which was unsigned and vague ("too many to list... mainly books, site visits, case studies"), so the respective total number of answers is zero in Table S1. Finally, Question 9 asks for examples of the satisfactory materials respondents found in their searches. Although 29 respondents were satisfied with material found, there were only 24 answers to this complementary open-ended question, most of which were inadequately detailed. As a result, Question 9 yielded only eight valid recommendations (see Table S3 in Supplement A). Table S3 is the only instance in the paper where an answer from an incomplete questionnaire is included, because it was a valuable answer (a textbook recommendation). Again, a good number of the answers were vague, precluding access or review of the materials mentioned. A common characteristic of many answers, valid and invalid alike, was that they focused mostly on sources (e.g. URLs of websites or repositories, names of scientific societies), i.e. they followed the "yellow pages" approach, without giving recommendations for specific examples (e.g. which video from the website was satisfactory, which guidance document from the scientific society was useful).

3.4 Dreaming of educational materials for geotechnical engineering

A total of 47 responses were received for the open-ended Question No 11, which asked for examples of "dream educational materials". The answers from the TC306 group and the ISSMGE group were merged, because their differences were non-significant. The answers vary in length from 1-2 lines to full paragraphs; gathered together, they extend over five pages (over 2500 words). Many of the answers are thoughtful and imaginative. However, lack of adequate detail and specificity also characterized these responses. This was equally true for both groups, despite the fact that TC306 members, who were contacted about the questionnaire via e-mail, were sent as an example the first author's "wish list" with specific examples (see excerpt No 6 in Table S4) in order to encourage similarly detailed examples or, at least, choosing from the given wish list (only one respondent chose from the list). Perhaps, and understandably so, respondents felt that a detailed answer would not qualify as a dream. In the absence of detailed answers, the authors followed a 3-step analysis procedure, which is described next.

As a first step, they read the comments several times in order to develop a sense for recurring ideas. A first coarse categorization distinguished answers on the basis of the purpose of the desired educational material. According to this coarse categorization, instructors mostly need: (a) suitable educational materials (e.g. videos, case histories) to present in their lectures specific topics to students (55%, appears in 26/47 answers) and (b) materials to engage students, especially outside lecture time, such as software, textbooks, notes, videos, games, competitions (43%, appears in 20/47 answers). Fifteen of the answers (32%) mention a variety of specific topics: foundations and constitutive modeling are the two most popular topics, mentioned in 8 answers, followed by retaining walls (4 answers), groundwater flow and slope stability (3 answers each).

In the second step, they devised the detailed coding scheme shown in Table 2, in order to quantify the frequency of the themes appearing in the answers. Fifteen different themes were identified, grouped in the following three categories: i) medium, for ideas addressing the means of instruction; ii) teaching and learning, further subdivided in three subcategories –components of instruction, applications, promoting certain attitudes–; and iii) assessment, for proposals related to the evaluation of the students. Videos are by far the most frequently proposed medium for a wide range of "dream proposals" (it appears in 43% of the answers), coupled with the following characteristics:

Table 2. Coding Scheme for answers to "Dream materials" for geotechnical engineering instruction.

Themes	Frequency (in 47 answers)
Category: MEDIUM	
Written text (e.g. books)	6
Video	20
Online material (e.g. portal, hypertexts, app)	5
Software[1]	3
Photographs	4
Illustrations (figures, graphs)	4
Category: TEACHING AND LEARNING	
Subcategory: Components of instruction	
Basic theory (lecture)	5
Example problems (tutorials)	8
Lab and field testing	9
Subcategory: Applications	
Case histories (good practices, failures)	15
Example projects	2
Subcategory: Promoting certain attitudes	
Visual and conceptual understanding	8
Active involvement	10
Category: ASSESSMENT	
Exam questions	2
Self-assessment	1

[1]The focus of the questionnaire is on introductory – undergraduate courses, hence software is viewed as a medium for understanding, i.e. the emphasis is on its results, not on learning to run the software.

short (very often mentioned), engaging, animated, selected, well done. Within the teaching and learning category, among the many themes selected by a good number of respondents –e.g. case studies, example problems and laboratory-related educational materials– it is worth pointing out the significant request for materials that address visual and conceptual understanding and the active involvement of students.

In the third step, each author made an independent selection of the subset of answers that either describe an exciting prospect or provide adequate detail for the production of educational material. When these answers were longer than a few lines or contained a list of wishes, the authors excerpted the most inspirational parts and those illustrating the frequent themes in Table 2. These excerpts from 14 selected answers are included in Table S4 of Supplement A (Pantazidou & Calvello, 2023a). Six of the 14 selected answers (43%) make reference to case studies, indicated by the coding procedure to be the most popular "teaching and learning" theme. To underscore the high frequency of the references to case studies, which appear in 15 of all answers (32%), the relevant excerpts from these answers are included in Table S5 of Supplement A.

3.5 Obstacles preventing dreams from materializing

When asked about the obstacles that prevent respondents from developing themselves the educational material of their dreams (Question No 12), the distribution of responses from the two groups are nearly identical (see Figure 6a). The major obstacle reported is insufficient time (which indirectly reflects lack of funding) at a frequency of 80% (49/61 answers), followed by insufficient knowledge of IT (46%), insufficient support by assistants or funding (38%), and insufficient recognition for work in education (38%). A small but not negligible percentage (15%) mentions as obstacles insufficient communal content knowledge and/or insufficient personal content knowledge. From these two answers, most interesting is the realization that the geotechnical community lacks some knowledge necessary for the production of quality education materials, which may point to outstanding research needs. A more detailed picture emerges when only the responses of the more experienced cohorts are taken into account, as shown in Figure 6b. When considering the most experienced respondents (> 15 years), none has selected insufficient communal content knowledge and a very small minority has selected insufficient personal content knowledge and insufficient soil data. However, the second most experienced cohort (5-15 years) appears to be of markedly different opinion with regards to whether communal knowledge is sufficient: this most dynamic cohort of geotechnical engineering instructors is of the opinion that we lack not only the financial and technical means but also content knowledge.

Figure 6. (a) Answers to Question 12 "What might make it difficult for you to develop the 'educational material of your dreams'?" (b) Obstacles for developing the 'dream educational materials' (Question 12) vis a vis instructional experience (Question 14).

3.6 Investigation of trends

Further investigation of trends between cohorts produced some expected results, e.g. that experienced instructors have developed more shareable educational materials, as well as some findings initially deemed unexpected, e.g. respondents with some formal training in education (Question 16) have developed less shareable educational materials (Figure 7). A possible explanation for this trend could be that respondents with formal training in education have higher standards and are less willing to embark on a very demanding task. Another explanation may be that training in education, as already mentioned, is domain-general and, as a result, gives precedence to method and de-emphasizes content.

4. Discussion of results and recommendations

4.1 Lacking adequate educational materials: is Geotechnical Engineering an exception?

The high percentage (45%) of the geotechnical engineering instructors who replied negatively to Question 8 “were you satisfied with any material found after searching” establishes that there is room for improvement. It is probable that this high dissatisfaction percentage is related to Geotechnical Engineering’s unique feature to deal with a natural material, which necessitates making connections with true soils (see answers 1, 2, 7 in Table S4, Supplement A) and actual cases (all 15 answers in Table S5, Supplement A). In order to investigate any peculiarity of Geotechnical Engineering, a comparison was made to the answers of the similar question “Did you have difficulties finding sources of educational material for your courses?”, from a questionnaire sent to all the engineering instructors at the National Technical University of Athens (NTUA), the home institution of the first author. From the 213 NTUA instructors from all engineering disciplines who responded, only 21 (9.9%) reported having difficulties (NTUA-CTL, 2023). The NTUA respondents were further asked to give the thematic fields for which they had difficulties locating sources. Thematic fields mentioned include both established fields, e.g. metallurgical engineering and databases, and cutting-edge topics, e.g. nanomaterials and computer vision. Interpretation of the significant difference in the percentages reporting difficulties should take into account two salient differences between the two questions. The NTUA question is phrased negatively (did you have difficulties), restricting the number of respondents who answer the accompanying open-ended question, and it does not further inquire whether material found was satisfactory, in which case the difference between the two sets of percentages would be smaller. It is worth noting that because funding from the Greek Ministry for Education resulted in the creation of Centers for Teaching and Learning (CTLs) at all Greek universities at the same time during the academic year 2022-2023, like NTUA-CTL, CTLs from other Greek universities circulated their own version of “needs assessment” questionnaire. The questionnaires of these other CTLs, which are created by specialists in Education, focus mostly on training needs of respondents in matters of pedagogy and lack a question about needs for educational materials. In contrast, because NTUA is a strictly technical university, its CTL is coordinated by an engineering faculty member and, as a result, the NTUA questionnaire included questions on needs for educational materials. Hence, it is possible that the abundance assumption will never be a topic for investigation at centers for teaching and learning serving the domain-general education needs of tertiary education instructors and, as a result, this unexamined assumption will survive like urban legends do.

4.2 Lacking a culture for sharing meaningfully and reviewing critically educational material

The results presented in Sections 3.2 and 3.3 taken together suggest that the practice of providing inadequate

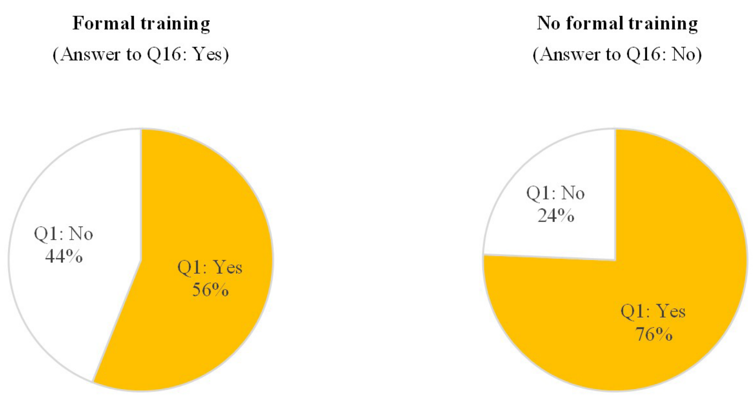


Figure 7. Answers to Question 1 “Have you ever developed shareable educational material yourself?” vis a vis formal training in Education (Question 16).

documentation for educational material is widespread, as shown by the often incomplete information provided by respondents for their own educational material (Question 2), and by the high frequency inadequate documentation is given as a reason for dissatisfaction with educational material found (Question 10). It is likely that this is an ingrained habit for educators, hence changing this "no explanations given" culture will require concerted interventions. One such intervention could be to require educational material to be accompanied by brief "teaching notes" including the purpose/reason for creating it.

Educators also appear to be uncomfortable with judging existing materials and selecting the most useful: only in a few instances complete references are given to specific materials (i.e. not the entire list of publications of a scientific society). This paper, as a mild intervention to change this "no choice" culture, reports some usable open-ended answers to Questions 2 and 9 (Tables S2, S3 in Supplement A), when possible with complete references and a particularly interesting specific example (see No 1 in Table S2 and No 3 in Table S3, Supplement A).

Shulman (1993) wrote in his inspirational article "Putting an end to pedagogical solitude" about the drawbacks of the private nature of teaching, and urged instructors to adopt instead the public culture of research, i.e. publicize their educational material and take the responsibility of judging the educational material of their colleagues. The creation of opportunities for instructors to offer small-size contributions to the geotechnical engineering education community (ISSMGE, 2023) may be a step towards the change of teaching from private to public endeavor. Small-scale contributions can be more easily reviewed and circumvent the obstacles mentioned in the answers to Question 12 (lack of time/funding/support, lack of recognition).

The sizeable difference in searching for educational materials between the TC306 and the ISSMGE groups might be (partly) attributed to the higher instructional experience of the TC306 respondents. It is unfortunate that those who can better judge educational materials are less likely to search for them. Hence, it would be desirable to establish some communication lines between more junior and more senior colleagues, for instance with the juniors searching and submitting carefully selected materials to the seniors for reviewing.

The results of the detailed investigation of the reasons why some materials are unsatisfactory (Question 10) underscores the difference between merely uploading raw educational material and truly sharing educational material, i.e. facilitating review and use by others, through appropriate accompanying documentation (an "education manual" so to speak). It is recommended that educators move away from considering "uploaded" and "shareable" to be almost synonymous and towards providing mini manuals of use explaining their thinking to their colleagues. In terms of infrastructure, it is recommended to create a repository for case studies developed specifically for geotechnical engineering instructors, consolidating in one place prior TC306 efforts (Belokas et al., 2013; Orr & Pantazidou, 2013; Pantazidou, 2016; Viggiani, 2018).

5. Conclusions

- The majority of geotechnical engineering educators do not have available the educational materials they would desire. This finding contradicts the –largely unexamined– popular belief that there is no scarcity of quality educational material at the university level.
- Not surprisingly, the responses of geotechnical engineering educators indicate that quality educational materials require team efforts, IT support and funding. Confirming the need for quality educational material for geotechnical engineering instruction will improve the odds for securing funding for its development.
- Less expected and worthy of further investigation is the finding suggested by more than 10% of the responses that additional research may be necessary for improving the quality of educational materials used in geotechnical engineering instruction.
- Recommendations for the enrichment of educational materials used in geotechnical instruction include (i) developing a varied infrastructure for publicizing and reviewing educational material, such as a repository for references and brief descriptions of case studies developed specifically for instruction, (ii) promoting infrastructure permitting small-scale contributions and (iii) developing educational material for specific topics with the desired attributes identified in the literature, i.e. educational to educators and students alike, and herein, i.e. interactive and aiding visual and conceptual understanding.
- While no one topic stood out clearly above all others, educational material for foundation topics and in particular bearing capacity and stress distribution underneath loaded areas will be useful to a good percentage of geotechnical engineering instructors.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Marina Pantazidou: conceptualization, questionnaire – original draft, initial data analysis, writing – original draft. Michele Calvello: questionnaire – review & editing, final data analysis, writing – review & editing.

Data availability

The datasets generated and analyzed in the course of the current study are available in online Supplement B (Pantazidou & Calvello, 2023b) as an EXCEL file.

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An international initiative on geosynthetic education

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Article

Keywords
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Abstract

An international educational initiative to facilitate the exposure of geosynthetics to undergraduate civil engineering students has been conducted by the International Geosynthetics Society (IGS) for over a decade. Geosynthetics is a comparatively new topic within geotechnical engineering and, consequently, has only been sporadically introduced into undergraduate Civil Engineering curricula. In particular, geotechnical engineering professors themselves may have not been exposed to the basics of geosynthetics to be able to comfortably transfer such knowledge to their students. As part of this educational program, civil engineering professors are invited to take a course on geosynthetics, for which they receive fellowships covering their expenses. The course also includes complementary components such as a workshop consisting of practical demonstrations, pedagogical material, and technical documents. Implementation of the program involves multiple parties, including the IGS, its national chapters, and geosynthetics industry, who are allotted the responsibilities of supporting the program instructors, offering practical project-oriented input. This paper describes the course structure, the educational tools employed, the impact on the program caused by the pandemic, and results from feedback surveys that assessed how the knowledge on geosynthetics acquired by the participants was transferred to their students in terms of new courses on geosynthetics, inclusion of geosynthetics topics in existing undergraduate disciplines, etc. Emphasis is given on the experience of the Brazilian Chapter of IGS, which has already conducted programs. The educational outcomes of the programs currently offered are being evaluated and they suggest excellent acceptance of the course by participants and undergraduate students at the universities.

1. Introduction

Civil engineering (CE) programs are currently facing increasing technical challenges in relation to the continuously evolving nature of engineering works, which require knowledge of new materials and technologies. However, while CE curricula need to provide such new knowledge to young engineering graduates, they also need to limit the offerings of disciplines in undergraduate civil engineering courses. Accordingly, to ensure that these courses remain relevant and effective, new materials such as geosynthetics must be included but in a way that become integrated into existing syllabi. In this context, geosynthetics are a comparatively new technology in civil engineering, and therefore introducing them into undergraduate courses is a priority but also a challenge for disseminating such knowledge among future civil engineers.

An international training program called "Educate the Educators (EtE)", initiated in 2012 under the auspices of the International Geosynthetics Society (IGS), is addressed to university professors in civil engineering, and aims at providing the content and pedagogical tools necessary for them to teach undergraduate civil engineering students on geosynthetics. An important goal of the EtE program is to provide undergraduate civil engineering students with, at least, a one-hour lesson on geosynthetics. This content should be offered in mandatory disciplines of the fundamental engineering courses, so that every undergraduate engineering student will have received a basic knowledge of geosynthetics before they graduate.

The EtE program provides participants with grants to cover their expenses for a typically two-day-long course. Instructional material from theoretical and practical classes and instructional documents are provided to the participants.

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The EtE program also includes more advanced modules addressing the design of geotechnical systems using geosynthetics, such as retaining walls, embankments, roads, and waste containment facilities. The educational outcomes of the programs currently offered are being evaluated and they suggest excellent acceptance of the course by participants and undergraduate students at the universities.

2. Timeline

Geosynthetic materials were introduced more than half a century ago and have been widely adopted in engineering applications to fulfill functions such as separation, stabilization, drainage, wastewater and landfill applications (cushions and liners) (Koerner, 1986; Zornberg et al., 2020). Over four decades ago, on November 20th, 1983, the International Geosynthetics Society (IGS) was established (Zornberg 2013) and the first edition of the landmark textbook "Designing with Geosynthetics" (Koerner 1986) was published. The IGS is a learned society dedicated to the scientific and engineering development of geotextiles, geomembranes, related products, and associated technologies. The purpose of the IGS is to provide understanding and promote the appropriate use of geosynthetic technology worldwide.

In the early days of geosynthetic use, applications focused primarily on the use of geotextiles for projects involving drainage, filtration and soil reinforcement and of geomembranes for applications requiring a barrier function. Over the past 50 years, these products have evolved significantly and nowadays there is a wide variety of geosynthetic products from an ever-increasing number of manufacturers, as exemplified in the annual Geosynthetics Specifiers Guide (IFAI, 2019). The functions and applications of these materials in geotechnical and environmental protection works have also expanded significantly.

A of using geosynthetics include their speed of installation, ease of deployment in remote areas, comparatively low construction costs, availability of a wide range of products, reduction or elimination of the use of natural construction materials, uniformity of mechanical and hydraulic properties, increasing number of established design methodologies, and reduced environmental impact of geosynthetic solutions compared to conventional alternatives. Research carried out in recent decades has also shown that engineering solutions using geosynthetics result in more sustainable alternatives, having lower impact on the environment than traditional solutions (Palmeira et al., 2021).

According to Zornberg et al. (2020), despite the aforementioned advantages, geosynthetics continue to be regarded as a new product by many practitioners in the civil engineering industry, mostly due to the lack of familiarity with geosynthetics and their benefits. The adequacy of current design approaches involving geosynthetics has been validated certified through the success of a myriad of existing projects, the availability of numerous standards (ASTM, ISO, CEN, ABNT and others), the increasingly effective quality control in testing procedures, as well as the availability of design manuals and training courses.

A more plausible explanation for the still insufficient adoption of geosynthetics is the lack of education on geosynthetics, as most undergraduate university programs do not include geosynthetics in their curricula. The IGS Council decided in 2010 to set up a program to educate academics about geosynthetics so that they could introduce geosynthetics into their undergraduate courses and thus train future generations of engineers. The objectives of the "Educating the Educators" program were established to assist the educator in introducing geosynthetics as a relatively new and promising technology within civil engineering.

EtE programs result from the initiative of a national chapter IGS, with subsequent involvement from the IGS. The IGS provides financial support to cover travel expenses of the instructors of an EtE event, and also provides educational materials such as a sustainability video, technical handouts, and glossary of geosynthetic terminology. The overall implementation of an EtE event requires a partnership involving the IGS, the local IGS chapter, the local geosynthetics industry, and national civil engineering faculty associations.

To support the IGS mission, an international foundation (the IGS Foundation) was established in 2021 with the objective of collecting donations from different segments of the geosynthetics community for subsequent allocation to important initiatives such as education outreach. For example, a recently supported initiative involved the production of a series of educational videos by two professors from universities in the USA and Brazil. The videos, including basic content on geosynthetics and instructions about practical workshops of the EtE course, were published and are publicly available, for use by undergraduate professors at their universities.

According to Zornberg et al. (2020), The inaugural "Educate the Educators" program was held in May 2013, in Carlos Paz, Cordoba Province, Argentina. This first event was organized by the Argentinian chapter of the IGS, with the support of the International Geosynthetics Society and in cooperation with the Argentinian Society of Geotechnical Engineering. The event brought together 40 professors from 18 different Argentinian universities, representing 19 different cities across the country and the selection criteria involved the professor's stage in the academic career, experience, maximum academic degree reached and geographic diversity. At least one professor was selected from each university.

From the inaugural program in 2013 to April 2023, a total of 22 additional EtE programs have been conducted. Figure 1 shows the locations of the EtE programs completed to date. As the figure illustrates, 23 EtE programs have already been conducted (Zornberg et al., 2020; International Geosynthetics Society, 2023). Three more EtE are planned to be held in 2023, reaching 26 events in 15 countries, with over 700 educators trained. Demand for implementation of additional programs has continued to increase.

The broad geographical implementation of the EtE program illustrates the significant interest in geosynthetics education worldwide and the motivation of IGS chapters. However, Figure 1 shows a comparatively higher concentration of EtE in the American continent.

Table 1 presents results from the IGS evaluation of EtE programs conducted from 2015 to 2020 (International Geosynthetics Society, 2023). The results show that 17% of the participants from have been able to include geosynthetics in existing disciplines and have created disciplines on geosynthetics.

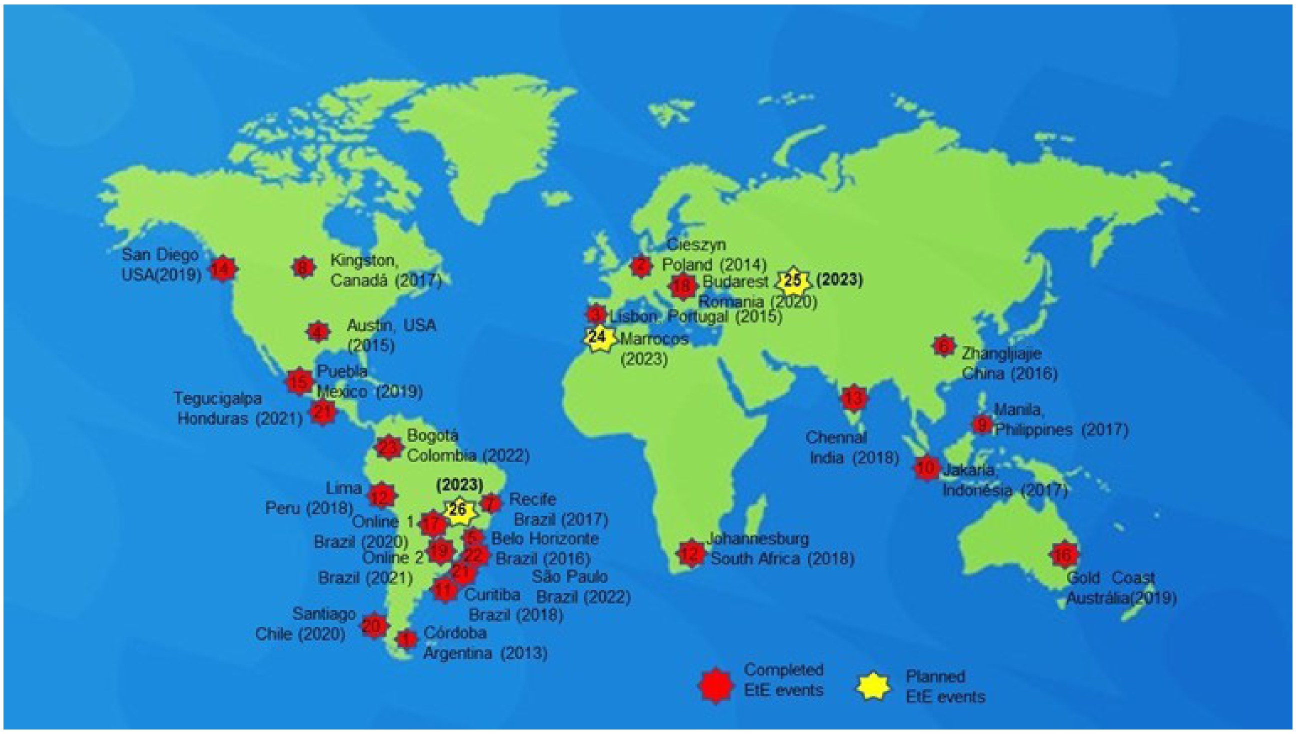

Figure 1. Geographic distribution of Educate the Educators programs conducted up to April 2023 and planned within a 12-month period.

Table 1. Outcomes of the EtE programs conducted from 2015 to 2020 in the world (International Geosynthetics Society, 2023).

Year	Country	Number of students	Included GSY in existing disciplines (%)	Created a discipline on GSY (%)
2013	ARGENTINA	25-50	NA	NA
2015	USA	0-24	20	20
		25-50	0	20
		51-100	0	0
		100-150	10	0
2017	CANADA	0-24	17	0
		25-50	0	8.3
		51-100	17	0
		100-150	17	17
2019	USA	0-24	8,3	0
	USA	25-50	17	0
	AUSTRALIA	25-50	17	17
	PERU	25-50	17	17
	AUSTRALIA	51-100	17	7
	MEXICO	25-50	NA	NA
2020	TAIWAN	0-24	10	0
		25-50	0	0
		51-100	0	0
		100-150	0	0

Note: NA = not available; Data on Brazilian EtE's to be presented later in this paper.

3. Structure of the EtE Program

3.1 Objectives

As previously mentioned, the overall goal of the EtE program is to provide basic knowledge about geosynthetics to all undergraduate civil engineering students.

The consensus is that the focus on education should involve providing basic information about geosynthetics, even if only a one-hour course within a four-year program, but to all undergraduate civil engineering students. Since they share the same curriculum as civil engineering, geotechnical, structural, environmental, transportation, construction, and hydraulic engineers will also benefit from at least this basic knowledge of geosynthetics before they graduate.

Achieving the goal of the EtE initiative may be especially challenging since civil engineering programs are facing increasing challenges from a vastly expanded curriculum base and the need to limit the entry of new disciplines.

With the ultimate beneficiary of the EtE program being the undergraduate student, the effort of this initiative focuses on training the university professor, who will thereafter provide this basic knowledge of geosynthetics to their students. The specific objectives of each EtE course are as follows:

- Provide material for immediate implementation in at least one class on geosynthetics offered to all civil engineering students at the undergraduate level;
- Provide additional information on geosynthetic applications for implementation in upper-level undergraduate courses;
- Offer information that can also be used for advanced classes or graduate courses;
- Offer information that can also be used for advanced classes or graduate courses;
- Evaluate ways to implement the educational material provided in the classroom;
- Outline the basis for curriculum changes that include geosynthetics teaching.

The specific objectives of each EtE program were often tailored to address needs of the country or region of the event.

3.2 Educational content

The EtE educational program is delivered by geosynthetic engineering experts (usually 3 professors), from universities in the country where the course takes place or invited from other countries. The content of each EtE program is adapted according to the needs of the local chapter in order to facilitate conveying the experience on geosynthetic by the actual experts delivering the program.

The philosophy of the program has been to offer it only as in-person forums to facilitate the experiential nature of the technical content. Such an approach has allowed EtE faculty delivering the course to interact with attendees, facilitating discussion on teaching methodologies and curriculum issues beyond the technical geosynthetics content. However, during the pandemic period, years 2020 and 2021, continuity of the program required that its delivery be conducted. For example, two of the EtE programs implemented by the Brazilian chapter were conducted online. The Chilean chapter has also conducted its EtE program during the Pandemic using an online format.

The duration of EtE programs is usually two days, with at least 16 hours of instructor contact time. Other durations, such as 2.5 days and 3 days, have been implemented, at least by the Brazilian Chapter, but a duration of two days is deemed the best suited. Each EtE event involves a partnership between the international society and its national chapter, the local geosynthetics industry, and national associations of civil engineering professors.

IGS provides funds to cover travel expenses for program instructors. The responsibilities of the local IGS Chapter are to coordinate activities and funding related to the venue, compilation of educational material (e.g., geosynthetic samples), promotion of the event, and design and execution of the application process and selection of event attendees. The local IGS Chapter, along with industry sponsors, fund local travel expenses (e.g., hotels, meals) for the attending university professors, with only the transportation costs being paid by the participants.

The structure of the different EtE programs has been reasonably similar. For example, the program conducted in Austin, Texas (USA), in 2015, consisted of four modules, which considered four typical undergraduate CE courses (Zornberg et al., 2020). Table 2 presents the structure of EtE 2015, Austin, Texas, USA (Zornberg et al., 2020).

- Module 1: A typical “Geotechnical Engineering I” core class
- Module 2: A typical “Geotechnical Design” technical elective class
- Module 3: A typical “Pavement Design” technical elective class
- Module 4: A typical “Environmental Design” technical elective class

In the EtE programs, introductory topics were presented to illustrate the didactics and level of detail expected in undergraduate civil engineering courses. The advanced topics were presented at a higher level with a focus on technical content and should illustrate the level of complexity that designers of systems using geosynthetics must achieve. Discussions were focused on the theoretical content delivered and the implementation of basic and advanced topics in undergraduate courses.

EtE Brazil introduced several innovations, such as an initial class on pedagogical tools for participants to use in their disciplines; two practical workshops presenting different engineering projects to be analyzed using geosynthetics; and the development of the Pedagogical Plan for the discipline of geosynthetics, which was developed during EtE and delivered at the last class by each of the participants.

Another interesting innovation introduced by EtE Brasil was the creation of a Mutual Support Network (MSN), with the aim of integrating the participants with each other, with the teachers, and with the IGS Brasil secretariat, during and after the course. The MSN would grow with each EtE held and interconnect participants from all regions of Brazil.

4. EtE Programs in Brazil

4.1 General description

To satisfy the demand for the program, a total of six EtE courses were implemented in Brazil (2016, 2017, 2018, 2020, 2021 and 2022). Figure 2 illustrates the origin of the attendees throughout the Brazilian territory (modified from Zornberg et al., 2020). The events implemented by the Brazilian Chapter of the IGS are described in this paper as a case study to explain the metrics collected from the participants and the overall outcomes of the EtE programs. The first EtE event in Brazil was held in 2016 in the city of Belo Horizonte (southeastern region of Brazil) and included participants from the entire country. Considering the vast territorial extension of Brazil, it was decided to organize the subsequent EtE's courses in different geographic regions to facilitate outreach to a high number of professors. The regional events included: North and Northeast, Midwest, Southeast, and South. Specifically, the 2017 event was held in the city of Recife (north and northeastern regions); the 2018 edition took place in the city of Curitiba (southern region); the 2020 event, which was the first online EtE (due to the COVID 19 pandemics), aimed at participation from the Midwest region; the 2021, which was also an online event, aimed at participation from the Southeast region. The most recent (2022) event was held in São Paulo and included participants from the entire country. Table 3 summarizes information from the six Brazilian EtE courses, the regions where they were held, and the number of participants in each one.

Table 2. Typical structure of an EtE program.

Introductory Topics	1. Introductory class on types and functions of geosynthetics materials
	2. Introductory class on geosynthetics in soil reinforcement applications
	3. Introductory class on geosynthetics in roadway systems
	4. Introductory class on geosynthetics for environmental protection
Topics	1. Fundamental properties and related tests on geosynthetics materials
	2. Advanced topics on geosynthetics-reinforced soil walls
	3. Geosynthetics-reinforced steep slopes
	4. Geosynthetics for stabilization of unpaved roads
	5. Geosynthetics for stabilization of paved roads
	6. Prediction of leakage through geosynthetic liners
	7. Factors affecting the service life of geosynthetic liners
Support Activities	Workshops
	Case histories
	Discussions

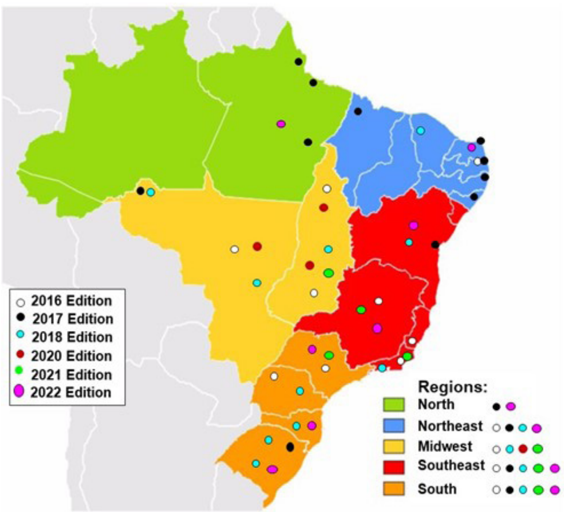

Figure 2. Origin of the attendees to the EtE programs implemented in Brazil.

Table 3. EtE held by region in Brazil and number of attendees.

EtE date	Region	City	Number of attendees
2016	All regions	Belo Horizonte	27
2017	Noth/Northeast	Recife	27
2018	South	Curitiba	30
2020	Midwest	Online	34
2021	Southeast	Online	28
2022	All regions	São Paulo	24

Despite the country's significant size and the wide distribution of its population, a relatively diverse distribution of participants' origins can be observed in Figure 2, with a greater number of attendees coming from the southeastern and southern regions of Brazil. The organization of such courses has had a major impact on the dissemination of geosynthetics among undergraduate students in Brazil, as will be detailed below.

Consistent with the technical content previously described for the EtE program, the EtE courses given in Brazil examined different aspects of geosynthetics applications in civil and environmental engineering works. Overall, the following topics were addressed:

- Introduction to the teaching of geosynthetics at the undergraduate level; objectives of the "Educating the Educators" program; course methodology, pedagogical techniques;
- Geosynthetic types and functions;
- Geosynthetic properties and testing;
- Geosynthetics in filtration and drainage;
- Geosynthetic-reinforced walls;
- Geosynthetic-reinforced steep slopes;
- Reinforced embankments on soft soils;
- Geosynthetics in roadway applications;
- Environmental applications of geosynthetics;
- Hydraulic applications of geosynthetics.

Following core sessions on a given theme, sessions focusing on case histories of engineering works involving geosynthetics were presented to provide additional context involving recent projects. Pedagogical workshops with groups of activities were also conducted, including integrated panels, workshops on recognition of geosynthetic samples, customer and supplier exercises, and a pedagogical workshop for the preparation of the geosynthetics course plan (Masetto, 2003; Coelho, 2012; Coelho, 2016; Gardoni & Coelho, 2016; Hjalmarson et al., 2021, Merrett, 2023).

The workshops involve the application of teaching techniques and group dynamics, followed by a discussion of the pedagogical knowledge that underpins class planning, learning evaluation, and the relationship between the teacher, the students, and knowledge. This pedagogical setup is better aligned with the practical learning outcomes associated with geosynthetic materials in engineering, such as the selection of types and functions that the geosynthetics can fulfil, as well as their properties. Participants are also exposed to project challenges during the course to better prepare their undergraduate students for the project challenges they will encounter during their careers.

The Pedagogical Workshop reviews the pedagogical techniques experienced during the course (Integrated Panel, Client, and Supplier), the pre-planning of teaching for the subject based on the knowledge acquired in the course, and the Mutual Support Network proposal for continued interaction among attendees, instructors and manufacturers.

4.2 Analysis and results

The benefits derived from the various courses implemented in Brazil were assessed by interviewing attendees at the end of the event and two years thereafter to evaluate if the major course objectives had been achieved. Figures 3a to 3f present evaluations at the end of the event by the attendees of the six events in Brazil (from 2016 to 2022) (Zornberg et al., 2020). Specifically, the attendees evaluated the courses by assigning a grade ranging from zero (poor) to 5 (excellent) regarding quality of learning, quality of course content and overall satisfaction. As indicated by the ratings shown in Figure 3, the attendees thought very highly of the course in the different categories and in the various events. The evaluations of the three types show increasing scores for EtE 2022 compared with previous years. However, for "Quality of learning" and "Satisfaction with the course", the rating reached 100% compared to the last years.

As part of the evaluation process of the benefits brough by the EtE program, the participants were also interviewed two years after course completion to assess if the main course objectives were accomplished. Approximately 60% of the participants in the 2016 to 2022 courses responded to a questionnaire aimed at evaluating the influence of the course on encouraging them to disseminate the knowledge acquired.

Figure 4 shows that geosynthetics topics had been incorporated to existing disciplines in undergraduate courses by 62% of the 2016 course attendees; elective disciplines on geosynthetics had been created by 15% of them; geosynthetics were included in routine academic events at their institutions by 54% of the attendees. In addition to coursework activities, 15% of the attendees indicated having delivered keynote addresses; and 15% indicated having participated in the offering of geosynthetics short courses.

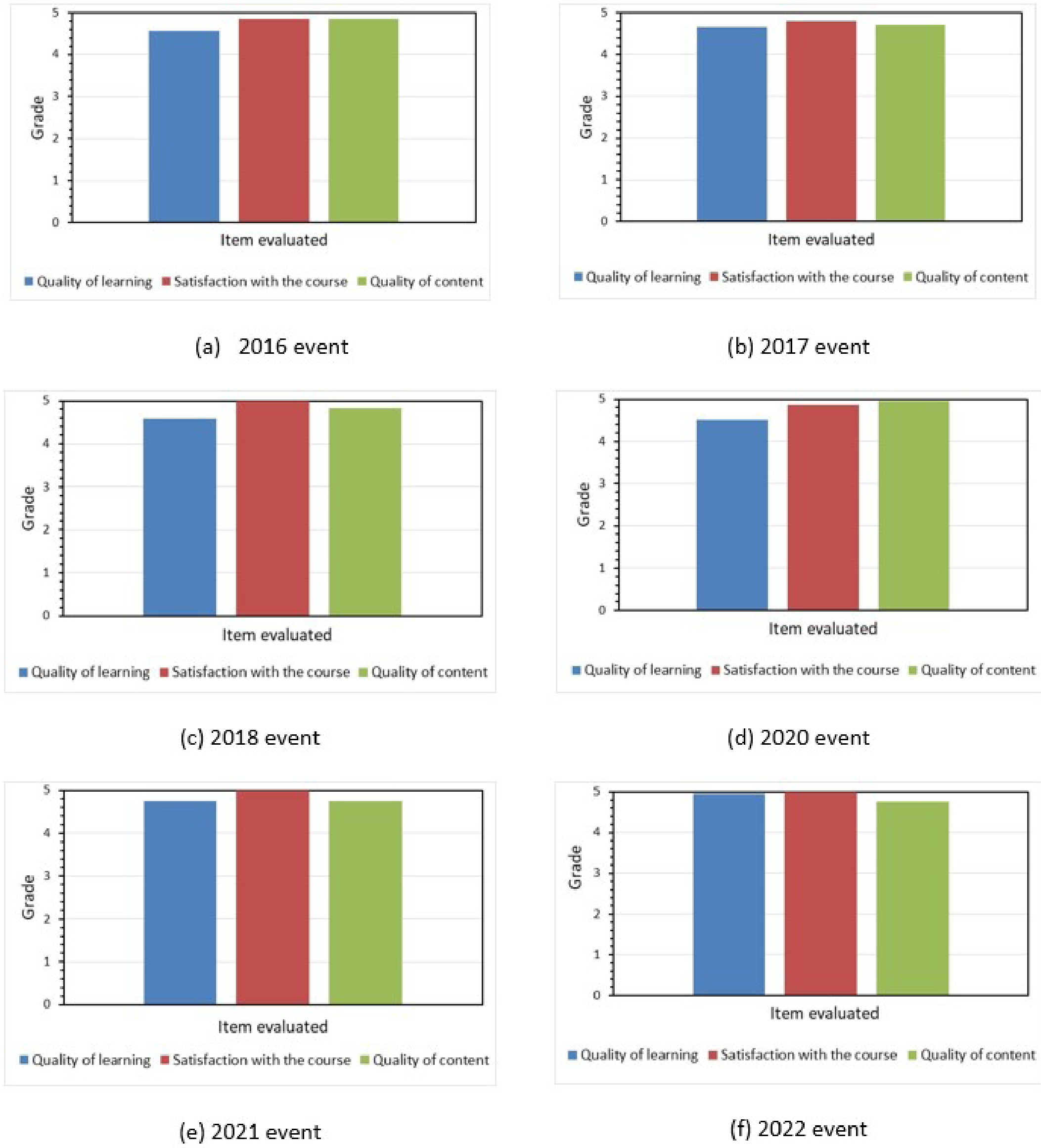

Figure 3. Evaluation of EtE course by attendees.

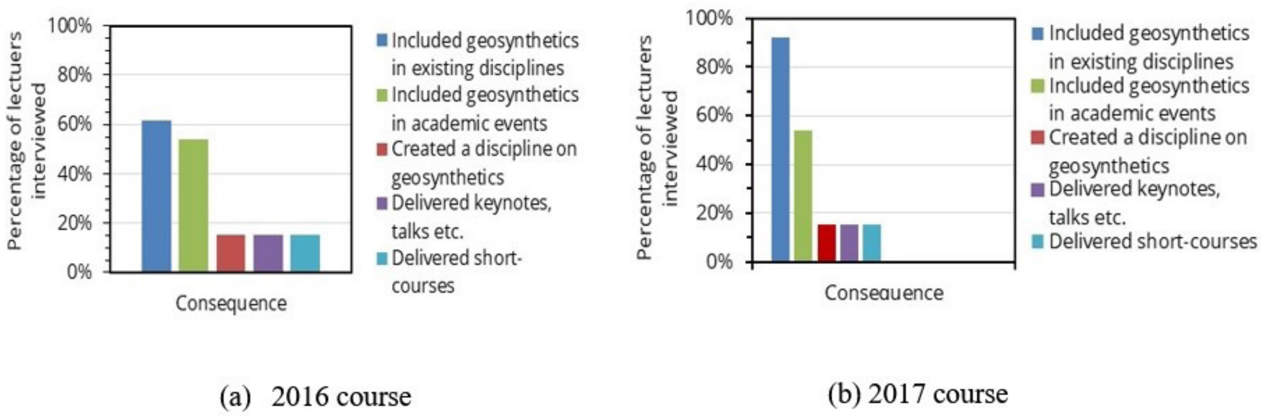

Figure 4. Percentage of Respondents of EtE programs conducted in Brazil, after two years.

Table 4. Number of students enrolled in classes on geosynthetics because of EtE programs in Brazil.

Number of Students	2016	2017	2018	2020	2021
	(%)	(%)	(%)	(%)	(%)
5-20	8	8	6	17	33
20-70	31	38	50	58	34
70-150	23	23	28	17	33
Over 150	15	8	17	8	0

Inspection of the information in Figure 4 reveals some notable highlights, including the fact that geosynthetics topics were included in existing disciplines in undergraduate courses by 90% of the 2017 course attendees (See Figure 4b); 54% included geosynthetics in academic events; 10% created a discipline on geosynthetics; 11% delivered keynote addresses and 6% offered geosynthetics short courses.

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An important achievement regarding the percentage of lecturers who successfully introduced the subject of geosynthetics into existing disciplines was observed. While the 2016 EtE showed 62% of the course attendees having this initiative, for 2018 and 2020 EtE that percentage reached 100%. While the objective of the EtE program was not necessarily to support the creation of a new discipline, it was interesting to observe that 15% of the attendees to the 2016 and 2017 events reported affirmatively to the question "have you created a discipline on geosynthetics?". However, some decrease in this specific outcome was observed in the outcomes of the subsequent EtE events. Yet, the reason for such decrease in this ambitious outcome may have been the determination of the Brazilian Ministry of Education to reduce the number of disciplines in undergraduate courses. In fact, the results of the EtE program in Brazil so far can be clearly qualified as a huge success since a survey pre-dating the EtE program (of the year 2000) had shown that only two universities in the country with disciplines on or incorporating geosynthetics in the curricula of undergraduate courses (Palmeira 2000).

Table 4 shows the number of students enrolled in courses including geosynthetics that the participants in the four EtE programs had delivered by year 2021 in their institutions. Differences between the results of the EtE courses are likely a consequence of differences in academic conditions, curricula, and facilities of the host institutions in different regions of the country.

Analysing the results obtained in the online EtE's in relation to the face-to-face EtE's, immediately after the end of the course, they remained practically the same for both, with an increase in "Satisfaction with the course and "Quality of the content. However, in relation to "Inclusion of geosynthetics in existing subjects" there was a significant increase in EtE2020 online compared to the previous in-person courses, but the other items evaluated showed decreasing results. This can be explained by the pandemic that occurred in Brazil in 2020 and 2021.

5. Conclusion

An international educational program to facilitate the exposure of geosynthetics to undergraduate civil engineering students, Educate the Educator has been introduced by the International Geosynthetics Society (IGS). Some conclusions that can be reached from the evaluations on this initiative are:

- The EtE initiative has been successfully implemented throughout the world, as evidenced by the 23 EtE events conducted so far, which took place in 14 countries, providing access to geosynthetics knowledge to a geographically diverse number of undergraduate students;
- The demand for EtE worldwide has been continuously increasing, which attests to the program's effectiveness;

- Brazil has conducted 6 EtE with 161 participants from various universities from all regions of the country. The evaluations carried out after the course and two years after its completion show that teaching activities such as introduction of the subject in existing disciplines, creation of optional subjects, academic events, lectures and mini courses were implemented in all the universities that attended the program;
- The participants of EtE Brazil have been continuously interacting through the Internet in a Mutual Support Network, helping each other with materials, suggestions for classes, practical workshops etc.;
- Regarding the online EtE, IGS Brazil adapted the online version of the practical classes so that could be reproduced online. Several adaptations were necessary for the course to work. One of them was the sending of geosynthetics samples by mail one week before the start of the course and the students received the photos of the samples that they were supposed to separate from the box before the practical class;
- Despite the excellent evaluations received from the online EtE participants, the course coordinators and instructors have concluded that the in-person format is the most suitable and that it best meets the EtE's objectives. There are several reasons for this, such as: the dedication of the participants is much greater in the in-person EtE, since they are totally immersed in the course, while in the online version they continue to carry out their university activities. The participant's contact with the instructors is so important as is the student's contact with the teacher in the classroom. The practical activities were greatly affected in the online version since there was no connection between the students during the project discussions. In conclusion, the Brazilian experience has shown that for a course with the philosophy of EtE, th in-person version is essential.

Bearing in mind the significant size of the Brazilian territory, it may be concluded that the EtE program in Brazil has been a great success for dissemination of the geosynthetics knowledge in the country, serving as example for successful implementation of similar initiatives by other countries.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Maria das Graças Gardoni Almeida: conceptualization, data curation, formal analysis, methodology, visualization, writing – original draft. Jorge G. Zornberg: conceptualization, data curation, supervision, validation, writing – original draft. Ennio Marques Palmeira: formal analysis, conceptualization, data curation, supervision, validation, writing – original draft. Nathalie Touze: data curation, supervision, validation, writing – original draft.

Data availability

The datasets generated analyzed during the current study are available from the corresponding author upon request.

Abbreviations

ABNT	Brazilian Association of Technical Standards
ASTM	American Society of Testing Materials
CE	civil engineering
EtE	educate the educator
IFAI	Industrial Fabrics Association
IGS	International Geosynthetics Society
IGS-Brazil	Brazilian Chapter of the International Geosynthetics Society
INRAE	Institut National de Recherche pour l'agriculture, l'alimentation et l'environnement
ISO	International Standards Organization
NA	not available

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Interaction of geotechnics with society through education

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Article

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Abstract

The Federal University of Goiás (UFG) and the University of Brasília (UnB), in partnership with the company Eletrobras Furnas, have developed research and, based on this, extension projects aimed at education in a broad sense, in which they seek to disseminate and popularise technical-scientific knowledge. This paper aims to present and evaluate educational actions carried out in the area of soil science and geotechnics applied to engineering, geography, and the environment. To do so, the educational experiences developed within the scope of two extension projects are shared. Besides that, the relevance of publishing books and primer, with language adapted to lay society, within the scope of research projects, is analysed. The results collected regarding the effectiveness of the extension actions as a tool for learning point to a positive evaluation by the students. Furthermore, social networks are an important tool for scientific dissemination and have the potential to disseminate knowledge more widely than in a classroom course. By comparing the number of citations in Google Scholar of the books and booklets with the papers arising from these projects, one can observe the reach of this type of publication, although its purpose is the popularisation of science, with reach in places not considered in the technical-scientific publication metrics. Finally, for effective scientific development, it is necessary to have public policies, effective interaction between universities, research centres and schools, and the participation of professional associations, funding and evaluation agencies, Education Departments and the Ministry of Education, Science, Technology, and Innovation.

1. Introduction

Science communicates its research, scientific questions, investigative and analytical methods, as well as the results of this research and its answers, correct or not. In general, this is done in the form of a text with a formal technical language specific to each area of knowledge. In this way, this communication is presented and validated among peers, fundamentally in specialised journals and conference proceedings. This is very important for the advancement of science, since such communication enables the knowledge produced to be subject to evaluation, criticism, reproduction, and modification, but it also means that it is circumscribed within the professional environments of science. It is worth remembering that scientific practices take place within society and for society, yet this type of communication, as a rule, does not reach them in an accessible way. So how to reach the general population with scientific knowledge? The strategies used for this purpose are in the field of scientific dissemination.

According to Silva (2006), scientific dissemination is not restricted to a single type of text, but is associated with historical, cultural, and technological contexts. According to this author, the circulation of the first scientific books for children dates back to 1770. Claret (2007) points out that the advent of electronic techniques may extinguish the traditional book printed on paper, whose content could be passed on by other means. Nowadays, books in digital format are very popular, and there are even specific electronic devices for this type of reading, although it is also possible to download, store and read this type of book on cell phones. Cell phones have increasingly sophisticated technologies linked to social network applications, which are a great option for the diffusion of knowledge.

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However, on this platform, all kinds of information circulate, not always with reliable quality and not necessarily grounded on scientific bases, which generates a dangerous condition for lay people seeking to access information.

A study on the public perception of science and technology in Brazil developed by the Centre for Strategic Management and Studies of the Ministry of Science, Technology, Innovations and Communications indicates that 73% of Brazilians think that Science and Technology (S&T) brings only benefits, or more benefits than harm to society, and consider it very important for the future (CGEE, 2019). However, they expect greater investment in this sector, including for greater access to and consumption of information about science. If the various areas of science are not concerned with disseminating and making scientific knowledge accessible, people may access poor quality information that is harmful to society and to the maintenance of the credibility of scientific endeavours. The COVID-19 pandemic has exposed a scenario of disinformation, with the intensification of rumours, fake news, and conspiracy theories, as discussed by Carvalho (2022). According to this author, this discredit to science led to political actions in Brazil, which, associated with cultural and educational aspects, culminated in the promotion of drugs without any scientific basis for the treatment of COVID-19 and even the non-recommendation of vaccination, which ultimately contributed to the occurrence of thousands of deaths.

What does scientific dissemination, the democratisation of scientific knowledge and the disastrous management of a health crisis in a pandemic context have to do with geotechnics? Geotechnical engineering, based on the science of soil mechanics, rock mechanics and the knowledge of engineering geology and geography, evaluates the mechanical behaviour of soils and rocks and, therefore, has a great responsibility for the prevention and mitigation of natural phenomena with the potential to damage society and human lives, such as landslides, erosion, silting, and flooding. As an example, we have the threats to life and to private and public property generated by erosion that are occurring in Buriticupu - MA (Globo, 2023). Every year, in all parts of the world, thousands of lives are lost in disasters that are considered natural, but which would have great potential to be predicted and avoided if we could broaden our view in time and space and invest more in the broad education of society.

According to the ONU (2021), natural disasters accounted for 45% of all deaths in the last 50 years in the world. According to Kobiyama et al. (2006), historically, disasters such as floods are the ones that caused the greatest loss of life in Brazil. However, it is not difficult to observe, by broadening our gaze, that most of them have their origins in human practices land occupation. Macedo & Sandre (2022), when analysing the database of deaths from landslides of the Institute of Technological Research of the State of São Paulo (IPT), observed that the total number of fatal victims was 4,146. The larger the cities, the greater the number of victims, since in these places there is a more complex socioeconomic dynamic associated with the occupation of slopes. Estarque (2023), through the Integrated Disaster Information System, points out that at least 7.7 million Brazilians have been forced to move in the last 18 years. Among them, 6.4 million were made homeless or displaced by natural disasters. This author reinforces the assertion of Kobiyama et al. (2006) that floods are among the disasters that most displace Brazilians (45%) and in second place flash floods (32%).

The mitigation or prevention of most natural disasters must go through stages of planning, regulatory legislation, and infrastructure works that are properly planned and executed. In this context, education stands out as a powerful tool for the prevention of natural disasters, especially those of a geotechnical nature. Managers should be concerned to be educated and updated to keep these issues in mind within the legislative and executive fields; engineers need to be educated and well trained about the most current techniques and the socio-environmental impacts of their work interventions; and society needs to be educated and enlightened to recognise risk situations, to avoid them, as far as possible, through appropriate initiatives and practices, and to pressure public management for strategic actions. Thus, in Brazil, teaching in schools as well as through non-formal education about floods, erosion, and landslides can have a great preventive function. Of course, it is necessary to consider all the social segregation issues involved in the occupation of risk areas, but knowledge of the inhabited geographic space is the first means of citizen emancipation. It was knowledge of the inhabited space, the peculiarities of the soil, the river dynamics, seasons, and types of plants that first allowed human civilisation to stop being nomadic and settle in the Mesopotamian plain and fertile crescent of the Nile.

Thus, the interactions of geotechnics with society through education should occur in different ways and considering multiple social spheres, which are: the development and use of specialised and diversified teaching material; publication of articles at local, regional and national events; publication of articles in journals; publication of primers, book chapters and technical books with language accessible to those with different levels of education, also reaching lay people; publication of videos, posts, folders, and brochures, among others. The production of these materials occurs in the context of research and extension actions whose fruits can reverberate throughout society. It is noteworthy that education in the field of geotechnical engineering should not contain social or gender limits, as illustrated in the book "Conversations between girls and engineers: planting opportunities for gender equality in science" (Hora et al., 2021).

From this general context, this article aims to present and evaluate some experiences of geotechnical interaction with society through extension activities, teaching, and research, in some cases using social networks, developed at undergraduate and graduate level.

2. Extension as a strategy for socialising teaching

2.1 Extension projects

Aiming to promote the interaction between undergraduates, graduates and society through accessible educational practices for the socialisation of teaching, learning, research, knowledge, science and technologies generated, and meeting the current regulations of the Ministry of Education (Brasil, 2018, 2019) and the Federal University of Goiás (UFG), during the COVID-19 pandemic, two extension projects linked to the Graduate Program in Geotechnics, Structures and Civil Construction (PPGGECON) were created.

The extension project “Multiplying knowledge: a new look at education in geotechnics” (EP1) was created in October 2020 and closed in December 2022, in partnership with the extension project “Multiplying knowledge about soils” of the Institute of Socio-Environmental Studies (IESA) of UFG, which aims to use knowledge of soils as an instrument of appropriation and construction of knowledge about the geographic space that one inhabits and as an instrument of environmental education aimed at the prevention of processes of soil degradation and the environment. As a theoretical reference, we have the papers by Camapum de Carvalho et al. (2018), which mention the need to delve into the processes of education and teaching, developing reflection and a critical sense, and the papers by Gonçalves et al. (2018), Limiro et al. (2018), Oliveira et al. (2018), Mascarenha et al. (2018), Matos et al. (2019), Carvalho & Jesus (2019), Carvalho et al. (2020), and Mascarenha et al. (2021), which present experiences of university extension action focused on soil education.

EP1 was inserted in two classes of the subject Tropical Soils, taught remotely due to the context of the COVID-19 pandemic, between May and October 2020. The classes were organised in groups in order to develop didactic videos to present the concepts of the subject and the knowledge achieved in research projects related to the topic, in a dynamic and didactic way and with accessible language. Matilda et al. (2021) developed the activity called “The Itas that form our soil”, referring to soil mineralogy, while Aguiar et al. (2021) adapted the tablet method for expeditious soil identification (São Paulo, 2006) for home execution. Souza et al. (2023) presented concepts of expansive soils and the adapted methylene blue test (Fabbri, 1994), totalling nine videos that were posted on the Instagram account @saberessobresolos. Here is a brief addendum: the contents of unsaturated tropical soils, predominant in countries with tropical climates and with remarkable particularities, as is the case of Brazil, should be inserted in the teaching and learning process of society in its different stages.

The extension project entitled “Use of Instagram as a teaching tool, dissemination of knowledge and popularisation of science applied to paving” (EP2) was initiated in August 2021, focusing on the area of paving, with a duration of 5 years.

The content produced in the project and presented in this article was disseminated via Instagram in the period from 05 August 2021 to 17 June 2022 with the professional account @labasfalto.ufg. The graphic design platform Canva (2023), version Canva Pro, was used to produce the design of the images and videos of the posts. In the period of analysis presented two series were produced, namely: Series 1 - Dissecting Asphalt Pavement: formed by 20 weekly posts referring to basic topics on asphalt sidewalks; Series 2 - Sustainable Pavements: formed by 21 weekly posts (Table 1) referring to topics related to sustainability in paving, this being a more current theme or with newer content.

Table 1. Titles of the contents published in each series.

Series 1 - Dissecting Asphalt Pavement		Series 2 - Sustainable Pavements	
Post	Post Title	Post	Post Title
1	Series Presentation	1	Series Presentation
2	How good is our asphalt?	2	Do you know the different types of sidewalk?
3	S-day science video	3	How to reduce the impact on wildlife caused by a highway? Ecoducts/Green bridges!
4	Is asphalt sidewalk an engineering structure?	4	What is the influence of sidewalks on heat islands?
5	How to determine the load acting on this structure?	5	Is it possible to reduce urban traffic noise?
6	What about climate? Does it interfere with sidewalk behaviour?	6	The sidewalk as an ally in the generation of sustainable electric energy.
7	Starting to understand the sidewalk from its foundation...	7	Permeable concrete sidewalk.
8	And what is on top of the subgrade?	8	Permeable asphalt: safety and renewable resource capture.
9	And what is on top of the sub-base?	9	Can asphalt be recycled? The use of milled asphalt in the composition of asphalt surfacing.
10	Can every type of soil be used in the sidewalk structure?	10	Foamed bitumen, what is it?
11	How to choose the materials for asphalt surfacing?	11	Not only can asphalt be recycled, it can also be reused. How? Incorporating milled asphalt into granular soils.
12	How to dose an asphalt mixture?	12	Can other granular waste be used in sidewalks?
13	How can the quality of an asphalt mix be guaranteed?	13	Where can vehicle tyres go at the end of their useful life? Introducing: “Asphalt-Rubber”.
14	How to size an asphalt sidewalk?	14	Traffic on plastic waste.
15	What must not be missing when laying asphalt?	15	Can industrial co-products be used in the base layers of sidewalks?
16	And after the work is done?	16	Can industrial co-products be used as aggregates in paving?
17	Which defects should be noted?	17	The evolution and applicability of animal bioligands.
18	How can a sidewalk be restored?	18	The great possibilities offered by vegetable bioligands.
19	Does UFG carry out studies on this subject??	19	And finally, are there any examples of sustainable sidewalk?
20	And finally!	20	How can the use of advanced technologies and equipment contribute to sustainability?
-		21	See you soon!

In the mentioned projects, the use of Instagram was prioritised to disseminate the produced content since, with the COVID-19 pandemic, the consumption of information within social media increased significantly (Volpato, 2021). As presented in the We Are Social (2020) report, Instagram was the fourth most used social network in Brazil in 2020, with 95 million users, second only to Facebook, WhatsApp, and YouTube. The use of Instagram as an auxiliary tool in educational practices and dissemination of technical-scientific content was reported by Alves et al. (2018), Ansari & Khan (2020) and Moreira et al. (2021). In engineering and related areas, some positive reports on the production and dissemination of technical-scientific content through digital platforms or social media can be observed in the works published by Lima et al. (2019), Silva et al. (2019), Gomes et al. (2021) and Cipriano et al. (2022). It is understood, therefore, that universities can interact in all spheres and areas of activity with this platform and contribute to the popularisation of science in society and to the training of qualified human resources with the professional skills and competencies currently required.

2.2 Results

2.2.1 Extension project "Multiplying knowledge: a new look at education within Geotechnics"

The videos produced under this project were published on the Instagram of the project "Multiplying knowledge about soils" @saberessobresolos. Most users who access the content of the account are from Brazil (93.1%), with a small audience in the United States (2%), Portugal (0.3%), Australia (0.3%) and Colombia (0.3%). In Brazil, the audience comes from the cities of Goiânia (26.6%), Aparecida de Goiânia (4.6%), Rio de Janeiro (< 2%), São Paulo (< 2%), and Brasília (< 2%), i.e., the reach of the content is local and regional. Having a local niche audience demonstrates the potential of the account in making scientific dissemination that values the geographic and spatial specificities, in order to arouse greater affinity and the interest of the specific audience, because, according to Moreti (2019), the mobilisation of affective dimensions should be considered in the process of knowledge construction.

The main age group of users accessing the account is between 25 and 34 years old (44.4%), followed by those between 35 and 44 years old (24.2%) and between 18 and 24 years old (18.9%). The other age groups account for a public percentage of less than 13%. Of this audience, 60.8% are women and 39.1% are men. The fact that this Instagram account has a multidisciplinary bias with soil content interfacing between Geotechnical Engineering, Agronomy, Pedology, Geography, Geology, Ecology, Environmental Sciences, Forest Engineering, Arts and other areas of knowledge may contribute to the fact that there is a mostly female audience. An opposite scenario usually occurs on Instagram accounts with very specific engineering content, as the engineering field has proportionally more male professionals. It is noteworthy that multidisciplinarity can favour the equalisation of gender issues by bringing broader conceptual approaches, uniting several areas of knowledge, and providing the lay public with a more global and integrated assimilation of the phenomena, in this specific case associated with tropical soils.

Table 2 shows the main interactions concerning the publications produced in the context of the project "Multiplying knowledge: a new look at education within Geotechnics", in order of the dates of their posts. Observation of the data indicates a significant number of interactions.

As the number of posts on the subject increased, the number of views increased significantly. It is worth mentioning the number of referrals and saves, which indicate that the user liked the content to the point of indicating it to another person and saving it for himself. The language level adopted in the videos was considered to be easy for high school and technical students to understand. However, it is believed that the didactic quality of the explanations facilitates the understanding of undergraduate students as well.

Table 2. Metrics of the videos published on Instagram @saberessobresolos.

Post	▶	♥	💬	➤	🔖	Accounts reached		
						Non-followers	Followers	Total
Soil formation	354	78	1	1	4	62	92	154
Soil Aggregation	336	63	8	23	5	103	330	433
Soil mineral formation	210	46	2	15	13	89	295	384
Minerals 2:1	166	36	0	1	7	93	241	334
MCT expedition	301	28	2	18	5	92	298	390
Expansive soils 1	2237	139	16	77	14	1378	502	1880
Expansive soils 2	1520	83	4	40	6	917	354	1271
Methylene Blue Adsorption	1110	50	3	18	8	609	365	974
Mean	779	65	5	24	8	418	310	728
Standard deviation	764.3	35.4	5.2	24.7	3.8	500.5	116.4	596.0
Coefficient of variation (%)	98.1	54.1	116.4	102.5	48.6	119.8	37.6	81.9

▶: views; ♥: likes; 💬: comments; ➤: sharing; 🔖: saves.

The Geotechnical Engineering graduate students who produced the videos, after finishing the course, answered a questionnaire to evaluate the teaching method. Of these students, 82% reported that, among the academic activities of the course, the production of the teaching videos was the activity that required the most preparation time. Despite this, the evaluation was positive, since, in the same percentage, the students considered that there should be more extension initiatives with graduate programs. Some other questions were answered considering a scale of 1 to 5, with 1 being absolutely no contribution and 5 a high contribution. When asked if the interaction teaching and extension contributed to the learning in the discipline, 73% gave the maximum score (5). Eighty-two percent of the students considered that extension had the potential to sensitise society about knowledge in soils, and that the production of didactic materials in the context of extension collaborated in the construction of technical and scientific knowledge in geotechnics. It is also noteworthy that 64% of the students consider that extension activities help add knowledge that can be applied to solve problems in engineering projects and works. These positive responses from the students regarding the interaction between extension and graduate studies and research reinforce the importance of extension in the technical and scientific training of the Geotechnical Engineer.

2.2.2 Extension project "Use of Instagram as a teaching tool, dissemination of knowledge and popularisation of science applied to paving"

The audience that follows the Instagram account @ labasfalto.ufg has the following profile: 27.9% from Goiânia, 3.4% from Aparecida de Goiânia, 2.3% from São Paulo and 1.9% from Belo Horizonte; 89.5% from Brazil, 1.5% from Colombia, 1.0% from Mexico and 0.9% from Peru; main age groups: 43.4% between 25 and 34 years, 22.3% between 18 and 24 years, 19.3% between 35 and 44 years and 8.5% between 45 and 54 years; 57.1% are men and 42.8% are women.

From the profile of the account @labasfalto.ufg, it appears that its reach is still local, with most of the public located in the metropolitan region of Goiânia. The audience is mostly formed by young people under 34 years old, which is the most common profile of Instagram users, and male, which is still a characteristic of the engineering area.

During the development of the project, the following aspects were observed: the interaction among all project participants, regardless of institutional ties, stimulating the integration between undergraduates and post-graduates as well as between teaching, research and extension; the experience and sharing of technical and scientific knowledge about the paving area with the search for updated information, from reliable and verifiable sources, during the writing of the texts of the captions of the posts; the encouragement of critical analysis during the planning, content development, and metrics monitoring phases, as well as ethical and integrity practices throughout the process; the development of skills related to the responsible use of new technologies, teamwork, creativity, and communication with peers and society. Table 3 presents the mean, maximum, minimum, standard deviation, and coefficient of variation values obtained for the metrics evaluated in this work seven days after publication.

With the monitoring of the publications of the two series linked to the project "Use of Instagram as a tool for teaching, dissemination of knowledge and popularisation of science applied to paving", the following analysis can be performed:

a) Before the existence of the extension project, the account @labasfalto.ufg had 880 followers, after the publication of Series 1 this number increased to 989 and, at the end of Series 2, it reached a total of 1066 followers. This increase in followers demonstrates the interest of society in accessing technical-scientific information published via Instagram;

Table 3. Mean values obtained for the metrics on Instagram @labasfalto.ufg after seven days of content dissemination.

Post						Accounts Reached		
						Non-followers	Followers	Total
Series 1 - Dissecting Asphalt Pavement								
Mean	239	28	2	2	1	175	329	504
Maximum	511	49	8	25	4	787	490	1211
Minimum	86	14	0	0	0	3	201	272
Standard deviation	117.6	9.7	1.7	5.5	1.2	173.2	85.7	224.3
Coefficient of variation (%)	49.3	35.0	72.1	260.5	92.9	99.0	26.0	44.5
Series 2 - Sustainable Pavements								
Mean	219	35	4	13	3	350	310	664
Maximum	452	138	10	25	26	653	555	1006
Minimum	120	15	0	8	0	22	193	215
Standard deviation	89.3	25.6	2.5	5.0	5.6	160.0	97.3	207.9
Coefficient of variation (%)	40.8	74.0	69.3	38.7	166.7	45.7	31.4	31.3

: views; : likes; : comments; : sharing; : saves.

b) The values of the metrics of the reach of the account increased in Series 2 compared to Series 1, which can be explained by the increase in the number of followers of the account and by the possible greater interest in the topic of Series 2 compared to that of Series 1;
c) It is also observed that the publications were also accessed by a considerable number of non-followers, which may indicate an interest in viewing more on the basis of a specific subject than in constantly following the publications of the series;
d) The two series had a frequent following of a little over 300 followers. This number may be considered small when compared to other profiles in the area, but when thinking about this content being taught in a classroom course with 50 students, it can be seen that the team's effort had a six times greater impact on the dissemination of knowledge during a semester, and may even have reached other parts of society;
e) It is noteworthy that the content published in the Feed can be freely disseminated, accessed, or retrieved at any time, which will also increase access to updated and reliable technical-scientific information.

3. Technical-scientific research as a strategy for the socialisation of education

In order to popularise science, the Graduate Program in Geotechnics, Structures and Civil Construction (EECA/UFG) and the Graduate Program in Geotechnics (FT/UnB) have worked on the publication of books and primers with language adapted to lay society in the scope of three research projects: Prevention and recovery of potential areas of degradation by surface, deep and internal erosion processes in the Midwest of Brazil (RP1), Rainwater infiltration structures as a means of flood and erosion prevention (RP2) and Monitoring and study of alternative techniques in the stabilization of erosive processes in UHEs reservoirs (RP3). These materials are freely available on the websites of the mentioned Programs (UFG, 2023; UnB, 2023) and of partner institutions (ABMS, 2023; Eletrobras Furnas, 2023). The books are aimed at professionals, and university students and teachers, and the primers, within the same theme, are aimed at teachers and students in kindergarten, elementary and high school, and apply to formal and non-formal education. The participants in these publications, authors and consultants, are linked to various areas of science, thus enabling the texts to be useful in the multidisciplinary, interdisciplinary, transdisciplinary, and disciplinary fields as far as reflection and practices related to land use and occupation are concerned. The free availability, the adaptation of the language to the target audience and the various perspectives represent the effort of the working groups to ensure that research is not confined within the walls of universities and to a restricted audience, but reaches society as a whole.

Although there is often resistance to taking more applied geotechnical content and concepts into elementary and high schools, such practice is relevant because, in addition to contributing to the reduction of environmental and engineering problems, it then facilitates teaching and learning at the university level. For example, in the booklet "Environment: Infiltration" (Lelis & Camapum de Carvalho, 2011), aimed at first to fifth grades of elementary school, there is an activity in which the child learns, by playing, the first concepts about soils and the behaviour of unsaturated soils. Although this is just one example, others may be conceived, because children who work with this content will already arrive at the university course of Engineering and related areas knowing basic concepts about soils and unsaturated soils, thus facilitating the teaching-learning process.

Another example is contained in the primer "Environment: Erosion" (Camapum de Carvalho & Lelis, 2006), aimed at first to fifth grades of elementary school, in which children are introduced to the relevance of planting in contour lines.

The primers "Environment: Infiltration" (Lelis & Camapum de Carvalho, 2011) and "Environment: Erosion at Reservoir Borders" (Ribeiro et al., 2016) introduce the rights and duties in relation to the environment contained in the Federal Constitution, thus opening space for the introduction and discussion of other federal, state, and municipal legislation.

Moving into the discussion of social issues, the booklet "Environment: Erosion at a Reservoir Edge" (Ribeiro et al., 2016) introduces children to the relevance of accessibility while showing the need to avoid erosive processes.

Although one should, as far as possible, seek to universalise technical-scientific knowledge, it must go through adjustments of style, language, and sometimes also content. Carvalho (2008) & Silva (2007) developed rainwater infiltration systems and the techniques developed were set out, in a language appropriate to elementary school, in the booklet "Environment: Infiltration" (Lelis & Camapum de Carvalho, 2011), as illustrated in Figure 1. The same content was developed in the booklet "Infiltration" (Camapum de Carvalho & Lelis, 2010), aimed at elementary school and high school. In this case, there are more construction details regarding the materials used, and an example of an infiltration well is shown in Figure 2. The children and adolescents who receive this education will take it with them into their lives and, for sure, will contribute to avoiding problems such as flooding and erosion. It should be clear that this form of education is aimed at building awareness and not at generating technical training, which should occur in engineering courses, as it involves detailed studies of the soil and definition of project parameters.

It is emphasised in this opportunity that the geotechnical content to be transferred to society in a broad sense should be based on knowledge consolidated through research, experience, and observations, requiring adaptations of language to different levels of schooling, whether in formal or non-formal education.

Figure 1. Infiltration structures (modified from Lelis & Camapum de Carvalho, 2011).

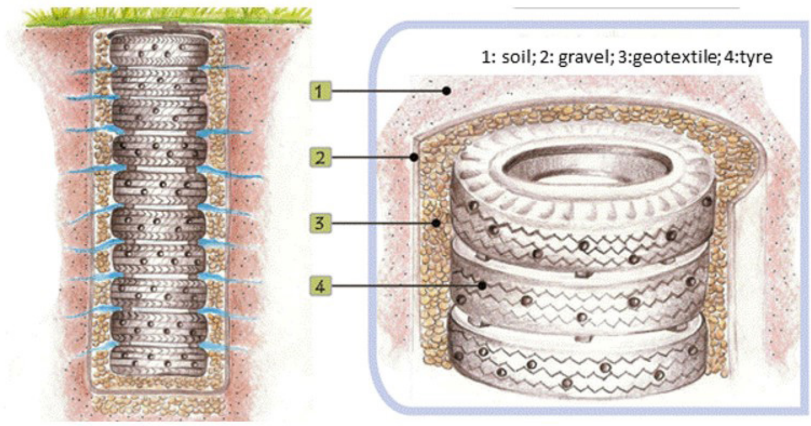

Figure 2. Infiltration well (Camapum de Carvalho & Lelis, 2010).

Figure 3 shows the number of citations observed in Google Scholar of the various publications within the project, as well as the most cited book chapters. As expected, there are fewer citations of the primers, due to the nature of the publication, its target audience and the weak link in this field between the Universities, the Ministry of Education and the State and Municipal Departments of Education, lacking, despite being a public policy, efforts to popularise science.

Figure 4 shows the number of citations of journal articles related to each of the themes (erosion, seepage and erosion at reservoir edges), originating from the abovementioned projects. Comparing Figures 3 and 4, it can be seen that the books of RP1 have from four to nine times the number of citations of the most cited paper, showing the reach of this type of publication, although its purpose is the popularisation of science, with reach in places not considered in the technical-scientific publication metrics. It is worth emphasising the importance of the engagement of public institutions in the dissemination and use of these materials in their various technical and educational activities.

In Engineering, most studies are of an applied nature and often require multidisciplinary action, requiring adequate dissemination and acceptance of the work developed by disciplinary axes of science.

Camapum de Carvalho (2023) has shown that countries with a higher human development index (HDI) value non-citable publications more highly than countries with lower HDI. For example, the primers presented in Figure 3, although not part of the citable publications themselves, are of fundamental importance for the development of society and reinforce the need for the dissemination of knowledge generated in scientific development to involve both citable and non-citable publications.

In addition, the purely disciplinary framing and valuation of publications hinders the work and the due valuation of multidisciplinary actions, which are indispensable to scientific development and to the solution of society's problems.

Another problem concerns the need to go beyond the specific disciplinary content. For example, Valencia (2009) presented an appropriate technique for the control of erosive processes through the use of native bacteria, and Muñetón (2013) showed that it is possible to use the same soil treatment in sidewalk structures. Both studies counted on the effective participation of a biologist and a veterinarian, but the fusion with contents generated by the different areas of knowledge starting with Geotechnics was not an easy task. It is worth mentioning that the study, given its originality, gave rise to a patent application by the University of Brasilia.

4. Discussion of education in technical scientific conferences

Professional associations can develop an important role not only for the transfer of knowledge generated in universities and research centres to engineering professionals, but also to promote discussion, establishing links with other disciplinary

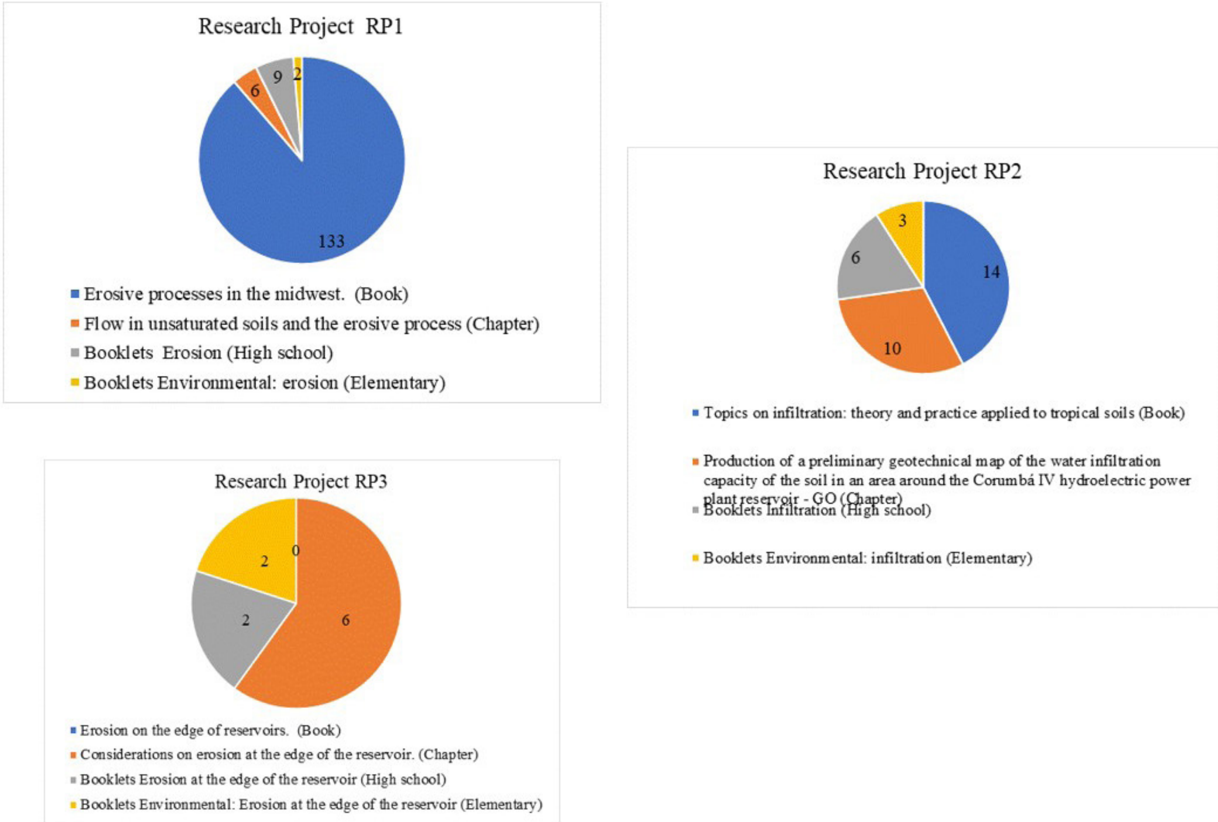

Figure 3. Number of citations of publications collected on March 15, 2023 from Google Scholar.

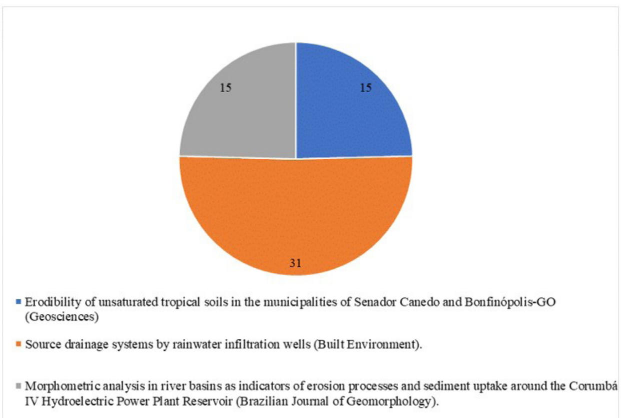

Figure 4. Number of citations of papers collected on March 15, 2023 from Google Scholar.

backgrounds and with society itself in the broad sense. The Brazilian Association for Soil Mechanics and Geotechnical Engineering (ABMS) is the professional association of engineers working in Geotechnics and is composed of nine Technical Committees: Slopes, Risk, Dams, Field Investigation, Geosynthetics, Foundations, Unsaturated Soils, Environmental Geotechnics and Pavements.

ABMS does not have a specific committee focused on education, unlike the Brazilian Society of Soil Science (SBCS), the professional association of agronomists who work with soil science, which has a committee on soil education and the public perception of soil. It should be noted, however, that more recently ABMS promoted the XIX Brazilian Congress of Soil Mechanics and Geotechnical Engineering (COBRAMSEG 2018), in which, in an unprecedented way, it presented a specific session for education in geotechnics.

This session focused on education in geotechnics had 15 papers published in the proceedings of this event, about 1.6% of the published papers, representing a historical advance with ABMS and COBRAMSEGs, as it was the first time that a session on education was proposed in this event. The regions that collaborated most with the submission of papers were the Northeast (5 papers), the Southeast (4 papers), and the Centre-West (4 papers). The southern and northern regions contributed one paper each.

Figure 5 shows that the lines of research addressed in the articles were teaching materials (TMt), public perception (PP), Project Based Learning (PBL) pedagogical projects, bibliometrics (B) and teaching methodology (TM). It can be observed in this set of articles that most of them have a very specific focus on the formality of teaching the contents of the subjects. This pedagogical concern of professors is very relevant in the context of teaching practice, considering that most university professors in technological areas, although

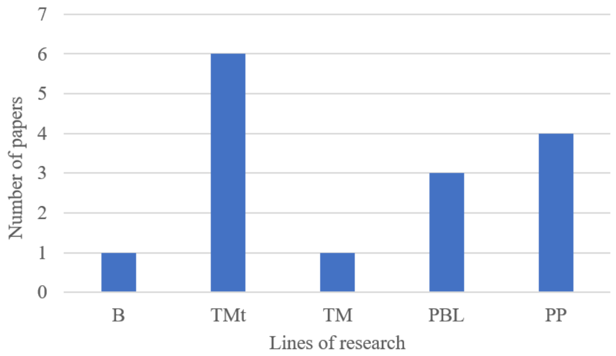

Figure 5. Research lines addressed in the Education Session of COBRAMSEG 2018.

highly qualified scientifically, do not have pedagogical training. Even so, it is considered that there is a long way to go to transpose the pedagogical concern beyond the university boundaries through actions that are more directed to society in general. A reflection of this path can be seen in the fact that four studies focused on the dissemination and popularisation of knowledge about soils for society. However, only three papers indicated education as a keyword in their abstracts.

Another action focused on education was the IV Symposium of Geotechnical Engineering Practice in the Midwest Region (GEOCENTRO 2017), which enabled the exhibition of educational content on soils produced by students of the Geotechnical League of the School of Civil and Environmental Engineering (EECA) of UFG under the extension project "Understanding soil erosion as a tool for environmental education". This project was the result of a multidisciplinary partnership between engineering professors from EECA and geography professors from IESA (Institute of Environmental Studies) and involved engineering students as well as students from Geography, Environmental Sciences and Ecology, and biology professors from both institutes. As news of the project became known, undergraduate students from several courses requested to be part of the working group, leading to the expansion of the project, which now has a more comprehensive name to accommodate the multidisciplinarity, resulting in the additional reference to "multiplying knowledge about soils".

In 2019, GEOCENTRO included a booth for the presentation of teaching materials, which was widely visited. The students participating in the project reported, at the end of the event, that they had acquired a more integrated view of the environment and the potential for its inclusion in the performance of engineering works and social aspects.

These discussions highlight the importance of multidisciplinary to establish links between different levels of education and society. With an eye on multidisciplinary, the Symposium on Tropical Soils and Erosive Processes in the Midwest was created, held in Brasília in 2003, in Goiânia in 2005, and in Cuiabá in 2013. The idea of this regional event was to enable discussions bringing together professionals with different backgrounds and not only civil engineers, but it was incorporated into the Geocentre, returning to the disciplinary emphasis. Meanwhile, erosive processes and problems related to tropical soils are increasing in the Midwest region, as well as in the rest of the country, and these, like it or not, are beyond the strict geotechnical domain.

5. Conclusions

Nowadays, social networks are an important tool for scientific dissemination and have the potential to disseminate knowledge more widely than in a classroom course, according to the metrics presented in this article by the accounts @labasfalto.ufg and @saberessobresolos. The results, although positive, point to the relevance of drawing up new dissemination strategies to engage the followers in their publications, increasing their reach and the impact of the project and the democratisation of teaching-learning, including more direct links with society through professional and localities associations, schools and universities.

The students' evaluation of the effectiveness of the curricularisation of extension in learning the content of academic disciplines, in the construction of technical-scientific knowledge in geotechnics, and in solving problems in engineering works reinforces the importance of extension in the technical-scientific education of the geotechnical engineer. Although applied soil studies are usually restricted to university education, many topics are of great relevance to society. As soil is ever-present in people's lives, knowledge of it has great relevance, even with regard to certain topics of a more applied nature, such as erosion, slope ruptures and flooding.

Formal studies on soil should begin in childhood, when children begin to interact with it in their daily lives, from a simple walk to leisure activities and art exercise. Camapum de Carvalho (2022) showed that primers such as the ones cited in this article can and should be used in the education of society to avoid socio-environmental problems such as slope ruptures and floods. In non-formal education, as many have not had access to this knowledge in elementary and high school, the focus should turn to the socio-environmental context, which will often require adaptations to the language and form of addressing the issues, as well as the didactic suitability in order to better enable the training and awareness-raising of society about the content and its relevance.

Finally, it is noteworthy that the scientific development achieved, however applicable and practical it may be, ends up, in countries like Brazil, being disseminated and made available to an extremely restricted public and usually with a high level of knowledge, serving almost solely for the development of new research or the continuation of existing works. For further-reaching links to be successfully made, public policies are needed, as well as effective interaction between universities, research centres, and schools. The effectiveness of these interactions almost always requires a broader participation of professional associations, funding and evaluation agencies, education departments, and the Ministry of Education, Science, Technology and Innovation.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Márcia Maria dos Anjos Mascarenha: writing – original draft, methodology, investigation, formal analysis. José Camapum de Carvalho: writing – original draft, methodology, investigation, formal analysis. Andrelisa Santos de Jesus: writing – original draft, methodology, investigation, formal analysis. Lilian Ribeiro de Rezende: writing – original draft, methodology, investigation, formal analysis. Mauricio Martines Sales: formal analysis, writing – review & editing. Marta Pereira da Luz: formal analysis, writing – review & editing.

Data availability

The datasets of this current study are available from the corresponding author on request.

List of symbols

ABMS	Brazilian Association of Soil Mechanics
B	Bibliometrics
COBRAMSEG	Brazilian Congress of Soil Mechanics and Geotechnical Engineering
EECA	School of Civil and Environmental Engineering
EP1	extension project 1
EP2	extension project 2
GEOCENTRO	Geotechnical Engineering Practice in the Midwest Region
HDI	higher human development index
IESA	Institute of Socio-Environmental Studies
IPT	Institute of Technological Research of the State of São Paulo
MEC	Ministry of Education
PBL	Project Based Learning
PP	public perception
PPGGECON	Graduate Program in Geotechnics, Structures and Civil Construction
RP1	Research Project 1
RP2	Research Project 2
RP3	Research Project 3
SBCS	Brazilian Society of Soil Science
S&T	Science and Technology
TM	teaching methodology
TMt	teaching materials
UFG	Federal University of Goiás
UnB	University of Brasília

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Methodological teaching-learning experiments applied to Geotechnical Engineering

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Article

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Abstract

The use of problem-based and project-based learning is beneficial. The teaching-learning process requires the development of a critical, objective, and rational mind. This paper analyzes methodological experiments from the teaching-learning process carried out in the geotechnical area of the civil engineering program at three universities in the state of Pernambuco, Brazil, for more than 40 years. Three integrated experiments are presented. In the first experiment, undergraduate students in geotechnical engineering courses interacted with companies operating in the area, conducting laboratory and field tests and geotechnical instrumentation. The second experiment integrated students and teachers from different areas of the civil engineering program around a multidisciplinary project, while the third brought together undergraduate and graduate (master and doctoral) student research activities into a single project that extends from the development and construction of geotechnical equipment and applications of new soil improvement techniques to land use planning and occupation. This study shows the use of teaching-learning experiences carried out in geotechnical engineering, contributing to the development of technical skills and professional competencies of civil engineers. It contributed to the advancement of knowledge in the development of new equipment, soil improvement, testing techniques and in the use, planning and occupation of soils. The interaction between the university, society and government institutions in problem solving also contributed.

1. Introduction

The soil formations found in the city of Recife, the capital of the state of Pernambuco, Brazil, are the result of several geological events that gave rise to a morphology composed of two distinct topographic sets: the basins or plains that occupy the central-eastern portion and the contiguous hills that dominate the northern portion and surround the city to the west and south (Ferreira, 1982; Alheiros et al., 1990). The central urban core sits on a fluvial-marine alluvial plain around which rises, to the north, south, and west, the Barrier Formation, forming a semicircle. To the east, the oceanic coastline develops, which, protected by coral reefs, provides favorable conditions for the establishment of commercial ports (Ferreira, 1982; Gusmão Filho, 1990).

The fluvio-marine sedimentary process was responsible for the creation of the plain resulted in a considerable diversity of heterogeneous soft clay soil profiles (Souza et al., 2017; Ferreira et al., 2022; Dias et al., 2022), which can reach thicknesses of over thirty meters and are generally saturated due to their low elevation above sea level, when sandy (Oliveira et al., 2016). Peat soils (Cadete, 2016; Barbosa, 2018) and deposits of coral fragments (Oliveira, 2012) are also found.

The northern portion of the hilly area is less dissected, with more continuous plateaus and a fluvial network embedded in vertical valleys, while the central, western and southern portions are intensely dissected into isolated hills of different geological units (sediments, crystalline basement, etc.). In the northern portion, the tops of the hills have elevations of around 100 m, dropping to approximately 30 m near the lower basin areas (Alheiros et al., 1990).

On hillsides and slopes in Recife, the anthropic component is the most important trigger of landslide hazard situations (Gusmão Filho, 1990; Gusmão Filho et al., 1997). The destabilization of the environment is mainly due to cuts and embankments on slopes from low-income housing construction, following random invasions and lacking any land use or land occupation planning. Erodible, dispersive soils (Quental & Ferreira, 2008; Portela et al., 2021) and expansive, collapsible soils (Ferreira et al., 2020; Maior & Ferreira, 2022) are found on the slopes.

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Associated with this, the city of Recife has the second smallest urban area among Brazilian state capitals and a high population density, factors that lead to increasingly verticalized construction on soils that often lack sufficient support conditions and can excessively deform (Fonte et al., 2005; Oliveira et al., 2016). The current foundation construction practices are strongly governed by the subsoil characteristics, although other factors may influence the choice. In light of this complexity, it is also important to note that the monitoring of building performance becomes even more relevant because projects do not often take into account the mechanism of soil-structure interaction, which can cause a series of effects on the buildings.

The city of Recife is a challenging and motivating experimental field for the development of soil mechanics and geotechnical engineering. Investigating and understanding hydro-geomechanical behavior, analyzing and proposing solutions, and planning soil use and occupation are all goals in the formation of the geotechnical engineer and the development of his or her skills and competencies.

Teaching-learning in the educational system is a process of interaction between teachers and learners, to change behavior and develop new attitudes and skills. The Constructivist-Freirian perspective (Freire, 1997) promotes learning that is not based only on the transfer of knowledge but adds experimentation and research based on prior knowledge that people have to contribute to the teaching-learning process. Perception and understanding are fundamental for the development of learning, education and teaching activity (Kubo & Botomé, 2005; Muggler et al., 2006).

The learner's motivation is directly related to the incentive provided by the teacher. With objectives and content selection appropriate to each subject, they will interact so that the objectives are achieved, using strategies that can be applied to the universe of the learners. The learners will be more interested and therefore more likely to perform well, contributing to self-fulfillment, generating new incentives and new motivations as needed.

Each phase of the teaching-learning process is extremely important in ensuring its effectiveness. The evaluation, not only of the learners, but of the entire process, is fundamental for planning and executing new stages, aiming to correct failures, mitigate weak points, and identify and strengthen the positive points of each phase. Good pedagogical practice is guided by these principles.

This paper presents and analyses methodological experiments of the teaching-learning process conducted in geotechnical engineering educational system (undergraduate and graduate studies) at three universities in the state of Pernambuco, Brazil, two of which are public institutions, one federal and one state, with the other being private and confessional, applied for more than 40 years. The adopted methodological experiments of the teaching-learning process aim to improve the learning motivation and learning performance of the geotechnical engineering students.

2. Materials and methods

The creation of a geotechnical laboratory nucleus with equipment ranging from conventional and basic to the most modern, and which has adequate functional space, is essential for carrying out experiments with laboratory and field tests (Ferreira, 1987, 1993; Ferreira & Lacerda, 1993; Ferreira et al., 2020) The creation of an environment with space where different research groups can be brought together to interact, with computer programs and equipment capable of simulating field conditions, helps to stimulate teaching, research, and extension, and favors the pedagogical teaching-learning process in the educational system. Mechanical and electronic workshops contribute to the setting up of special laboratories for unsaturated soils and environmental geotechnics, as well as computer graphics that assist in the teaching-learning process. The development, construction, and acquisition of new equipment are important moments in learning, sharing, and socialization of knowledge. When working in teams, everyone grows when knowledge is shared. The development of new equipment stimulates creativity and entrepreneurship. The research lines and projects bring together undergraduate and graduate students, each with objectives and strategies to help reach the established goals.

There is a one-to-one correspondence between the elements that participate in the teaching-learning process. The teacher, the learner, the objective, the content, and the strategy must interact dynamically and cyclically to guarantee each phase of the process, whether planning, execution, or evaluation. The structure of the teaching-learning process presented in Figure 1 is used in the development of each experiment. The teacher interacts with the learner, initially indicating a proposal for an experiment or accepting another one presented by the learner. Goals and objectives are defined. A set of bibliographic references is consulted, test techniques are selected, equipment and projects are elaborated. The strategies for carrying out the experiments are defined in time and space. The initial planning is thus underway. During the execution of the experiments, the strategies, goals and objectives are evaluated, being able to be validated, adjusted or reformulated and what was initially planned can be revised. Thus the experiments are monitored.

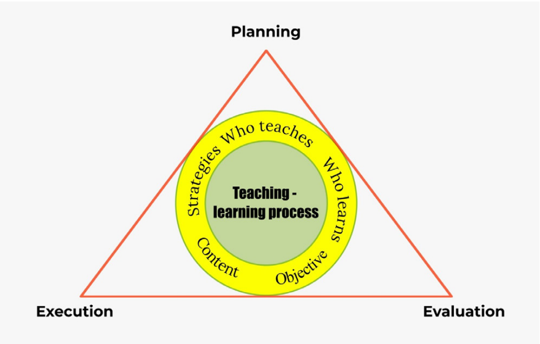

Figure 1. The structure of the teaching-learning process.

Three integrated methodological experiments from the teaching-learning process carried out in the area of geotechnics at three universities in the state of Pernambuco, Brazil, are presented. The first one was developed with undergraduate students in specific disciplines of geotechnical engineering who interact with companies that operate in the sector, performing laboratory and field tests and geotechnical instrumentation. The second experiment integrates students and professors from different areas of activity in the civil engineering programs around a multidisciplinary project and, finally, the third experiment brings together undergraduate and graduate student research activities in the same project and in an environment that extends from the development and construction of geotechnical equipment, through the development of new soil improvement techniques, to land use and occupation planning. The experiments were developed along two fields of research. One addresses hydro-geomechanical soil behavior with the topics of problem soils, soil improvement, equipment development, adaptation, and construction, and the other addresses land use and occupancy with the topics of geotechnical cartography, slope stability, foundations, and environmental geotechnics.

In the methodological experiments developed with the soil mechanics and foundations students, the theoretical and practical contents taught in the classroom were applied in the laboratory and on field trips. The students were divided into groups (maximum five people) and received samples of different types of soils to perform physical characterization, permeability, compressibility, and shear strength tests, accompanied by laboratory technicians and professors. They prepared and defended technical reports. Field visits were carried out to monitor percussion drilling, determine the penetration resistance index, and collate samples. The visits were described in a report. Each activity was part of the evaluation of the teaching-learning process.

In the slope stability course content, students visit a hillside in the city, where they perform a topographic survey, collect undisturbed samples, perform shear strength tests in the laboratory, and use software to analyze stability. The students also simulate variations in shear strength with variations in humidity and infiltration and then present and discuss the results in seminars and evaluate both the other teams and their teams (self-evaluation).

In the foundations course, students, in groups of five, create fictitious companies to design foundations. They are given data from real structures, a load plan, and a geotechnical investigation program from another site to prepare the foundation design. As the theoretical lectures are given, the design is developed by the students. The teacher plays the role of a technical consultant as the teaching-learning process develops. The project is presented, discussed, and defended, and must meet all the requirements of a real project, with elaborated alternatives, justifications, calculation log, budget, and construction details. The defense of the project is a moment of celebration, a time to observe the students' development, creativity, and team interaction, associating academic activity with the practice of calculating an actual project. This experience was lived by the author, while an undergraduate student of Professor Jaime Gusmão Filho at Federal University of Pernambuco, and was later applied in the courses he teaches as a professor.

In the methodological experiments integrated with multidisciplinary projects, final-year civil engineering students had the opportunity to participate in and follow the design and construction stages of a commercial building, in fields such as geotechnical investigation, planning, budgeting, building services, and construction.

In methodological experiments integrated with research and extension, undergraduate and graduate (masters and doctorate) civil engineering students participate in the same project developing research and extension activities. Each of the specific subprojects contributes to achieving the overall goal. All of the experiments are integrated in time and space.

3. Analysis and results

The integration of lecture classes with practical activities in the field, laboratory, technical visits, and project development, accompanied by teachers who encourage and motivate those who learn through the interaction of theory and practice, favors the teaching-learning process.

The paper presents a significant amount of new information and discusses the importance of providing significant experiences to students (undergraduate and graduate degrees) with a broad-based education for civil engineers to work with the multidisciplinary skills required for engineering industry such as: technical and computer science skills, problem-solving, research and critical thinking.

3.1 Methodological experiments integrated with multidisciplinary projects

In the Improving the Quality of Engineering Education projects at the Center for Technology and Geosciences of the Federal University of Pernambuco (UFPE) and the Final Course Project for Civil Engineering, funded by the Brazilian Financier of Studies and Research (Finep) of the Engineering Development Program/Reengineering of Engineering Education (PRODENGE/REENGE), the final-year students prepared tutorials on geotechnical soil characterization, laboratory tests, lowering of the water table, water analysis, technical bulletins on soil suction, dispersive soils, and on roads and transportation (Dourado & Ferreira, 1996; Ferreira, 1996, 1997; Ferreira et al., 1997). They accompanied the design and construction stages of a commercial building, accompanied by professors and engineers from the construction company. They had the opportunity to participate in the execution of the foundation soil improvement process with sand piles, the pouring of the foundations and execution of the structure, masonry, and cladding.

3.2 Methodological experiments integrated with university research and extension

Figure 2a shows the quantitative evolution of the students who participated in the integrated methodological research experiments from 1982 to 2022, which contributed to the academic and professional training of 158 students (undergraduate, masters, and doctoral students). Of the undergraduate (scientific initiation) research assistants (85), 32% are master's degree students, and of these, 46% are DSc. students. Master's students totaled 62, with 13% obtaining DSc. and 15% pursuing a DSc. The total number of master's and doctoral students who participated in the methodological experiments was 73, of which 40% are university professors. Figure 2b shows that 26% of the master's and DScs participated in the experiments in problematic soils, 18% in soil improvement, 7% in development and adaptation of equipment, 21% in environmental geotechnics, 13% in foundations, 9% in slope stability, and 6% in geotechnical cartography.

3.2.1 Scientific initiation

The Scientific Initiation program plays an important role in academic education and, later on, in the professional life of the undergraduate. It is relevant for the teacher in research development. One of the main objectives of scientific initiation in universities and research centers is the formation of human resources that have a scientific spirit, where the solutions to problems are pursued seriously and methodologically. Learning how to solve problems and not simply acquire "ready-made" scientific knowledge or "magic" formulas, but develop a creative, critical, analytical, and proactive mindset that, combined with the scientific spirit, makes it possible to find more adequate solutions. This is the mentors' responsibility in the work of scientific initiation in the teaching-learning process.

Knowing how to refine the evaluation criteria to distinguish and separate the principal from the secondary and the essential from the accidental, is an important critical analysis in research. The objective and goals must be well defined and delimited in time and space (Ferreira, 1992). "I think so" or "I believe so" do not satisfy the objectivity of knowledge and the rationality of the scientific spirit. Being humble and recognizing limitations, accepting the possibility of mistakes and errors, being impartial, honest, and courageous, and having initiative and perseverance are some qualities of the scientific spirit that should be developed and encouraged in the young researcher (Ferreira, 1996).

Students in the scientific initiation program should not be merely performing disorganized tasks, and they should not participate in multiple research projects simultaneously, nor be considered interns. The scientific initiation training program demands objectivity, a spirit of observation, analysis, synthesis, reflection, and creativity. It is essential to develop a scientific spirit, which seeks adequate, impartial, objective, and rational solutions when examining the problems that are presented.

The University of São Carlos, in the state of São Paulo, Brazil, has held the Scientific Initiation Congress since 1981, and some of the UFPE students mentored were encouraged to present their SI projects. However, the distance, reconciliation of the academic calendar, and the operational cost of the students' trip made it difficult for them to participate. These factors inspired the creation of the 10th Symposium of Scientific and Technological Initiation in Pernambuco, in 1989, which had 91 registered projects, and involved about 100 students, 67 professors, 20 departments, 4 universities, and the Pernambuco Research Agency. A total of 230 people participated. In subsequent years, UFPE organized scientific initiation congresses for all areas of knowledge and began to organize the event with the financial support of an organization of the Brazilain federal government named the National Council for Scientific and Technological Development (CNPq).

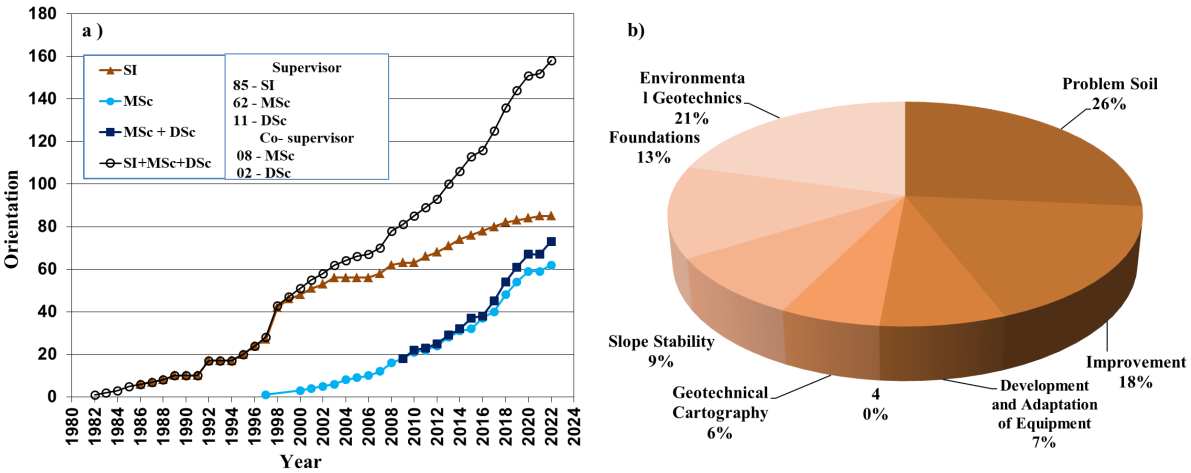

Figure 2. Evolution of experiment participants over time: a) quantitative evolution of the students participating in the experiments; and b) distribution of participants by research activity. IS - Scientific Initiation, MSc - Master of Science, DSc - Doctor of Science

Scientific initiation students accompanied the installation of the inclinometer and participated in the monitoring of displacement over time. They prepared reports and participated in scientific initiation congresses. Some of the students received master's degrees and doctorates, and many are today professors at public and private universities, designers, or federal and municipal public employees.

3.2.2 Dissemination of methodological experiments

The results of the integrated methodological experiments were published in 326 publications, of which 59% were on the Geomechanical Behavior of Soils, 39% on Soil Use and Occupancy, and 2% on Teaching, as shown in Figure 3a. Under the theme of Geomechanical Behavior of Soils, 49% were about Problematic Soils, 7% on Soil Improvement, and 7% on Equipment Development and Adaptation, as shown in Figure 3b. Under the theme of Soil Use and Occupancy, 3% were in Geotechnical Cartography, 3% in Slope Stability, 7% in Foundations, and 17% in Environmental Geotechnics, as shown in Figure 3c.

A group of experiments were carried out field and laboratory on expansive soil in the same location municipality of Paulista, Pernambuco which resulted in dissertations, theses and made it possible to: a) monitor the crack propagation process through photographic images in the field (Figure 4a), in an area without (Figure 4b) and with vegetation (Figure 4c), during dry and rainy seasons, (Araújo, 2020); b) develop and adapt equipment that allows for the removal of anchored piles (Figure 5a) with loading and unloading cycles (Figure 5b), drying and wetting cycles (Figura 5c), and monitoring of the crack propagation process (Araújo, 2020); c) develop laboratory equipment to monitor the crack propagation process through drying and wetting cycles, with variations in soil weight, temperature, relative humidity, and suction (Araújo, 2020); d) evaluate the stress-strain resistance behavior of soil and its mixtures with lime (Morais et al., 2017; Paiva et al., 2016), with tire fibers (Menezes et al., 2019; Faustino et al., 2023; Silva & Ferreira, 2023); e) analyze the interaction between soil particles with the addition of sand, lime, rice husk ash (Bezerra, 2019) using squeeze flow; f) evaluate the variation of the cone tip resistance with depth, using the Dynamic Penetrometer Light (DPL) in soil under natural moisture conditions and when flooded (Borges et al., 2016) and g) evaluate the soil microstructure before and after expansion using computerized tomography (Barbosa, 2019).

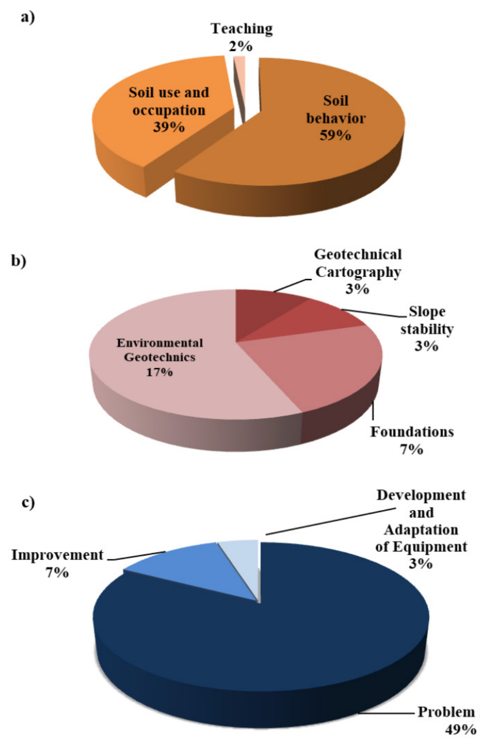

Figure 3. The number of experiments disseminated: a) Total publications; b) Land use and occupation; and c) Soil behavior.

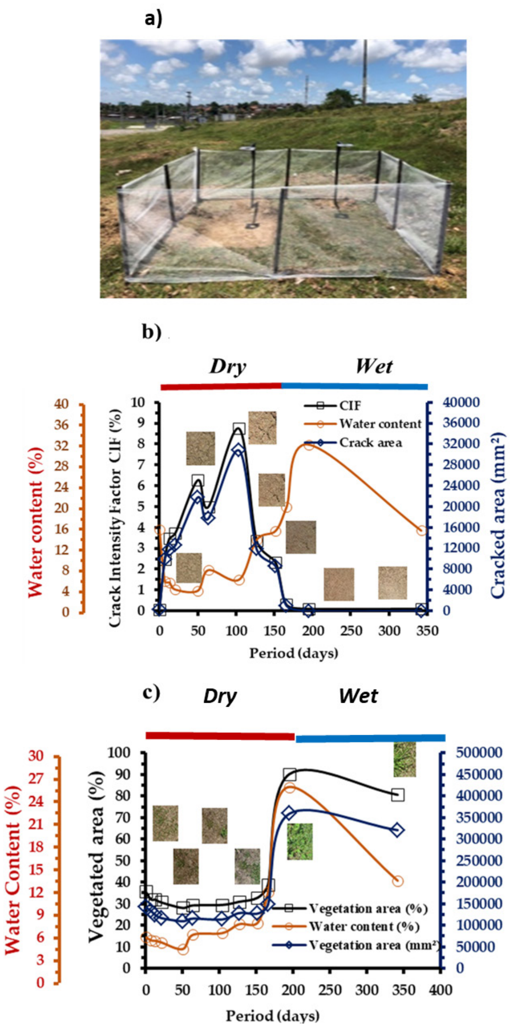

Figure 4. Methodological experiments were carried out on expansive soil in the municipality of Paulista, Pernambuco: a) Field experiment; b) Area without vegetation; and c) Area with vegetation.

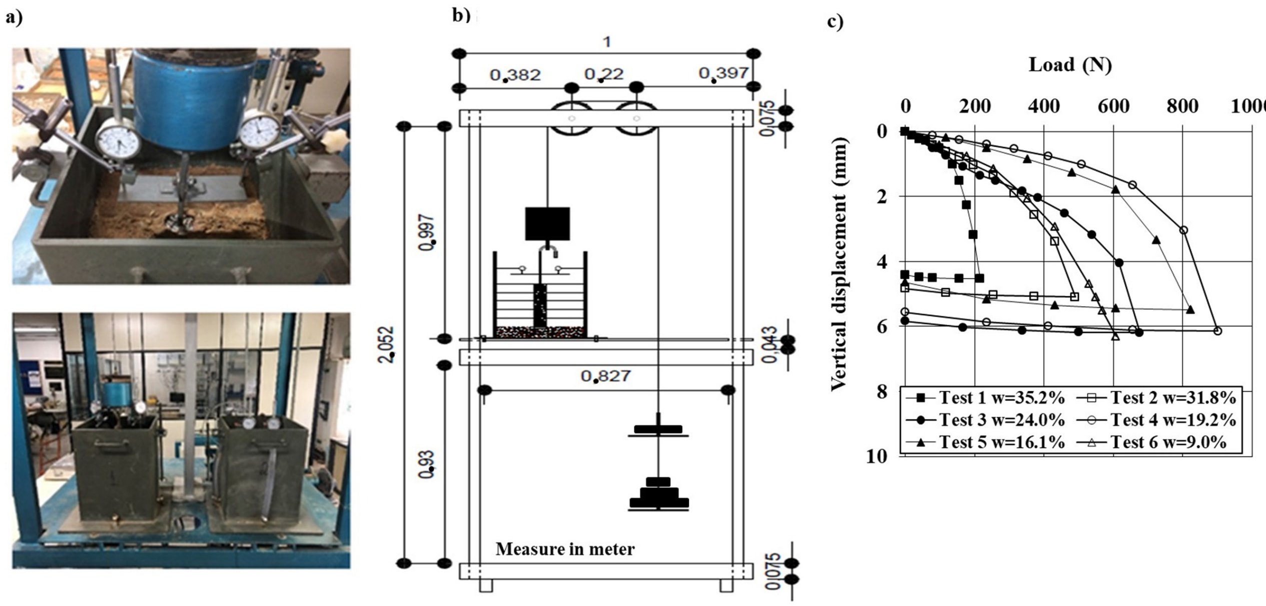

Figure 5. Methodological experiments to pullout tests on Granular Pile Anchor (GPA): a) Laboratory experiment – pullout test; b) Schematic details of the test; and c) Load displacement curve - pullout test.

In the expansive soil of the municipality of Cabrobó, PE, methodological experiments were conducted to evaluate the stress-strain behavior of soil and its mixture with hydrated lime (Paiva et al., 2016; Ferreira et al., 2017) and rice husk ash (Lacerda & Ferreira, 2020). Rice husk is a byproduct of rice processing that can cause environmental problems when performed on a large scale. To reduce the impact and the amount discarded, rice producers use the husk as fuel in the boilers of the parboiling process. Beyond being used for power generation and steam production, rice husk can be used to make bricks. The Rice husk ash (RHA) is a fine material with cementitious properties that has a high silica content and high pozzolanic activity. The experiment used RHA generated by a company in the municipality of Cabrobó, PE. The addition of RHA to soil reduced its expansiveness and showed that it was feasible to use RHA to reduce environmental liabilities. This experiment was also used with expansive soils in the municipalities of Agrestina, PE and Brejo da Madre de Deus, PE (Silva et al., 2020a).

Several methodological experiments were performed on collapsible soils. The Expansocolapsometer were carried out to evaluate the potential for collapse of collapsible soils in housing complexes and irrigation projects in Petrolândia, PE (Ferreira & Lacerda, 1993, 1995; Ferreira & Fucale, 2014), in Petrolina, PE it was used in the Nova residential complex Petrolina linked to the Minha Casa Minha Vida program and the axis of the Pontal Azul canal in Petrolina, PE and the collapsible soil of Palma, TO during the construction of the airport runway (Ferreira et al., 2002). Torres (2014) evaluated the variation in tip resistance with a Dynamic Penetrometer Light (DPL) and a static penetrometer (cone) and evaluated the collapse potential with an Expansocolapsometer in natural and flooded soil at the Nova Petrolina residential complex in Petrolina, PE, linked to the Minha Casa Minha Vida program. Borges et al. (2016) evaluated the elasticity modulus and volume variation of soil in the field, with and without previous flooding. They used a Light Weight Deflectometer (LWD), Expansocolapsometer, Dynamic Probing Light (DPL), and Static Penetrometer (PE) to perform the physical, chemical, and mineralogical characterization of the soil in the laboratory. Alves et al. (2021) obtained the characteristic curve, permeability, and soil microstructure before and after flooding using Scanning Electron Microscopy (SEM) and 3D X-ray Computed Tomography (CT), analyzed the hydro-geomechanical behavior, Sewage sludge valorization for collapsible soil improvement (Feitosa et al., 2023) and made numerical simulations with the elastoplastic constitutive model known as the Barcelona Basic Model (BBM) (Ferreira et al., 2008, 2013).

Silva & Ferreira (2003) prepared maps of the susceptibility of the occurrence of collapsible and expansive soils in the municipality of Petrolina, PE, based on pedological units. Amorim et al. (2005) used pedological, geological, and climate classification units to elaborate maps of the susceptibility of the occurrence of collapsible and expansive soils in the state of Pernambuco. Aquino & Ferreira (2022) contributed to the geotechnical cartography of the municipality of Teresina, PI, by using geoprocessing to elaborate susceptibility maps for the occurrence of problematic soils and foundation practices. Holanda (2022) elaborated susceptibility maps for collapsible and expansive soils in Brazil by applying artificial neural networks.

The geomechanical behavior of the foundation soils of the Recife II/Bongi transmission line towers was performed by Quental & Ferreira (2008). Oliveira (2013) analyzed load tests on continuous flight auger piles and their reliability for commercial buildings in the Recife Metropolitan Area. He was awarded the Icarahy da Silveira prize promoted by the Brazilian Association of Soil Mechanics and Geotechnical Engineering (ABMS) for the best dissertation in geotechnics in Brazil during the biennium 2012-2014. An evaluation of the methods for prediction and control of load capacity in H-profile steel piles was performed by Silva (2013) and experiments related to soil-structure interaction were performed by Patricio et al. (2018) and Araújo Júnior (2022).

Slope stability experiments were performed by Ferreira et al., (1999) and Ferreira et al., (2001) on hillsides in Recife and slopes in Ipojuca by Pereira (2020). Experiments on erosive and dispersive soils were performed by Quental & Ferreira (2008) and Portela et al. (2021). The evaluation of dispersivity and compressive strength of soil composites from the Barreiras Formation with RCD and lime was evaluated by Silva et al. (2019, 2020b); Portela et al. (2021). The analysis of the erosive process of a slope in the Bom Jesus neighborhood of Ilha de Itamaracá, PE was performed by Santos et al. (2021). The area was mapped using an Unmanned Aerial Vehicle (UAV) and erosion was delimited and quantified using the Universal Soil Loss Equation (USLE).

3.2.3 Methodological experiments integrated with university extension activities

In the waste and citizenship university extension experiment, the activities were oriented towards the Integrated Final Disposal Project of the municipality of Rio Formoso, PE. The undergraduate students, scientific initiation students, master's students, and technicians participated in the process of selecting the area to locate the landfill, the diagnosis of the municipality's sanitation services, the master plan, the landfill project, the composting unit, and the plastic recycling unit. During the diagnosis, the Clean Swamp action was carried out, where a large joint effort was organized to clean a 2.0 km stretch of the river near the city center. Students from five public schools, about 500 elementary school students in total, were mobilized, along with a fishing colony and other associations. In this action, 163 tons of solid wastes were removed and 6000 folders were distributed, in a great example of citizenship. An environmental education booklet entitled "Trash: From Generation to Final Destination – Environmental Education" was prepared. The illustrations in the booklet were selected by the students based on the diagnosis of sanitation services of the municipality (Ferreira et al., 2005a, b).

To implement this project, an Environmental Impact Assessment was carried out, consisting of three distinct stages: diagnosis, prognosis, and conclusions. It encompassed studies about the area where the four units of the integrated system were implemented, addressing the physical, biological, and socio-economic environments, data and information collection, and field and laboratory investigations. Students in the scientific initiation program and graduate students participated in each of the stages. For effective control of the environment, a follow-up and monitoring program of the main impacting actions was developed, according to the environmental impacts identified in the prognosis, to minimize impacts caused during the implantation phase.

Based on the cultural and solid waste characteristics of the municipality, collected during the diagnosis of the student's research, the Integrated Final Solid Waste Disposal System of Rio Formoso, PE is composed of four units: the Center for Environmental Education (CEARF), a Recycling Plant, a Composting Plant, and a Landfill, as shown in Figure 6.

The project received an Honorable Mention from the National Health Foundation of the Ministry of Health for the work entitled: An Innovative Solution: Integrated System for the Final Destination of Solid Waste from the Municipality of Rio Formoso, PE, presented at the II International Seminar of Public Health Engineering, on December 3, 2004, in Goiânia, GO (Ferreira et al., 2004).

In this project, the implementation of a green barrier to surround the construction site was envisaged, through the planting of trees that can be easily rooted from "stakes," which will speed up the creation of the barrier. This could be done with Eucalyptus citriodora Hook planted with a two-meter spacing, with the barrier formed of two equal rows, two meters apart. The project counted on the participation of federal (National Institute for Agrarian Reform – INCRA), state (Department of Science and Technology and the Environment – Sectma and the Planning Department of the State of Pernambuco SEPLAN/PE – Promata), and municipal (Rio Formoso, PE Prefecture) governments, an international non-governmental organization Avina Group, the Producers Association of the Settlements of Engenho Serra D'Água, and two universities, one federal and the other private. The project was considered by the State of Pernambuco to be a pilot project and was extended to the neighboring municipalities of Serinhaém and Tamandaré through an inter-municipal consortium. The joint actions improved the standard of living and health of the population, improved the aesthetic and environmental aspects of the cities, and transformed the waste into a product that can increase employment and income.

Oliveira et al. (2019) described an innovative experiment of the leachate treatment process with *Moringa oleifera* Lam seed extract obtaining a useful residual sludge to obtain a biosolid. The invention lies in the fields of agronomy and environmental engineering. The experiment was carried out on compost (residual sludge) from the Landfill CTR-Candeias in Muribeca, Jaboatão dos Guararapes, Pernambuco. Figure 7 shows the development of Lettuce Seeds through bioassays that allowed evaluation of the efficiency of using the waste sludge compost from sowing to germination at 25 days. The biosolid is equivalent to the use of commercial substrate, in the production of seedlings.

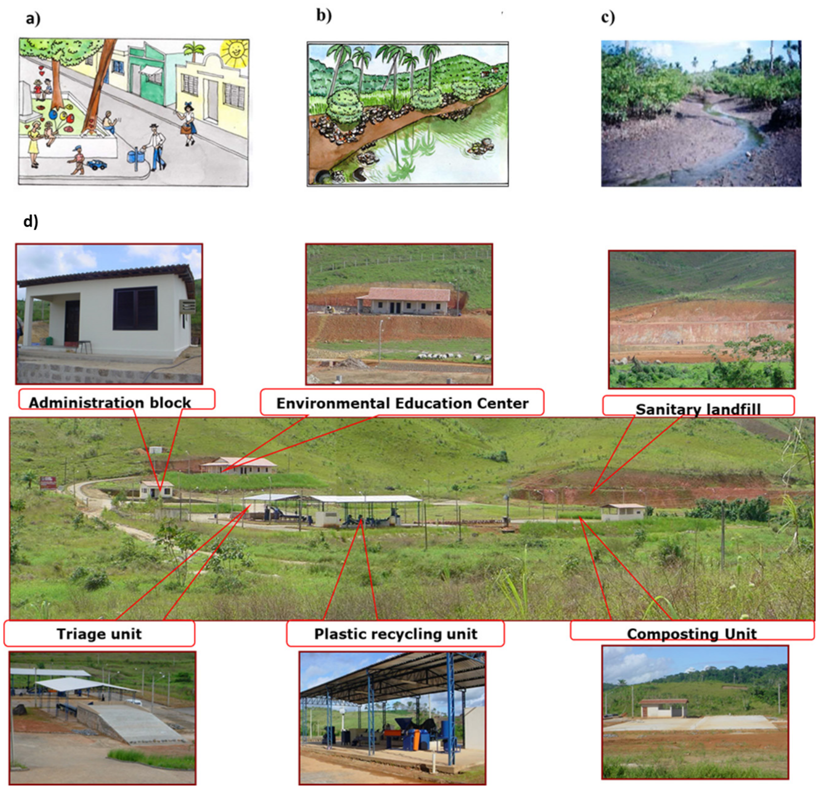

Figure 6. Methodological experiments integrated with research and extension: a) Guidebook; b) Clean slough activity; c) Cleaning slough; and d) Integrated Final Solid Waste Destination System of Rio Formoso, PE (adapted by Ferreira et al., 2005a).

Figure 7. Lettuce seeding: a) Sowing; b) Germination with 5 days; c) Germination with 15 days – control; d) Germination with 15 days compost; e) Germination with 25 days – control; and f) Germination with 25 days – compost (adapted by Oliveira et al., 2019).

Indicating the use as an alternative to compost for reuse in the landfill nursery fertilization for the production of seedlings and reforestation of the landfill area. Reduction of the risk of contamination of the soil, groundwater and riverbeds, reduces the use of chemical fertilizers in the planting areas. The proposed methodology presents efficiency and its use can be indicated for application on a full scale, aiming at its adoption by sanitary landfills. The leachate treatment process was registered at the National Institute of Industrial Property (Oliveira et al., 2019).

4. Conclusion

The methodological experiments integrated into multidisciplinary projects provide a suitable environment for interaction between the university, designer, engineering industry and civil society, favoring the teaching-learning process.

The methodological experiments that integrate undergraduate students, from the scientific initiation program with postgraduate students (master's and doctorate) promote the advancement of knowledge, the formation of more qualified human resources, competent and qualified to respond to new scientific challenges and technological.

Methodological experiments with university extension activities bring challenges, demands from society and opportunities for the academic environment to solve problems, favoring the teaching-learning process.

This study demonstrates the use of a positive teaching-learning experience conducted in geotechnical engineering education on the development of civil engineers who possess both technical skills and professional competencies.

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Declaration of interest

The authors have no conflicts of interest to declare. The contents of the paper and there is no financial interest to report.

Authors' contributions

Silvio Romero de Melo Ferreira: conceptualization, methodology, validation, writing-review & editing, data analysis, supervision.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

ABMS	Brazilian Association of Soil Mechanics
BBM	Barcelona Basic Model
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CEARF	Center for Environmental Education of Rio Formoso
CIF	Crack Intensity Factor
CNPQ	Council for Scientific and Technological Development.
CT	Computed Tomography
CTR	Waste treatment center
DPL	Dynamic Penetrometer Light
DSc	Doctor of Science
FINEP	Financier of Studies and Research
INCRA	National Institute for Agrarian Reform
IS	Scientific Initiation
MSc	Master of Science
PRODENGE	Engineering Development Program
PROMATA	Program to support the sustainable development of the Zona da Mata of Pernambuco
REENGE	Reengineering of Engineering Education
RHA	Rice husk ash
SECTMA	Secretary of Science and Technology and the Environment
SEM	Scanning Electron Microscopy
SEPLAN	Planning Secretary of the State of Pernambuco
UAV	Unmanned Aerial Vehicle
UFPE	Federal University of Pernambuco
USLE	Universal Soil Loss Equation

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The use of a video and a small-scale model for rain-induced landslides in geotechnical engineering education

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Article

Keywords
Landslides
Physical modeling
Disaster education
Slope stability
Educational video

Abstract

Small-scale physical models of geotechnical problems are thought-provoking didactic tools that motivate students by arousing their curiosity and facilitating the understanding of physical phenomena and theoretical concepts. This work presents the development of an educational video about slope stability failures and its contributing factors. It shows several small-scale models built in a glass wall tank measuring 150 x 50 x 10 cm. Layers of fine gravel were placed on a sloping surface of polystyrene to represent a slope with a layer of residual soil on rock. Toy houses and cars were used to represent anthropogenic agents, and water with dye represents the groundwater flow. Each model depicts a different scenario of shallow slope failure. The objective of the video is to show that most slope failures in urban areas result from natural and anthropogenic factors. Several influence factors are shown: porewater level rise, excavation, surcharge application, and solid urban waste deposition. The 6-minute video has had more than 130,000 views on YouTube. Thanks to its simple and concise language, the video is shown in basic education and science museum, as well as in graduate and undergraduate courses. A questionnaire survey was carried out with undergraduate students to assess how helpful the video was for the learning process. This article explains the construction of the model, the video script, and the strategies for its use, as well as its reception. It was found that the video promoted motivational and learning benefits of providing context, establishing relevance, and teaching inductively.

1. Introduction

Landslides are a frequent natural hazard and a major threat to humans and the environment worldwide (UNISDR, 2017). The rate of rain-induced landslide disasters has significantly increased in quantity and impact magnitude over time. However, being greatly underestimated, many were incorrectly attributed to other associated events such as floods, storms or earthquakes (Petley, 2012; Hernández-Moreno & Alcántara-Ayala 2017). Despite the fact that the numbers are underestimated, the International Disaster Database (EM-DAT, 2023), which uses the criterion of a minimum of ten fatalities for an event to be included in the database, recorded a total of 371 landslides causing 17,159 fatalities and about 4.8 million affected people during the period 2002 – 2022 worldwide. It is also important to mention that the participation of human activity as triggering factors of landslides, in particular in relation to construction and hill cutting, is increasing (Froude & Petley, 2018).

Based on the Brazilian Atlas of disasters (Brasil, 2023), 1,246 landslide disasters were officially registered in Brazil between 2001 and 2021, involving 604 fatalities and 4.2 million affected people. Similarly, to what occurs on a global level, these quantities are, however, heavily understated. The association of data from the 2010 Demographic Census with those deriving from mappings carried out in risk areas in 872 Brazilian municipalities monitored by the National Center for Natural Disaster Monitoring and Alerts in 2018 allowed estimating that the population living in landslide and flooding risk areas, in these municipalities, back in 2010, comprised approximately 8.3 million inhabitants (IBGE, 2018). Landslide disasters in Brazil reveal a form of social organization which results in rapid and disorganized settlement of landslide-prone areas by poor populations (Da-Silva-Rosa et al., 2015). According to Macedo & Sandre (2022), the ten most affected Brazilian cities between 1988 and 2022 comprised 63% of the deaths in Brazil. These cities have great importance for their states and metropolitan areas and attract internal migration that increases the pressure for occupation of landslide-prone areas.

The role of the university is highlighted in the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015), which is the main international tool for disaster risk reduction. One of its four main priorities is a clear understanding

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of the disaster risk by means of improving the knowledge in every educational level to make society more resilient. Oliveira (2009) assessed the future of Geo-Engineering Education, and highlighted the importance of environmental issues in geotechnics since they are associated to problems that may cause great harm to society, like natural hazards from inadequate land use, and landslides.

Given the current prevision landslide disasters, there is a growing demand for professionals prepared for the planning and implementation of risk reduction actions, according to the Sendai Framework strategies. The geotechnical engineer plays an important role in this process since he or she is the professional who, along with other geoscience professionals, such as geologists and geomorphologists, seeks to understand and model the different types of landslide phenomena and their various conditioning factors to propose the most suited mitigation measures for local realities. This issue, however, is not limited to the landslide mechanism. Rather, it involves the social system that can influence and be affected by it, at the same time. Malamud & Petley (2009) highlight that most disasters occur because of complex interactions involving hazardous processes and social systems, and the only logical way to address disaster risk reduction is to consider both elements simultaneously, which means an interdisciplinary approach.

In this context, geotechnical courses are needed to address the issue of slope stability considering the local reality of the social system using pedagogical resources that facilitate this understanding by students. However, it has been observed that normally geotechnical engineers trained in civil engineering courses, even with master's and doctoral degrees, become over-reliant on theories and their equations, being far from real field conditions, which in the case of landslide disasters have a major social component. Small-scale models may play an important role in improving the learning and teaching conditions. Black et al. (2018) advocate for greater adoption of experiment-based observation/demonstration to be embedded within the geotechnical undergraduate curriculum to enrich the student learning experience. Becker et al. (2018) used small scale models to assist students in understanding flow theory and applications. This work aims to discuss the conception of a didactic video that uses a reduced model to address the issue of slope stability, presenting the main anthropic aspects that may contribute to landslides, as well as their consequences. The work also presents how the video was used in different spaces of education and the evaluation by an undergraduate class in civil engineering at the Federal University of Rio de Janeiro.

2. Materials and methods

2.1 The basis of the design of the video on slope stability

Considering the demands mentioned above, the slope stability video was conceived by combining two basic principles, the observational method, and the real-world approach.

Engineering schools and professors have been told to adopt some directions to diminish the deficiencies in engineering education. Among these directions are teaching more about "real-world" engineering design and operations and producing graduates who are conversant with the connections between technology and society (Felder et al., 2000).

In a study on effective learning experiences that best support the development of expert professional practice in engineering courses, Litzinger et al. (2011) mentioned using context-rich, multifaceted problems as an approach to help students develop more sophisticated problem-solving skills than those built when solving typical textbook problems. This kind of approach is a strategy to link abstract content to realistic problems, which also increases the students' motivation.

The material used in engineering courses by the instructor can be categorized as concrete (facts, observations, experimental data, applications) or abstract (concepts, theories, mathematical formulas, and models). Although the use of these materials varies from one course to another, the balance between these two categories has shifted toward abstraction in recent decades. In this context, Felder et al. (2000) pointed out the challenge to provide sufficient concrete material to have a better balance. According to the authors, introducing new abstract information grounded in the student's existing knowledge and experience provided by concrete content helps to encode it in the students' long-term memories. Also, the concrete content should be tied to "real-world" situations to increase motivation.

Kusakabe (2022), in his work on development and challenges of physical modeling in geotechnical engineering, reminded the proverb "To see is to believe" to highlight that observation is the starting point for modern science. Observation should not be limited to engineering design activities. Rather, it should be extended to any process that requires consideration on material behavior and its consequences. In fact, some concrete materials, such as reduced models, have been used to represent various physical processes in geo-engineering education to improve student learning (e.g. Atkinson, 2007; Jaksa, 2008; Herle & Gesellmann, 2008; Seo & Yi, 2023).

In this regard, a video of a small-scale physical model interspersed with animation was conceived to be used in undergraduate courses of Civil Engineering to explain landslides. This video is a kind of concrete material to introduce the issue, considering the reality of the landslide disasters in human-occupied slopes, as described in the preceding section. The video was designed to be used as a thought-provoking didactic tool.

Simple language was used, and complex theoretical explanations were avoided to make the video suitable for the layman.

2.2 The video script

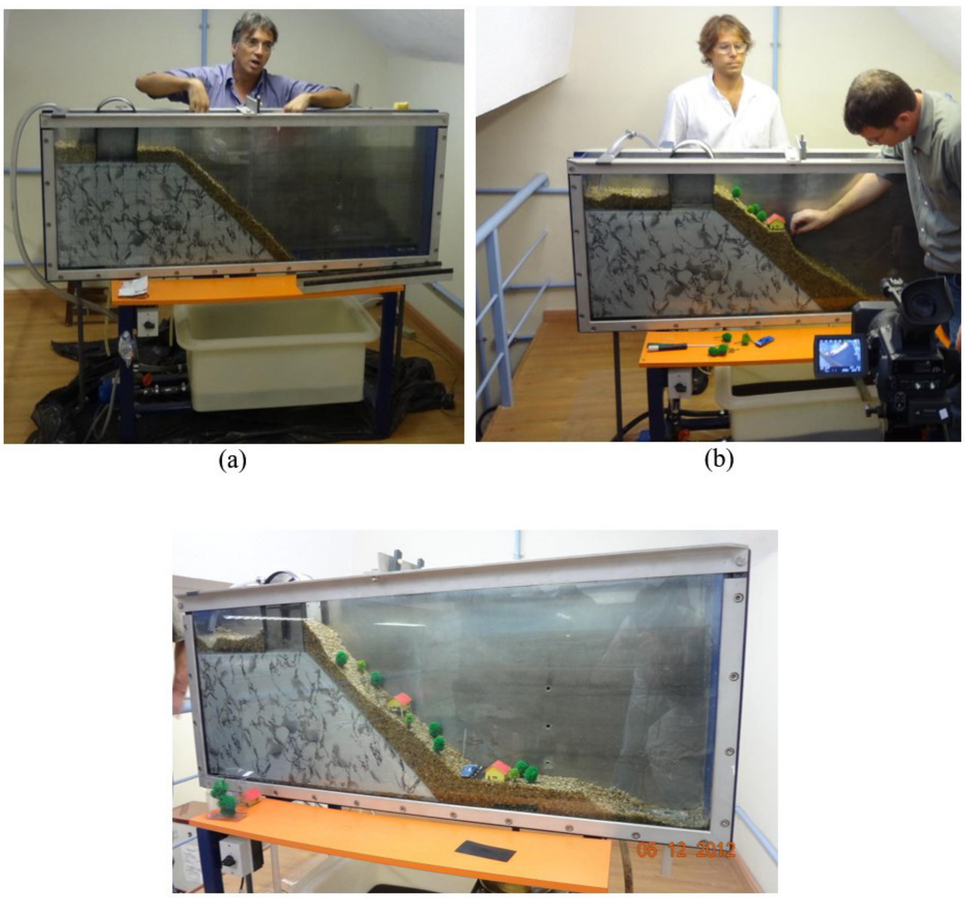
The video was conceived to address the following key points: to give a context of landslide disasters in Brazil; to show the building of the small-scale experiment; to conduct the experiment while addressing the natural and anthropic triggering factors; to address the impacts of landslides.

Shallow landslides (Hungr et al., 2014) are some of the most widespread natural hazards worldwide (UNISDR, 2017). Shallow translational landslide was the type of mass movement chosen to be simulated as it is the most frequent type observed in Brazil, and usually causing great harm to society (e.g., Wolle & Hachich, 1989; Lacerda, 2007; Coelho-Netto et al., 2007; Avelar et al., 2013). Some human activities usually found in areas of disorganized land use (e.g., cutting and filling to build houses or roads, solid waste dumping deforestation, and inadequate water supply, sewage and drainage systems) increase the landslides hazard (Mendonca & Guerra, 1997; Michoud et al., 2011). Therefore, some of those were represented in the model. Table 1 shows the video script.

2.3 Construction of the small-scale model

For the construction of the small-scale model, a tank of the Soil Mechanics Laboratory of the Polytechnic School of the Federal University of Rio de Janeiro was used. This tank is used for modeling water flow problems. It is made of a steel box 1.5 m wide, 1.0 m high and 0.1 m thick (Figure 1). A glass front wall and the insertion of dye in the water allow the observation of the flow lines. Below the tank, there is a water reservoir and an electric pump that may be used to establish a continuous flow in the model. An inclined plane of painted Polystyrene was inserted inside the tank to represent a sloping rock (Figure 1), on which shallow landslides occur. Fine gravel was placed on the inclined plane to represent a soil layer. Toy objects were used to represent houses, trees, roads and vehicles. Figure 1 shows some of the assemblies.

Figure 2 shows the images of the water level rising and the excavation (a, c, respectively), and the corresponding animations (b, d, respectively).



(a) (b) (c)

Figure 1. Steel tank for flow models: a) view of the tank and, below, the water reservoir and the electric pump; b) detail of the glass wall and the Polystyrene inclined plane that simulates the rock; c) slope and toy objects.

Table 1. Script of video available on YouTube (Mendonça & Becker, 2014).

Speech	Images (video time)
Part 1: Contextualization of landslide disasters in Brazil (0:27-1:44)	
Narrator: The objective of this video is to explain why landslides occur on the slopes, and to show how human occupation can influence these disasters.	Images of landslides, newspaper stories etc. (0:27-1:18)
The problem occurs in several regions of Brazil, especially in the rainy season, and is repeated every year, causing loss of life, social and psychological damage. In the last 3 years, just over a thousand people died in landslides in several cities in the state of Rio de Janeiro. Much larger numbers of people, including children, the elderly and the sick, were displaced or made homeless. Added to this is the physical damage caused by the destruction of homes, roads and water and sewage networks.	
The poor who occupy inappropriate areas in a disorderly fashion are the ones who suffer the most from this.To understand the causes of these disasters, it is important to analyze the slope's subsoil.	
One of the most common types of landslides occurs where there is a thin layer of residual soil onto the rock. The thickness of the soil layers below the surface is of a few meters. Below the soil there is rock.	
Narrator: When it rains, the water penetrates the ground through the soil layer until it reaches the rock, when it changes direction and flows down the slope.	Animation: A slope profile, showing a thin soil layer is shown. Blue arrows indicate the downward movement of the rain until it reaches the rock. Then the arrows change direction (parallel to the rock top), and the water level rises within the soil. The drawing shows a wet region within the soil and blue downward arrows parallel to the terrain. (1:19-1:44)
If the rain continues, the soil is saturated and the water causes a force that drags the soil down the slope.	
Part 2: building the small-scale experiment of landslides (1:45-2:37)	
Narrator: This model was created to represent a slope. The glass wall allows you to visualize what happens. An inclined plane made of polystyrene represents the rock. The soil is placed on top of it. A tank system with colored water and an electric pump represent the entry of rainwater into the land.	Model: footage of the model assembly.
Part 3: conducting the experiment addressing the natural factors (2:37-3:32)	
Narrator: The water level rises and increases the pore pressure in the terrain, but the strength of the soil is still enough to prevent a landslide.	Model: Steady water flow scenes in the model. (2:37-2:56)
Narrator: However, if the rain continues to soak the soil, the water level will rise until the strength of the soil is overcome.	Model: Scenes of water level rising and slope failure in the model. (2:56-3:14)
At this point, the landslide occurs.	
Narrator: As we can see in this video, the soil slides on the rock and hits everything in front of it with great energy.	Model: Scenes of the slide in slow motion. (3:14-3:32)
Part 4: conducting the experiment addressing the anthropogenic factors	
4.a - cut and fill in a slope (3:32-5:02)	
Narrator: A landslide can happen more easily if the slope is steeper. How does this happen? It is common to make excavations in the ground to have a level where a house or a street can be built. This makes the back slope steeper and easier to slide off.	Animation: step-by-step execution of two excavations on a slope, resulting in two plateaus and the "construction" of a toy house on one plateau and a toy road on the other. Then two landslides hit the house and the road.
	Model: show the failure of the small-scale model caused by the excavation procedure (no flow). (3:32-4:37)
Narrator: an embankment fill may be placed on the slope to make room for construction of houses or roads. If this construction is not performed properly, a slide can be triggered by it.	Animation: shows the embankment image that looks stable (section equal to the end of the excavation animation).
Narrator: Despite its "safe" appearance, the embankment fill constructed without care saturates during heavy rains, loses strength and slides.	Animation: shows the slide hitting the houses. (4:37-5:02)
4.b - solid waste dumped on the land (5:02-5:12)	
Narrator: It's even worse when one dumps rubble and solid waste on the slope.	Animation: show an accumulation of solid waste on the slope.
Narrator: This material may be weak and slide easily when it rains.	Animation: show the slide of solid waste and debris down the slope reaching the house below.
Part 5: Final Considerations (5:12-6:12)	
Narrator: The objective of this video was to explain how and why landslides occur on the slopes, and show how the occupation can influence the occurrence of disasters.	Collection of images of slopes and slope failures (5:12-5:38) Credits (5:38-6:12)
We hope you have understood why landslides occur and which are the actions that should be avoided to improve the safety of the slopes.	

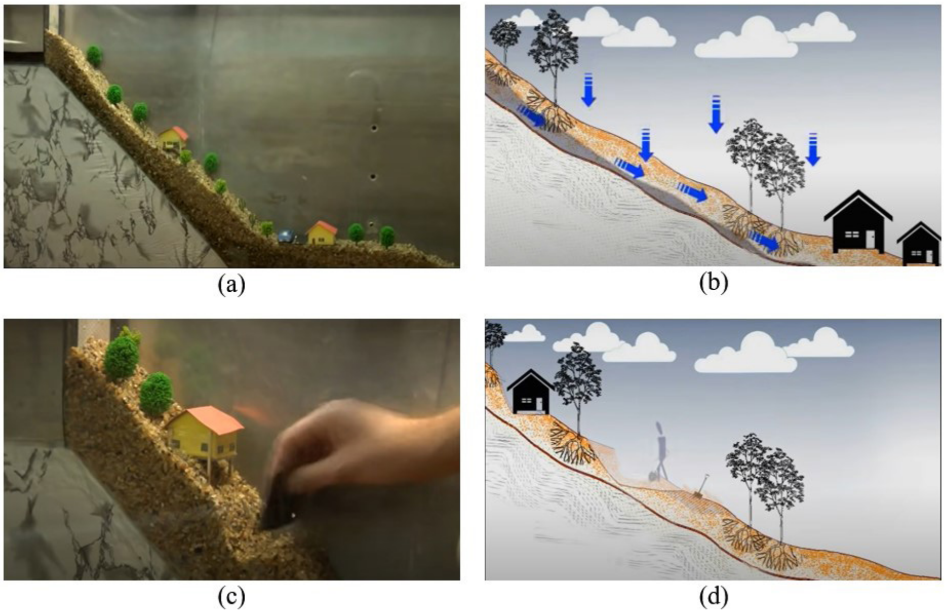


Figure 2. Still images of the video: a) dyed water level flowing in the soil layer; b) animation representing the rain infiltration and the rise of the water level; c) excavation in the slope; and d) animation representing the slope excavation.

3. Use of the video, assessment, and analysis

The video has a total playing time of 6min and 15s and is available on YouTube (Mendonça & Becker, 2014).

The video has been shown to undergraduate students in two disciplines ("Soil Mechanics" and "Slope Stability").

Slope Stability is taught in the last year of the Civil Engineering course. The video is shown to the students just before they learn to deduce the Factor of Safety of an infinite slope to help them visualize the translational failure, the flow pattern caused by the rain, its detrimental effect on the stability, and the human influence. The video also has a motivational effect, as will be shown later. During the showing, the professor usually pauses the video to emphasize the position of the water level and the soil movement. Sometimes the video is shown again after the theoretical class because it allows more discussions.

In the Soil Mechanics classes, the video is shown after a theoretical class to illustrate the effect of the pore pressure in the shear strength. The video is paused just before the water level rises to emphasize that the slope failure is caused by the pore pressure increase.

In each case, some time is allowed for the students to discuss the video.

The professor observes the reactions of the students during the exhibition of the video. In the opinion of the professor, the students like the video, and seem attentive during viewing. Moreover, the video seems to enhance their learning process, and they are more prone to discuss the subject after watching the video.

To assess more precisely the effect of the video as a didactic resource, two questionnaires were applied to 44 students, one before and the other after the exhibition of the video. The video was exhibited after a theoretical class about the safety factor of the slope, in 2022. The students were asked what part of the video they liked the most. They gave several different answers, but the small-scale model was the most preferred (45% of the students). Unlike most classes, in this experiment, the video was shown after the theoretical class instead of before. However, when asked to comment on the effect of the video on the lecture, several students asked that the video be shown before the lecture.

The length of the video (6') was considered adequate by all students, and helped increase the interest of the vast majority in the subject. Also, most students admitted paying more attention to the video than to the theoretical class (Figure 3).

Two questions were designed to assess if the students had really learned the topic, and the effect of the video. The students were asked if the safety factor of a slope could be different if it were under human occupation (Figure 4), and if they had understood the failure mechanism of an infinite slope due to rain (Figure 5). It is clear that the video helped the learning process in both cases.

Due to its simple language, and lack of mathematical equations, the video has also been used in other formal educational structures, such as elementary schools (Mendonça & Valois, 2017), and in non-formal education, such as science museums (Mendonça et al., 2019). The simplicity of the approach and the high relevance of the theme have made the video attract a significant audience on YouTube, reaching more than 130,000 views.

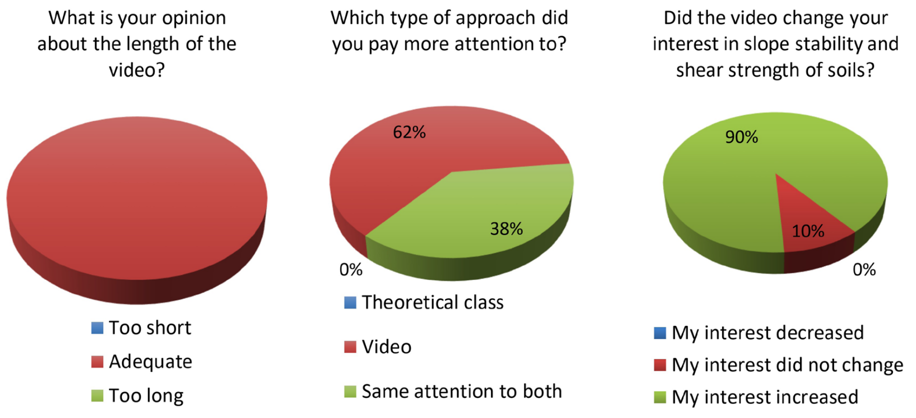


Figure 3. Opinions of the students about the video.

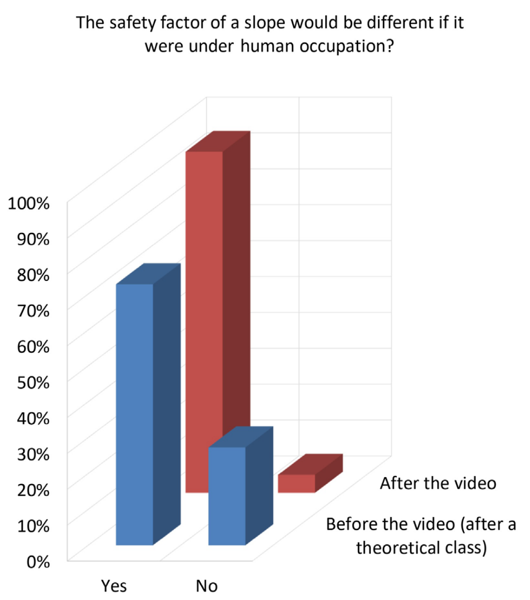


Figure 4. Students' understanding of the influence of the human occupation in the slope stability (before and after the video).

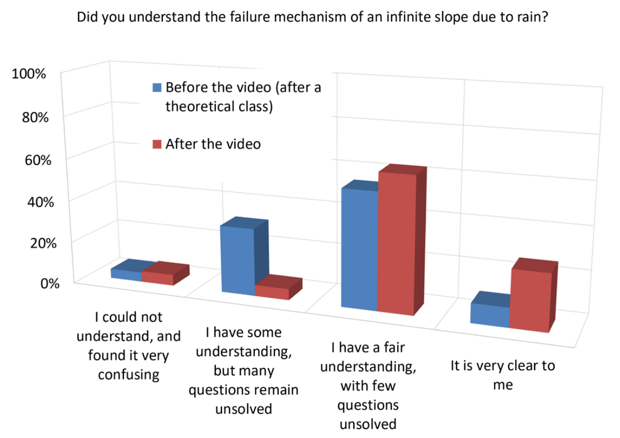


Figure 5. Students' understanding of the mechanism of a translational failure due to rain (before and after the video).

4. Conclusions

The video-model tool presented in this work sought not only to improve the teaching-learning process, but also to bring the slope stability theme closer to society, contributing for geo-engineering students to gain skills to tackle more realistic problems of landslide disasters.

The use of the referred video in slope stability and soil mechanics courses meets the convergent demands of interdisciplinary approach of disasters and the consideration of real-world to facilitate the learning process. Based on Felder et al. (2000), this kind of approach that addresses more complex and broad problems helps the students to acquire skills needed to tackle challenging multidisciplinary problems that require critical judgment and creativity.

The assessment of using the video indicated that the video promoted motivational and learning benefits of providing context, establishing relevance, and teaching inductively. It is best to exhibit the video before the theoretical classes.

The video proved very useful as a didactic tool for landslide disaster prevention in several educational environments, including non-formal educational spaces like science museums.

Moreover, the development of other videos using reduced models of different geotechnical problems is intended since the video usage as a pedagogical tool in the geotechnical engineering course of the Federal University of Rio de Janeiro has showed positive results. Interaction with society is also desirable, whenever possible.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Marcos Barreto de Mendonça: conceptualization, methodology, project administration, writing – original draft and review. Leonardo De Bona Becker: investigation, methodology, data curation, writing – review & editing.

Data availability

The video is available on YouTube, https://www.youtube.com/watch?v=K9i3JyXocgI.

All remaining data produced or examined in the course of the current study are included in this article.

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Historical aspects and challenges of teaching engineering geology to engineering students

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Article

Keywords
Engineering geology
Engineering courses
Teaching

Abstract

This paper discusses some points of the evolution of Engineering Geology based on a survey of historical facts, books, and other types of publications and technical reports and analyzes the teaching in engineering schools, specifically in the São Carlos School of Engineering, at University of São Paulo (EESC/USP). The survey involved the main topics considered in the teaching of Engineering Geology and both successes and challenges of the teaching experience at undergraduate and graduate levels at EESC/USP over the past 50 years are presented. Engineering Geology teaching has undergone different phases and adaptations to the evolution of knowledge and research procedures. According to the survey, it focuses on four large groups of didactic activities for the current decade and, perhaps, for the next one in several countries. The first group refers to access to materials of each topic in the format of books, videos, and lectures available on websites and the second includes face-to-face activities on the solution of practical problems related to a specific topic. The third group focuses on field and laboratory works, whereas the fourth comprehends development and analyses of specific civil work projects, mineral exploration, and environmental problems according to both face-to-face and non-face-to-face methodologies.

1. Introduction

Engineering Geology has been developed over the past 150 years in many countries and taught to students of Geology and Geological, Civil, and Mining Engineering courses, more effectively from the 1950s onwards, and to those of Environmental Engineering over the last 25 years. Records of Engineering Geology teaching were already kept at American universities in the last years of the 19th century (*e.g.*, a set of pioneering works published by William O. Crosbi - MIT and James F. Kemp - Columbia) in 1890 on the importance of the relationship between aspects of Geology and construction procedures of significant engineering works. Term Engineering Geology was introduced in the middle of the 19th century in several European countries and its name in Portuguese derived from the general translation of the following terms: Engineering Geology (English), Ingeniería Geológica (Spanish), InzhenernayaGeologiya (Russian), Géologie de l'ingénieur (French), and Ingenieurgeologie (German). In the first half of the 20th century, Engineering Geology spread more intensely in North America and Europe, but with special characteristics in each country or region, depending on their needs, such as types of engineering works or specific land use problems. Currently, Engineering Geology, along with Soil and Rock Mechanics, constitute the basis of the field of knowledge called Geotechnics (Krynine & Judd, 1957; JEWG, 2004; Giles, 2005). However, the relationships among the three areas of expertise vary from country to country. According to Müller-Salzburg (1976), Engineering Geology emerged as an independent field of knowledge (IDENTITY), generating quantitative information on geological facts necessary for engineering and mining projects to avoid problems during their execution and valuable life. On the other hand, technical terms currently used for the characterization and description of geological materials in aspects related to Engineering Geology can be found since the Mycenaean Civilization, as described in several publications. Zekkos et al. (2006), Morgan Stanley (2015), and Field (2018) discussed Engineering Geology in Homer's poems (HOMERIC POEMS), which also introduced the conceptual aspect of term risk in the epic poem Odyssey, which is still valid and applied in the most different areas of knowledge. However, Leonardo da Vinci's works (1452 - 1519) led several researchers (Olson & Eddy, 1943; Jones, 1962; Martínez Frías & Martínez Martín, 2023) to consider him the first practitioner of "applied geology" for environmental analyses and engineering works. Engineering Geology was first coined by William Smith (1800 to 1815), in England, in canalization projects in mining areas, and the study is considered the first geotechnical/engineering geological map and one of the bases of modern Geology by an influential group of professionals. Over the past 150 years, it has spread to different countries and the definitions provided have led to changes towards their adaptations to advances in technical and

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scientific knowledge involving Geology, Civil, and Mining Engineering and interrelated areas of expertise. After 1990, their adaptations were related to environmental problems, when Environmental Engineering emerged. The definitions provided below are considered the most cited ones and have guided associations and schools in different countries in training professionals. One of the oldest, i.e., the science that involves all aspects of geology and is important in the planning, design, construction, and maintenance of engineering structures, was proposed by Popov (1959), the founder of Soviet Engineering Geology. Komarov (1967) modified it by considering some conditions of the natural environment; whereas Sergeev (1978) added the viewpoint of some aspects of human activities. Currently, Engineering Geology is defined in the statutes of International Association for Engineering Geology and the Environment (IAEGE) as the science devoted to the investigation, study, and solution of engineering and environmental problems which may arise from the interaction among geology and the works or activities of man, as well as from the prediction and development of measures for the prevention or remediation of geological hazards. In general, Engineering Geology teaching has followed the evolution of knowledge in several topics and the insertion and use of technological resources developed for different areas of knowledge and that enable improvements in field and laboratory investigations. In the first period, which covered the mid-nineteenth century up to the 1950s, teaching focused more on geology for engineers, with an approach to fundamental geology topics such as minerals, rocks, geological structures, and geological maps, and more directly on the use of rocks as construction materials in dams and tunnels. The second period, between 1950 and 1980 and from 1950 onwards, Engineering Geology significantly expanded and its teaching was already consolidated in several universities of many countries. During that period, Brazil witnessed an intense development in dam construction and both engineering and geology schools incorporated various aspects of design and construction, advancing the knowledge and teaching of Engineering Geology. The third period encompassed the 1980 and 2000 and, in 2000, an important technical-scientific event took place in Australia involving the International Association of Engineering Geology and Environment (IAEGE), International Association of Rock Mechanics (ISRM), and ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering), which discussed the insertion of the three primary areas of Geotechnics under term “Common Ground”. Since then, its teaching has aimed at maintaining a more significant interaction with that of Soil and Rock mechanics. The fourth period, which covers the years from 2000 up to the present day, includes new topics such as models, spatial variability, uncertainties, and statistical methods applied to different aspects of Engineering Geology, and a substantial increase in environmental issues within its teaching.

However, Engineering Geology teaching has always faced challenges in both theoretical and practical aspects, due to the need to adapt teaching to the amount of new knowledge available, technological resources, professional demands, and relationships with statistical and mathematical resources. The theoretical sense refers to the supply of a perceptive understanding of rocks, minerals, geological structures, and geological processes to students and establishment of a basis for the understanding of how geological aspects positively or negatively affect engineering works and control of environmental conditions. In practical and experimental teaching, the challenges are related to laboratory conditions for identification and characterization of geological materials, geological and engineering maps on appropriate scales, equipment for unconsolidated and rock material testing, availability and authorizations for the use of data from construction sites, software for different purposes, and, especially, field activities. Difficulties concern budgets of educational institutions for educational fieldtrips, fieldwork and visits to engineering works and areas under environmental problems, purchase of software and computers, and rooms with multidisciplinary resources for teaching.

This study evaluated some points of the evolution of Engineering Geology based on a survey of historical facts, books, and other types of publications and technical reports and analyzed teaching in engineering schools, specifically in the São Carlos School of Engineering, at University of São Paulo (EESC/USP).

2. Brief historical

The following brief historical aspects are presented for supporting the understanding of advances in the teaching of Engineering Geology according to some specific points related to its development. A complete set of facts and publications in a chronological order about the beginning and advances of Engineering Geology and a full text on historical aspects can be found in Ribeiro et al. (2023).

The advances and development of Engineering Geology can be divided into different periods, of which the first encompasses part of the 18th and 19th centuries. In 1725, John Strachey developed a set of vertical cross sections to assist in the opening and excavation planning of Somerset mine (England) and in 1879-1880; W. H. Penning published the book Engineering Geology. Between 1799 and 1815, William Smith developed several works in England and a geological map to help the implementation of canals (http://earthobservatory.nasa.gov/IOTD/view.php?id=8733), which can be considered the first Engineering Geological Map. Important facts of the second period (between 1900 and 1925) included launching of several texts and books and, around 1906, publication of several versions of the London subsoil map by Woodward, towards guiding the planning of sanitation works. In the third period, between 1925 and 1950, among the several books published were Engineering

Geology, authored by Redlich, Terzaghi and Kampe, and A Comprehensive Treatise on Engineering Geology, by C.S. Fox. In 1935, K. Terzaghi published the text “Effect of minor geological details on the safety of dams”. In 1928, St. Francis dam collapsed in California (USA), killing more than 450 people and causing above 9 million-dollar losses, thus accelerating the implementation of Engineering Geology in the USA, with Charles Berkey as its exponent. During the fourth period, between 1950 and 1970, Engineering Geology teaching in universities was strengthened. In 1957 (London-England), the first graduate course in Engineering Geology was created at Imperial College, led by John Knill and open to geologists and engineers. In Brazil, the first Geology courses were created at Federal University of Rio Grande do Sul (UFRGS), University of São Paulo (USP), Federal University of Rio de Janeiro (UFRJ), Federal University of Pernambuco (UFPE), and Federal University of Ouro Preto (UFOP) and were fundamental for the training of professionals in the field of engineering geology and the creation of engineering geology disciplines in civil and mining engineering courses. Several essential publications can also be highlighted in this period (e.g., the book “Geology in Engineering”, published by John Russell Schultz (1955), with many editions until the end of the 1980s and considered an important bibliographic reference to date, and the text “The Vaiont Tragedy: geologic causes and engineering implications”, by G.A. Kiersch (1965), about the Vaiont disaster.

The fifth period, which encompassed 1970 to 2000, witnessed the greatest technical-scientific advances and those related to development, disseminated in several international and national congresses in several countries. Many books and didactic texts were published, culminating in an event in Australia, in 2020, involving IAEGE, ISRM and ISSMGE associations. At the event, Morgenstern discussed and gave a lecture on “Common Ground”, a term that encompasses the integration of the three basic areas of Geotechnics.

During the sixth period, beginning in 2000 and continuing to date, IAEGE held the 9th International Congress of Engineering Geology in Durban (South Africa), in 2002, and whose main theme was Engineering Geology for developing countries. Knill (2002) held The First Hans-Cloos Lecture - Core Values for Engineering Geology, which led IAEGE to promote debates on the topic. In2004, a set of issues considered Core Values, which serve as guidelines for teaching and training professionals, was published in IAEG News (Vol. 32, No 1, 2004).

Culshaw (2005) published the text “From Concept towards Reality: developing the attributed 3D geological model of the shallow subsurface”, addressing a fundamental theme for the understanding of the spatial variability of geological materials and geological structures, which gained ground in that decade due to advances in computational techniques. In 2006, H. Bock published the text “Common Ground in engineering geology, soil mechanics and rock mechanics: past, present and Future”, which points to future paths to be followed by the three primary areas of Geotechnics.

Among all aspects discussed by Engineering Geology over the past 10 years, two stand out: uncertainty assessments in the prediction of hazardous events and associated risks, whether related to engineering works, restoration of degraded land or prognostic of environmental problems, or natural processes and analyses in 3D/4D models. Over the last 20 years, many books on Engineering Geology with contents related to new approaches and uses of technological, statistical, and mathematical resources have been published (Ribeiro et al., 2023).

3. Development of Engineering Geology teaching

Engineering Geology teaching can be analyzed in a few periods, according to the topics taught in different countries, at both undergraduate level in civil, mining, and environmental engineering courses and graduate level, and the course content is usually reflected in several textbooks published.

The period between the mid-19th century and the 1950s can be considered the first. Teaching focused mostly on geology for engineers, covering the fundamental topics of geology, such as minerals, rocks, geological structures, and geological maps, and more directly on rock used as construction materials and in some engineering works, such as dams and tunnels.

From 1950 up to 1980, the second period, Engineering Geology expanded substantially. The book authored by Krynine and Judd was published in 1950 and addressed the interaction between Engineering Geology and Soil Mechanics, as well as the context of Geotechnics. In many countries, Engineering Geology teaching was already consolidated in several universities. The urbanization process also intensified and Engineering Geology aimed to adapt to data generation for urban area territorial and environmental planning. The first IAEG congress was held in Paris, in 1970 and, in Brazil, due to the intense development of dam construction, teaching in engineering and geology schools incorporated several aspects of design and construction.

In 2000, a technical-scientific event involving IAEGE, ISRM and ISSMGE associations took place in Australia and discussed the meeting of the three primary areas of Geotechnics as a function of the term “Common Ground”. A lecture on “Common Ground” was delivered by Morgenstern and one on “Total Geological History: A model approach to the anticipation, observation and understanding of site conditions” was given by Fookes, Baynes & Hutchinson. The event involved other proposals, resulting in the term “Ground Engineering”, coined by JEWG (2004). Since then, the teaching of Engineering Geology has aimed at a closer relationship with that of Soil and Rock Mechanics.

The fourth period, from 2000 onwards, has considered new topics, such as 3D-4D models, spatial variability, uncertainties, and statistical methods applied to the different aspects of Engineering Geology, all of them parts of books and texts published and of an interesting overview provided by Griffiths (2014) and Oliveira (2009).

4. Current themes in Engineering Geology teaching

The main subjects of Engineering Geology disciplines for engineering courses at universities in different countries, taken from references and texts published since the beginning of the 20th century, are provided in the supplementary materials (Ribeiro et al., 2023) and texts that are fundamental references for the understanding of advances in both technical and scientific development and teaching can be found in Appendix 1.

Such subjects can be adopted according to regional aspects and specific objectives of the country and the course, whether Civil, Mining, or Environmental Engineering, and taught in different disciplines or segments in function of each educational institute's characteristics and teaching conditions. Practical activities can be developed in classroom, laboratory, or field. Engineering Geology disciplines can emphasize local or regional subjects, depending on the country or region – as an example, based on the climate zone of their country, educational institutions can adopt different topics due to variations in the types of regolith, which are thicker in tropical climates and thinner in cold ones, with or without presence of permafrost. Other examples are the educational institutions in regions with heavy mining, such as the schools of Minas Gerais and Pará, in Brazil, and in other countries (*e.g.*, Chile, Canada, South Africa, and Australia). Specific content should be emphasized in Engineering Geology disciplines in areas subjected to earthquakes. In general, teaching focuses on the following 4 main groups of activities: the first, based on access to teaching materials for each topic in the format of books, videos and lectures available in libraries and websites created for the disciplines; the second, with face-to-face activities, involving solution of practical problems related to a specific topic and pertinent to the course (civil, environmental, mining); the third, centered on field and laboratory work, and the fourth focusing on development and data analysis resulting from different types and levels of investigation and their application in specific projects of civil works, mineral exploration, and environmental problems, with both face-to-face and non-face-to-face teaching methodologies. In this period, the use of data available in databases, technical reports, and field activities has gained importance.

Engineering Geology Teaching experience in the São Carlos School of Engineering at University of São Paulo.

The teaching of Engineering Geology at EESC can be divided into three main phases:

a) First phase

Disciplines related to geological knowledge have been part of the Civil Engineering course at the São Carlos School of Engineering at the University of São Paulo (EESC-USP), since the beginning of the course, more than 70 years ago. During the first few years, the subjects dealt with geology topics for engineers, and it was only approximately 10 years later that they began to include content related to Engineering Geology. The course was called Engineering Geology, which has remained the same to date and the disciplines were taught by Professor Alfredo José Simon Bjornberg, followed by Professors Nilson Gandolfi, Antenor Braga Paraguassu, and José Eduardo Rodrigues. The group's work and experience gave rise to a set of didactic texts intended for the teaching of Engineering Geology and which were intensively used until the end of the 1990s at EESC and at other universities. The undergraduate courses totaled 200 hours in the first 40 years and, recently, around 150 hours for the Civil Engineering course. The Engineering Geology disciplines totaled more than 200 hours for the Environmental Engineering course.

b) Second phase

In 1977, the Graduate Program in Geotechnics was created, and Engineering Geology was taught in 3 to 5 different subject groups. Therefore, Engineering Geology at EESC/USP is over 50 years old.

At the graduate level, Engineering Geology, Soil Mechanics, and Rock Mechanics were taught in the context of the term Ground Engineering (Figure 1), as proposed by Morgenstern (2000), JEWG (2004), Bock et al. (2006) and JTF (2004) and considering the comments pointed out by Terzaghi (1957) and Müller-Salzburg (1980). The topics are listed in specific Tables in supplementary materials (Ribeiro et al., 2023) and were taught through different approaches, however, in a more detailed manner than those taught in the undergraduate course. They followed the fundamental triangle of Engineering Geology proposed by Bock (2006) for providing conditions for the solution of different technical and scientific points, as considered by JEWG (2004).

Engineering Geology is mandatory in the graduate program for all students at the master's degree level. The course content focuses on practical components, identifying and characterizing geological materials, laboratory tests, and use of geological and engineering geological maps, consistently exceeding 50% of the didactic activities. The topics taught up to around 2000 at both undergraduate and graduate levels were: General concepts, Engineering Geology and Geotechnics, The Earth and its divisions, Minerals, Rocks, Geological Structures, Stratigraphic rules, Earthquakes, Unconsolidated materials, Weathering, Classifications of soils, Regional and detailed geology, Geological maps, Geological materials, such as different construction materials (*e.g.*, aggregates), Engineering Geology applied in Rock Excavation/Rock

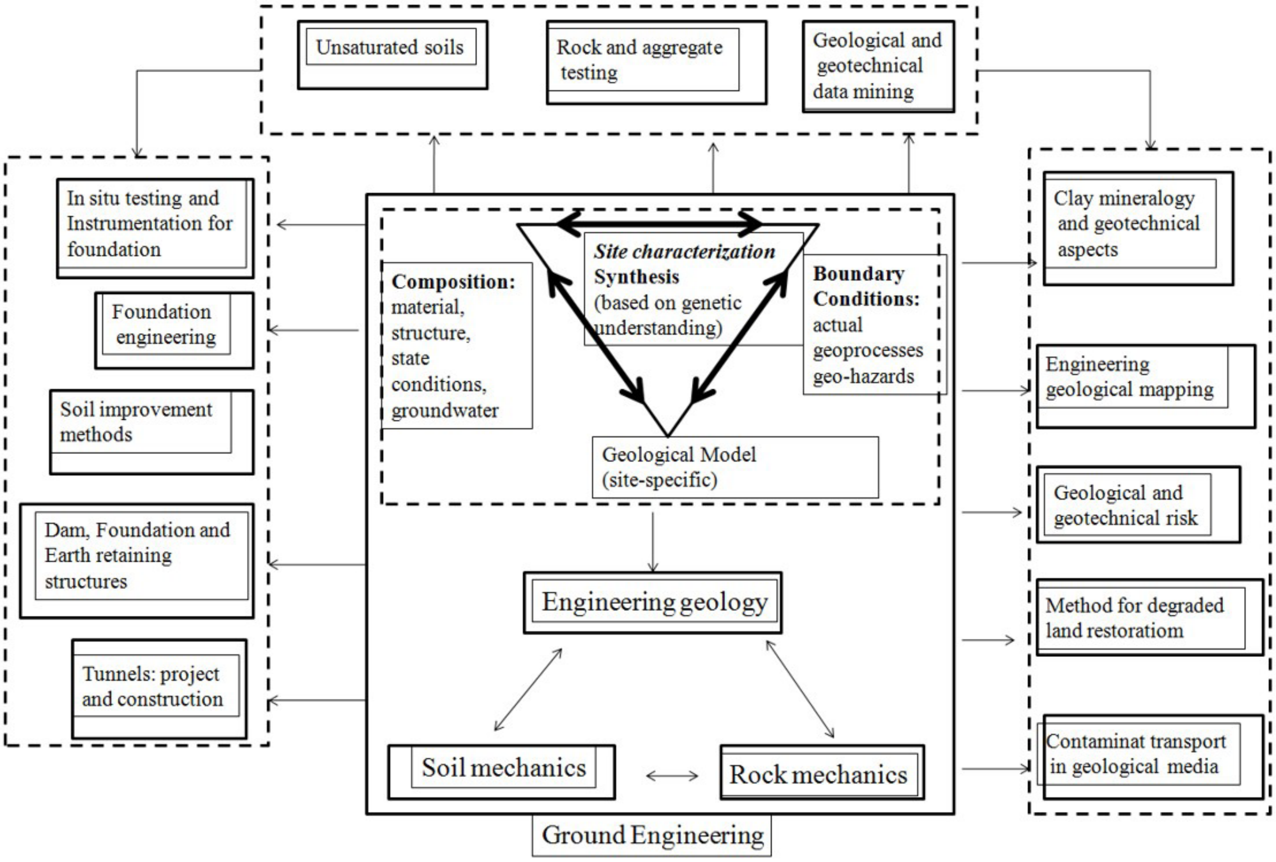

Figure 1. Flowchart with the basic disciplines offered by the Geotechnical Department at the graduate level.

blasting, Foundation, Dams, Embankments, Tunnel, Roads, Slopes, Geological and geotechnical investigation, Geological discontinuities, Rock mass classifications, and Gravitational mass movements in rock, and three field trips were programmed. More details about the topics can be found in supplementary materials (specific Table) in Ribeiro et al. (2023).

c) Third phase

From 2000 onwards, new content (subjects) has been added to the Engineering Geology disciplines at both undergraduate and graduate levels. The Environmental Engineering course was created at EESC/USP and new disciplines - totaling 7 – including topics and teaching methods were mostly related to environmental components, mainly geological media. New topics, namely, Geotechnical properties and physical and geological characteristics, Classifications of regolith profiles (saprolites and weathered rocks), Water (saturated and unsaturated zones), Models (geological and conceptual), Geological materials as different construction materials, Hydraulic Structures and Terrain models, and 3D and 4D analyses were inserted into different disciplines and the content varied according to the undergraduate course, *i.e.*, Civil or Environmental Engineering. More details about the topics can be found in supplementary materials (Ribeiro et al., 2023). It is noteworthy that those topics have been added in stages and challenges still must be overcome (*e.g.*, number of hours/classes to be inserted with due care and relevance and more practical activities and field works whereby students can be in direct contact with different engineering geological situations). Among such challenges, two, namely, financial support from universities and authorization from companies for fieldwork on highways, roads, and areas with outcrops of geological structures and geological materials with intrinsically essential characteristics for both understanding of environmental problems and engineering works must be emphasized. On the other hand, such problems are not pertinent at the graduate level due to the smaller number of students and the easier operationality to be solved in terms of costs and time.

Three points can be mentioned regarding challenges and perspectives. The first is related to the way to equip laboratories for practical classes with equipment developed with recent technology, from simple magnifiers to the most sophisticated devices for the obtaining of physical and chemical characterization parameters, as well as classrooms with computers and programs for different goals, ranging from data processing, preparation of 3D/4D models, and mathematical simulations, considering both geological and geotechnical data. The second refers to the use of data mining resources that provide access to data from different sources related to Engineering Geology pertinent to the sites investigated for different purposes. Finally, the third considers the possibility of developing artificial intelligence routines that can identify geological materials from basic physical characteristics using neural networks and estimate geotechnical properties based on databases from those characteristics. Over the last 5 years, attempts have been made towards the insertion of new topics such as Geological processes, Interaction with the works and as a source of risk, Engineering geological/ geotechnical maps, Environmental problems, Slope stability assessments and monitoring in active open-cast mines, Models in Geotechnics, and Engineering geology applied to offshore areas. They are advanced in Environmental Engineering courses due to the existing disciplines, which, besides the two classic ones, include Geomorphological, Geological and Hydrogeological Constraints, Recovery of Degraded Areas, Geological, Geomorphological, and Engineering Geological Cartography, and Geographic Information Systems, in which specific topics of Engineering Geology are adopted. More details about the topics can be found in supplementary materials (Ribeiro et al., 2023).

Figure 2 shows a simplified flowchart with the subjects taught by the Geotechnical Department and by other departments of EESC-USP (Hydraulic and Sanitation, Structural Engineering, and Transportation Engineering), which have interfaces with the contents taught in the Engineering Geology disciplines. A more complete figure can be found in the supplementary materials (Ribeiro et al., 2023). The issues considered in Engineering Geology 1 (EG 1) are essential, hence, related to all the other Geotechnical disciplines and those taught in other departments. Part of the subjects considered in EG 1 is the basis for teaching topics related to interactions of EG aspects with engineering works. Discipline Engineering Geology 2 (EG 2) covers subjects more directly related to the applied disciplines of Geotechnics and those of other departments.

Figure 3 displays a simplified flowchart with the subjects of Geotechnics and other areas of knowledge of EESC-USP (Transportation Engineering and Hydraulic and Sanitation Departments and Architecture School of São Carlos - University of São Paulo), in which content interactions are taught in Environmental Engineering course disciplines. A more complete figure can be found in the supplementary materials (Ribeiro et al., 2023). Part of the topics addressed in Engineering Geology, listed in the supplementary materials, are taught in five disciplines of the Environmental Engineering course and related to four others of the Geotechnical Department, with more applied approaches. The distribution of the themes into five disciplines favors the teaching conditions, since they are distributed in

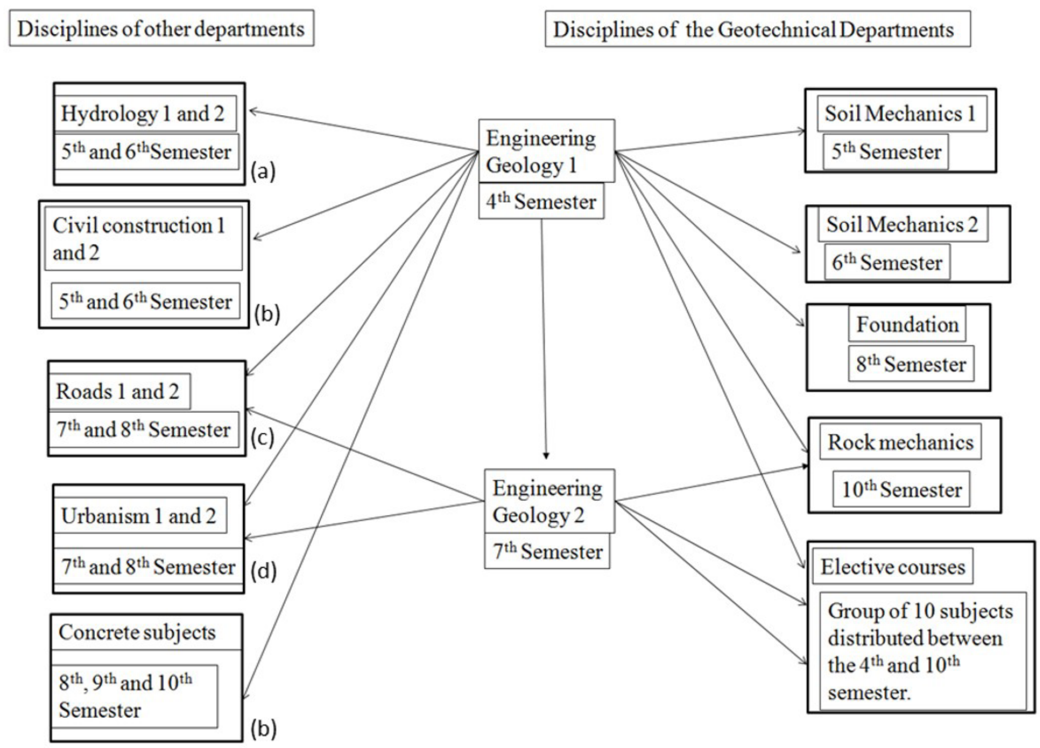

Figure 2. Relationship among the subjects of Engineering Geology and other disciplines in the Civil Engineering course of EESC-USP. Legend of the other departments: (a) Hydraulic and Sanitation, (b) Structural Engineering, (c) Transportation Engineering - Engineering School of São Carlos/University of São Paulo; (d)Architecture School of São Carlos - University of São Paulo.

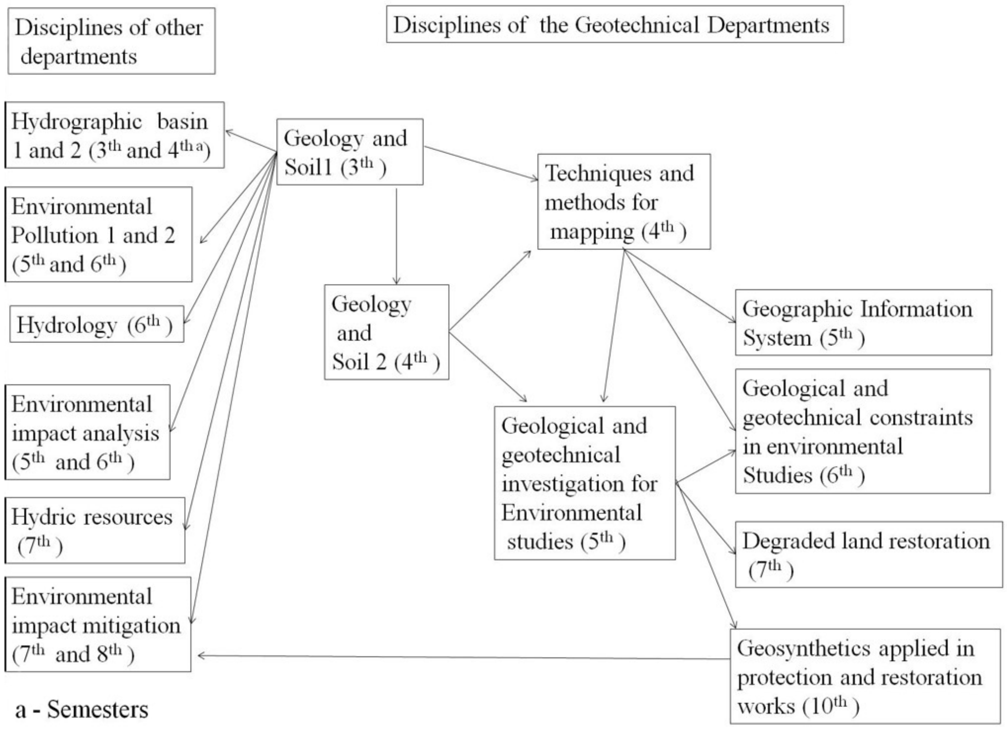

Figure 3. Relationship among the subjects of Engineering Geology and other disciplines in the Environmental Engineering course at EESC-USP. Legend: Other departments: Hydraulic and Sanitation, Structural Engineering, and Transport Engineering - Engineering School of São Carlos and Architecture School of São Carlos - University of São Paulo.

such a way one is the base for the other courses offered by the Geotechnical Department ad by other departments at EESC. The distribution of the courses from other departments between the 3rd and 8th semesters, with a certain parallelism with the five Engineering Geology disciplines, enables connecting topics among the disciplines.

5. Final considerations

Engineering Geology and its teaching have evolved with the development of areas fundamental to Geotechnics and the primary areas of knowledge (Physics, Chemistry, among others) and with the advances in technological resources that promote improvements in engineering geological investigation methods and data treatments. Moreover, the growth in the number of engineering activities, natural disasters, and environmental problems has demanded more knowledge on Engineering Geology. In general, theoretical content includes the following topics: minerals and rocks, geological structure, quaternary geomorphology, rock and rock engineering properties, groundwater, adverse geological processes and geological disasters, engineering geological problems of tunnels and underground caverns, engineering geological evaluation of special geological materials and sites, and engineering geological investigation and application, whereas practical content includes laboratory experiments, geological fieldwork, and comprehensive practices. Among them, rock and mineral recognition in the laboratory is a vital teaching link in Engineering Geology disciplines and the basis for field recognition and identification of rocks. Field engineering geology practice provides students with more direct knowledge on rocks, engineering geological conditions, engineering geological problems, among other contents. Students can understand the methods and steps of engineering geological evaluation by performing activities and improving their ability to solve practical engineering geological problems. Through comprehensive exercises, they can enhance their ability to integrate theory with practice and analyze issues comprehensively.

In Brazil, the progress of teaching Engineering Geology for Geology (which is not the objective of this text) and Engineering courses over the last 20 years has been insignificant, except for a few institutions; it is still at a very low level in most private institutions. In both public and private schools, the Geotechnical content is usually inserted into two subjects - one with the content of Geology and Soil Mechanics (elementary content) and the other with the content of foundations and earthworks. In some educational institutions with significant advances in Geotechnical education, Engineering Geology teaching has also advanced regarding both content and technological resources.

The prospects for Engineering Geology teaching are related to four general aspects. First, they concern advances in educational institutions related to course content and demands with regimental changes; second, they are related to the monitoring of the evolution of knowledge in geotechnics as a whole and interaction with soil and rock mechanics in terms of ground context; third, they refer to the way Engineering Geology will integrate technological advances of data analysis and processing in professional activities; finally, they regard the way to deal with advances in the use of actual data in studies and projects on environmental problems, estimates of dangerous events and risks, management, and responses to disasters, work in oceanic areas, and demands arising from global changes.

Knowing how professors and institutions will manage increasing subjects and contents in the curricula while maintaining the number of class hours is a challenge. The fundamental point is to consider the way didactic activities will be developed towards meeting the conditions for teaching, focusing on four large groups of resources, i.e., based on access to materials of each subject or topic in the format of books, videos, and lectures available on websites, face-to-face activities involving the solution of practical problems on a specific topic, field and laboratory works, and development and analysis of specific civil works projects, mineral exploration, and environmental problems, with both face-to-face and non-face-to-face methodologies.

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Declaration of interest

The authors declare no conflicts of interest. All co-authors have observed and affirmed the contents of the paper and there is no financial support to report.

Authors' contributions

Rogério Pinto Ribeiro: conceptualization, data curation, visualization, writing - original draft. Osni José Pejon: conceptualization, data curation, methodology, supervision, validation, writing - original draft. Lázaro Valentim Zuquette: formal analysis, funding acquisition, investigation, methodology, project administration, writing - original draft. All authors have read and agreed on the published version of the manuscript.

Data availability

All data produced or examined in the course of the current study are included in this article.

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Students' perception of the impact of a Geotechnical Engineering field activity on their competences development

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Article

Keywords
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In-class/ex-class activity
Competencies
Active learning

Abstract

The need to develop several students' competencies is one of the leading challenges for Engineering instructors in undergraduate courses. It has been quite exhausting in many cases, mainly due to the lack of professors' expertise in engineering education. Case studies may provide examples and help develop professors' ability to design effective learning experiences. In this context, this paper presents a case study of implementing an in-class/ex-class activity conducted in the Soil Mechanics-I course at the Federal University of Rio Grande do Norte. Additionally, it aims to discuss students' perception regarding development of the proposed activity and competences. The activity comprised three phases: selection of Geotechnical Engineering problems on university campus, documentation and analysis of each situation, and presentation of solutions considering technical, environmental, and social aspects. Students' perceptions were assessed using an anonymous online survey (18 Likert and open-ended questions), divided into three categories: general impressions, competencies development, and open statements. General impressions and competencies development were mostly positive, with deadlines reported as the most challenging aspect. Open questions responses provided positive feedback, emphasizing the main developed competencies, according to students' perspective (*e.g.* leadership, interpersonal relationship, and analytical view of the problem). The need of dealing with real problems and work in groups appears to be a successful approach for teaching Geotechnical Engineering courses and developing competences in Engineering undergraduate courses. This case study can support innovation in teaching any engineering course and help students face future professional challenges.

1. Introduction

Although engineering education has been valuable, it is widely acknowledged that it requires modifications to address new issues, such as challenges on promoting diversity, equity, and inclusion (Zanata & Silva, 2021), and developing engineering students' professional competencies (Carvalho & Tonini, 2017). The current engineering professional landscape requires engineers to develop social competences (*e.g.,* creativity, critical thinking, communication, leadership and interpersonal relationship) besides those technical skills commonly taught in undergraduate courses. Augustine & Vest (1994) stated the position of the American Society for Engineering Education (ASEE) related to the changes in engineering education at the time of its publication. They state that "*in today's world and in the future, engineering education programs must not only teach the fundamentals of engineering theory, experimentation and practice, but be relevant, attractive and connected*" (p. 17). In accordance with that, De Los Ríos-Carmenado et al. (2015) stated that the European Higher Education Area (EHEA) proposes an innovative approach to educational learning and encourages the adoption of a model based on competence development.

Palma et al. (2011) provided a list of competences appropriate for Engineering in Latin America by means of decoding them within a holistic approach. In Brazil, the need for modifications in engineering education is also recognized in the new Brazilian Guidelines for Engineering Undergraduate Courses (Brasil, 2019). This guideline was designed by a collective effort of multiple stakeholders, named the Brazilian Society of Engineering Education (ABENGE), Brazilian Council of Engineering and Agronomy (CONFEA),

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National Education Council (CNE), and Entrepreneurial Mobilization for Innovation of the Brazilian National Confederation of Industry (MEI/CNI). It introduces the competence-based framework to the Brazilian Engineering Education scenario and makes significant modifications to the way engineering is taught and learned at higher education level. For example, active learning is prioritized, which can promote practical development of both technical and social skills. Furthermore, the most recent guideline provided a more comprehensive list of competencies and abilities compared to previous Brazilian guidelines (Brasil, 2002) and proposed the foment of competencies such as entrepreneurship, research, communication, leadership, legislation, self-learning, among others.

The teaching-learning approach used in engineering education (e.g., lectures, laboratory experiences) is predominantly instructor-centered (Macedo et al., 2020) and remains the same even though engineering practice has been constantly changing due to technological revolution and globalization (Macedo et al., 2020). Similarly to other engineering branches, geotechnical engineering has also been taught in the same way over the years. Wirth et al. (2017) reported that many geotechnical engineering practices adopted nowadays are based on empirical aspects and limited by conventional boundaries. They emphasized that currently available geotechnical education curricula do not match the basis required to guarantee the engineer's success in the 21st century. Thus, the current engineering curriculum needs to be reviewed and reformatted in order to make significant modifications, which include encouraging multidisciplinarity and fostering transferable skills (Wirth et al., 2017).

Macedo et al. (2020) stated that non-traditional teaching approaches with the objective of promoting active learning in students bring relevant contributions to their professional and personal development. This approach addresses different learning styles and is more likely to be adapted to student's needs. In this regard, active learning activity may be defined as any activity that students engage in during class time that goes beyond a passive behavior (e.g., taking notes while listening to the teacher) (Hassan et al., 2012; Felder & Brent, 2016). It is also important to highlight that active learning is not a method, it orients methods that may promote active learning, but it is not a method by itself. It can be conceptualized as a mode of engagement in the learning process and centers the student as a co-constructor of their own knowledge (Chi & Wylie, 2014).

Among several active learning strategies, Problem-Based Learning (PBL) methodology uses real-world projects to foster critical thinking, problem solving, teamwork, and other skills (Larmer & Mergendoller, 2010; De Matos Junior et al., 2020). It has been widely used in different educational levels and study areas (Amaral, 2021). PBL implementation may vary based on the course and learning outcomes and may have the objective of creating a product and/or project, or only provide a solution to a common problem (Markham, 2003). In both cases it may be considered as one approach in which students can learn how to creatively deal with open-ended problems that resonate with their future professional practices (Larson et al., 2021). In addition, students can have the opportunity to present their contribution in front of an audience (Markham, 2011) and Amaral (2021) reported that PBL has been applied in all educational levels as well as in different study areas.

The implementation and results of PBL strategies are discussed in the literature (Quintela & Santana, 2007; Dalal et al., 2017; Zancul et al., 2017; Gratchev & Jeng, 2018; Chen et al., 2020; Oliveira et al., 2021; Larson et al., 2021; Naveh et al., 2022; Jumintono et al., 2022). They are widely applied in geotechnical engineering teaching contexts and their impacts are extensively discussed. Several examples are found in the literature regarding applications of PBL in geotechnical engineering courses (Pinho-Lopes & Macedo, 2014; Shiau et al., 2015; Larson et al., 2018; Macedo et al., 2020).

Engineering study cases are commonly used as part of the PBL methodology. Kelley (2008) presents them as a logical way to introduce the engineering design process to the students, who may not be familiar with it. He also describes the differences between 'case histories' (i.e., describing the problem, methods and procedures, and the actual implemented solution) and 'case problems' (i.e., an open-ended problem with several potential solutions in case problems). Through the use of engineering cases, students are able to learn how to search through the details of a case to find the key facts that will help them handle the pressing problems (framing). Students go from low-level knowledge and application to higher levels of learning, such as synthesis and assessment, when they are required to make judgments about the methods and practices used by a professional engineer (Kelley, 2008).

The objective of this paper is to discuss engineering students' perception regarding the development of a proposed activity and its relationship with the new Brazilian guidelines. It comprises a PBL-based case study of implementing an in-class/ex-class activity conducted in the Soil Mechanics-I course at the Federal University of Rio Grande do Norte, in the Northeast of Brazil.

2. Soil Mechanics-I course description

The Soil Mechanics-I course at the Federal University of Rio Grande do Norte (UFRN) is part of the Geotechnical Engineering field and is taught in the third year to undergraduate students after Engineering Geology and before Soil Mechanics-II. The course has in-person classes with both theoretical and practical activities and comprises both Civil Engineering and Environmental Engineering undergraduate programs. It corresponds to four credits (total of 60 h per semester), which include class and laboratory time. In addition, extra hours are commonly necessary for individual study time, preparation of reports, literature research and ex-class activities (e.g., field trips). Class size varies depending on the semester, but it consists of 20 to 30 students (average) per term.

Soil Mechanics-I is an introductory course in which the students are presented the basic concepts of Soil Mechanics. Its syllabus comprises soil formation and intrinsic properties, physical and mechanical properties of soils, weight volume relationship, soil classification, soil compaction, permeability and flow through soils, effective and geostatic stresses, and stresses due to applied loads. The perception of soil as an important factor in the behavior of any Civil and Environmental Engineering work can be mentioned as the main aspect to be taught in this course. For the semester in which the activity was conducted, most students (18) in class were enrolled in the Environmental Engineering undergraduate course. Only three of them were enrolled in the Civil Engineering course, resulting in 21 students.

3. Activity description

In order to address the engineering education changes necessary to the development of different students' competences, a new activity was performed in the Soil Mechanics-I course during the first semester of 2022, in which presential classes restarted after the Covid-19 Pandemic. The main objective of this activity was to evaluate the improvement in the competences established in the new Brazilian Guidelines for Engineering Undergraduate Courses (Brasil, 2019). The main competences aimed to be developed were related to the formulation, implementation and control of desirable engineering solutions, considering their users' needs, enhancement of communication skills in both written and oral forms, leadership and teamwork in multidisciplinary groups, and autonomous learning. As a secondary objective, we assessed the general aspects related to the performance of the activity (e.g., understanding the objectives, personal and group involvement, deadlines, instructor participation).

The activity was divided into three phases: (1) selection of the study areas, (2) field investigation and analysis, and (3) presentation of engineering solutions. The first stage of this activity comprised the search for different Geotechnical Engineering problems on and nearby the university campus. It was accomplished by the course instructor, accompanied by one randomly chosen student (volunteer). Eight locations were identified. From those eight spots, five were selected, as presented in Figure 1.

The criteria for choosing each location were based on two aspects: 1) presence of a typical geotechnical engineering situation, even though it was in its earliest stages, and 2) connection with the topics listed in the course syllabus. The selected spots presented geotechnical problems such as soil clogging, superficial erosion, bicycle lane pavement failure and intermixing of adjacent soils. The volunteer student made a presentation of the five locations to the class. It was considered part of her evaluation. Table 1 describes each location.

The second phase was performed by the students, organized in groups of 3 to 4 members. Each location was studied by one group with independent field work, documenting their observations related to geotechnical engineering, analyzing the problem and preparing the proposition of solutions, which must have considered technical, environmental, and social aspects. Competences related to the formulation, implementation and control of desirable engineering solutions, considering their users' needs, were thoroughly exercised in this step. This stage has ended with a 15 minute-long presentation to the class with the objective of providing a

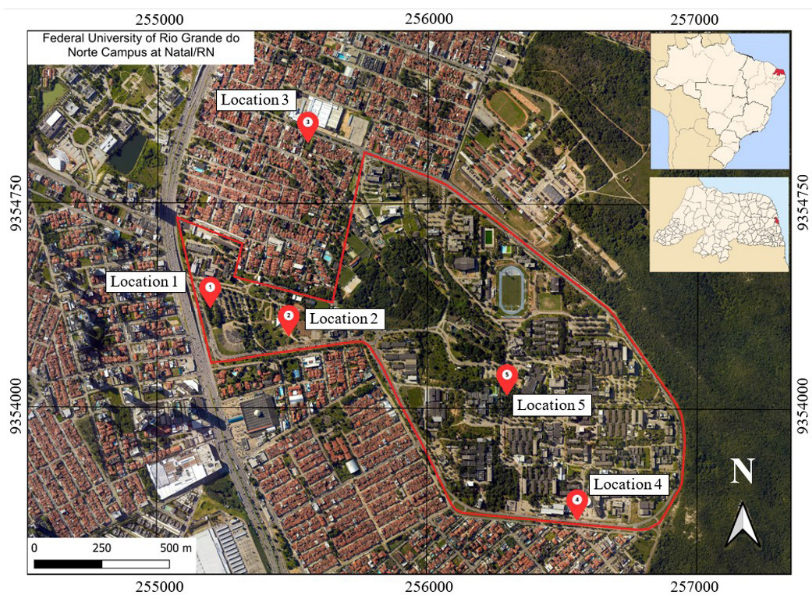

Figure 1. Location of five selected Geotechnical Engineering problems used in the activity.

comprehensive description of the problem and introducing the proposed solution. We emphasize that the course instructor has accompanied this phase by indicating references to study and promoting off-class discussions, providing an opportunity to stimulate students' autonomous learning ability.

At the end of stage two presentations, the instructor has proposed further considerations on each location. They consisted of instructions for each group, summarized in Table 2, regarding the solutions the students have presented in phase 2 and potential studies they must conduct in each field. Students had 15 days to accomplish this task, which was delivered to the class in 15 minute-long lectures. We emphasize that students had two presentations to deliver, which were considered opportunities to improve their oral communication skills, while written reports that accompanied the presentations aimed to develop the competence related to written communication. In addition, since the students are from two different undergraduate courses (Civil Engineering and Environmental Engineering), they were required to work with multidisciplinary teams. This is fully related to the improvement of their ability to deal with real professional situations in the future.

Students' performance and grading were assessed in groups, considering their participation in the activity and their two presentations. Assessment was divided into three items, as follows: the technical aspects of the proposed solution and whether it met or not users' needs, the teamwork developed during the activity, and the quality of both in-person presentation and written reports. If students were able to demonstrate the abilities expected by the instructor, their performance was judged to be satisfactory.

4. Survey description and participants recruitment

An online anonymous form survey was designed to evaluate student's perception regarding the activity and the development of those competences reported in the new Brazilian guidelines for engineering undergraduate courses. The students were invited to participate in the survey via internal academic system memorandum three months after the conclusion of the course. Student participation was voluntary, and no compensation was offered. The survey comprised 18 questions (15 Likert scale from 1 to 5, two open-ended and one yes/no questions). The Likert scale consisted in a numerical rating ranging from 1 to 5; no textual options were used. The survey was divided into three categories: 1) general impressions, 2) competences development, and

Table 1. Description of the locations selected in the activity.

Location ID.	Coordinates	Identification	Main identified geotechnical problems
1	5°50'12.165"S 35°12'38.978"W	Campus flood control retention pool	Vegetation growth, soil clogging and infiltration capability reduction
2	5°50'15.567"S 35°12'29.544"W	Erosion in pavement-soil contact	Superficial soil erosion and transport of sediments
3	5°49'52.453"S 35°12'27.216"W	Nearby flood control retention pool	Infiltration problems prior to finishing construction works
4	5°50'37.572"S 35°11'54.837"W	Bicycle lane pavement[a]	Bricks movements and vegetation growth in recently built bicycle lane pavement
5	5°50'22.633"S 35°12'3.267"W	Garden soil-rock mixture	Intermix of adjacent soil

[a]Coordinates of the closest point to the Center of Technology. The bike lane goes around and crosses the university campus.

Table 2. Further instructions provided after the first round of presentations.

Location	Identification	Main identified geotechnical problems
1	Campus flood control retention pool	Perform *in situ* permeability tests of the bottom soil of the retention pool and compare with those obtained by Amorim (2016) and Guedes (2017).
2	Erosion in pavement-soil contact	Prepare a detailed photographic record of the site and measurements of displacement of granite rock blocks (create a classification, for example a quantity of displaced blocks and loose blocks).
3	Nearby flood control retention pool	Provide a timeline of the retention pool water level during its construction using satellite images. Predict the infiltration rate through an indirect measurement of the water level in the pond.
4	Bicycle lane pavement	From walking along the entire stretch, identify and classify the points of damage on the bicycle path around UFRN.
5	Garden soil-rock mixture	Create an instructional video about the process identified, addressing the experiment conducted in class.

3) open statements and opinion. The survey was designed and shared with the participants in Brazilian Portuguese. Table 3 presents an English version of the questions used in this survey.

5. Survey results

The survey was responded to by eight students, from 21 enrolled in the course, which corresponds to 38% of the students. The results from the survey are presented in Table 4 and discussed as follows.

5.1 General impressions

A group of seven Likert scale questions comprised the first part of the survey. They were designed to assess general aspects of the activity development. Question 1 was intended to inform if the activity was well understood by the students and 100% of the answers were number 5 in Likert scale. It demonstrates that participants clearly understood the activity objectives. The clear understanding of the learning objective enacts students' motivation and allow a more effective learning process, since students are able to comprehend the reason faculty design each specific activity (Reed, 2012). Clear objectives also support faculty in the assessment process, since it is explicit what outcomes each activity should provide (Fiegel, 2013).

Questions 2 and 3 are related to the participation of students, by referring to their own and other members' involvement in the task. Regarding their own involvement, every student reported a high level of engagement. On the other hand, one student reported a very low involvement of group members. The instructor was able to identify the student who did not participate properly in the second phase of the activity, which may be the case reported herein. In order to avoid such behavior, the instructor may participate in the field work with each group. This may stimulate students' engagement in every phase of the activity.

Table 3. Questions used in the survey to evaluate student's perception and development of competences.

Question ID.	Type	Question
Q1	Likert 1-5	Did you understand the objectives of the activity during the explanations presented in the classroom?
Q2	Likert 1-5	What is your level of involvement with the activity?
Q3	Likert 1-5	What is the level of involvement of the other group members in the activity?
Q4	Likert 1-5	Did you like the topic[a] you developed?
Q5	Likert 1-5	Did you like the second part of the activity (completion of the solution)?
Q6	Likert 1-5	Was the professor attentive to questions outside of class hours?
Q7	Likert 1-5	Did you find the time available to perform the activity sufficient?
Q8	Likert 1-5	Do you think there was development of Competence 1 - formulating and designing desirable engineering solutions, analyzing and understanding the users of these solutions and their context?
Q9	Likert 1-5	Do you think there was development of Competence 2 - analyzing and understanding physical and chemical phenomena through symbolic, physical and other models, verified and validated by experimentation?
Q10	Likert 1-5	Do you think there was development of Competence 3 - conceiving, designing and analyzing systems, products (goods and services), components or processes?
Q11	Likert 1-5	Do you think there was development of Competence 4 - implementing, supervising and controlling Engineering solutions?
Q12	Likert 1-5	Do you think there was development of Competence 5 - communicating effectively in written, oral and graphic ways?
Q13	Likert 1-5	Do you think there was development of Competence 6 - working and leading multidisciplinary teams?
Q14	Likert 1-5	Do you think there was development of Competence 7 - knowing and ethically applying the legislation and normative acts within the scope of the profession?
Q15	Likert 1-5	Do you think there was development of Competence 8 - learn autonomously and deal with complex situations and contexts, keeping up to date with advances in science, technology and the challenges of innovation?
Q16	Open-ended	In addition to the general competences described in the new National Curriculum Guidelines, do you think you developed any additional competence(s) during this activity?
Q17	Open-ended	Feel free to use this space. Comments, suggestions, negative and positive aspects. All are very welcome.
Q18	Yes/No	One final and simple question. In view of all the experience with the activity, did you like it?

[a] Topic refers to the subject developed by each group of students.

Table 4. Answers delivered to Likert scale questions.

Question ID.	Likert scale response frequency				
	1	2	3	4	5
Q1	0	0	0	0	100%
Q2	0	0	0	0	100%
Q3	12.5%	0	0	0	87.5%
Q4	0	0	0	0	100%
Q5	0	0	0	12.5%	87.5%
Q6	0	0	0	0	100%
Q7	12.5%	0	0	12.5%	75%
Q8	0	0	0	0	100%
Q9	0	0	0	0	100%
Q10	0	0	0	12.5%	87.5%
Q11	0	0	12.5%	0	87.5%
Q12	0	0	0	12.5%	87.5%
Q13	0	0	0	0	100%
Q14	0	0	0	0	100%
Q15	0	0	0	0	100%

Questions 4, 5 and 7 were related to the activity development. All students have reported they enjoy the activity as a whole (Q4) and phase 3 was also reported as positive (Q5). We have gathered one answer at Likert scale 1 regarding the deadlines. In fact, the activity was executed in the last month of the semester, which might have affected the performance of some individuals due to other activities in different courses. Question 6 was elaborated to identify the instructor's availability in off-class hours and resulted in 100% Likert scale 5 answers. Instructor remained able to participate in both in person and online discussions about each location.

5.2 Competence development

The purpose of questions 8 through 15 was to assess how well the eight competencies listed in the new Brazilian guidelines (Brasil, 2019) were developed in the opinion of each student. Each question is related to one of the eight competences. Answers were mostly positive (Likert scale 4 to 5), with one neutral (Likert scale 3) in competence 4. It is related to the implementation, supervision and control of engineering solutions, which were only fictionally proposed in this activity.

5.3 Open statements

Questions 16 and 17 provided an open discussion space in which the students were able to freely write their opinions. Answers were de-identified in case the participant described their names or third-party names. Participants answered in their native language, the statements provided in this section were translated. They were first asked to list any additional competencies they developed while participating in the exercise (Q16). Leadership skills, interpersonal relationship and real problem understanding were the most mentioned topics. Despite these are considered in competences 1 and 6, students' perspective is that they are competences not listed in the new Brazilian guidelines. First author, who was the course instructor, analyzed the answers.

According to the open ended answers, the activity supports students' development of the target competences. This result is exemplified in one student's which describes that a broad group of competences were developed during the activity.

> *I believe I developed a broader view of situations. Predict future consequences that the proposed solutions could generate, and not only in the technical dimension of the proposed problem, but also social, economic, cultural, etc.* (Participant A).

Question 17 provided an opportunity to deliver comments, suggestions, drawbacks and limitations of the activity. Regarding the negative aspects, the deadlines were reported twice as a drawback. It is imperative to review this aspect and it is suggested to include the activity from the beginning of the semester. The main positive aspects cited in Q17 were related to the application of theoretical background in the solution of a practical problem. This is in accordance with the new Brazilian guidelines' purpose of promoting engineering learned based on competences. One student's answer is presented below to illustrate the positive aspects reported in Q17.

> *The assignment was well thought out by the instructor. We were able to surpass the theoretical knowledge and put into practice other theoretical aspects and competences. Besides, students' engagement created a very pleasant atmosphere during the semester. Everyone was dedicated to finishing the activity properly.* (Participant A).

A final question invited the students to simply answer if they enjoyed the activity. It resulted in 100% of the students answering positively. This question was included to summarize the activity survey and provide instant feedback about it. Despite being a Yes/No question, it can be used to inspire similar approaches to be used in class. Other literature were found with similar PBL assignments (Pinho-Lopes & Macedo, 2014; Shiau et al., 2015; Zancul et al., 2017; Gratchev & Jeng, 2018; Larson et al., 2018; Macedo et al., 2020; Oliveira et al., 2021; Naveh et al., 2022) in which positive results were also reported.

6. Instructor's perspectives

The PBL activity's instructor has shared his thoughts on how it was performed. The level of students' engagement was outstanding and there was a lot of discussion outside of class hours. Each group has visited their respective locations properly and followed individual instructions regarding the procedures and aspects to document and analyze. Instructor has provided specific explanations for each group, according to each geotechnical problem, and the students were clearly able to demonstrate their recently acquired theoretical knowledge accurately in class presentations. Every suggestion made after the first presentation was accomplished, except that related to *in situ* soil permeability tests in the retention pool (Location 1) due to operational difficulties. This also shows students' commitment during the assignment.

Two main limitations can be listed regarding the assignment. Firstly, as mentioned in the survey, the deadlines were quite difficult to meet. The activity was conducted during the last month of the semester. This period is recognized as the busiest part of the semester, in which several exams are taken, and other presentations are delivered. In case of repeating the activity, another period might be considered. The second limitation is related to the lack of instructor-guided field work. The instructor has decided not to join the students to each location. It has resulted in several off-class discussions that could have been avoided or mitigated. Both aspects may be changed in future PBL assignments.

Two aspects must be considered in this paper. Firstly, the survey was conducted three months after the end of the semester. This may change the students' perception. In order to clarify the objective of the survey and to remember the details of the assignment, the first page of the survey provided a detailed description of what they have done. Furthermore, the survey was sent to the students by the class instructor, which may have led to some discomfort in answering the questions honestly. These aspects need to be considered in future surveys.

Despite the limitations mentioned above, the instructor was able to list meaningful positive aspects of the activity related to the development of students' competencies. Firstly, the instructor emphasizes that undergraduate classes in both Civil Engineering and Environmental Engineering courses at UFRN are commonly based on passive strategies, focused on teaching one or a few more ways to solve a specific problem. This aspect is under modification and the implementation of active strategies has been strongly stimulated. The activity described herein is an approach to deal with this aspect and provided the opportunity to investigate an engineering problem without any first clue, which simulates real professional situations. Secondly, the students were highly stimulated to use and develop important social competences for current engineers, such as creativity, critical thinking, communication, leadership, interpersonal relationship, and time management. Moreover, the activity promoted integration among students from different undergraduate courses. Finally, the instructor mentioned the importance of encouraging students in an outdoor activity, which differs from the common classroom and laboratory ones. This aspect plays an important role in engineers' professional life, mainly in the geotechnical field, which frequently involves field works. In addition, it allowed the use of the UFRN campus infrastructure, which is not usually known by the students given that they are commonly restricted to the engineering courses area.

7. Conclusions

A PBL activity was assigned at the Soil Mechanics-I course at the Federal University of Rio Grande do Norte. It comprised the evaluation and analysis of a geotechnical engineering problem at the university campus, followed by the presentation of a solution considering technical, environmental and social issues. A survey with Likert scale and open-ended questions was performed to acquire student's perception of the activity. Instructor's perspectives were also provided. The following aspects can be drawn from the results.

- The students have evaluated the activity positively. Both Likert scale and open-ended questions show a high degree of acceptance and engagement.
- Likert scale questions regarding the development of competences listed in the new Brazilian guidelines were mostly positive (Likert scale 4 to 5), with one neutral (Likert scale 3) in competence 4 (implementation, supervision and control of engineering solutions). It demonstrates this PBL assignment has promoted the development of such competences.
- Leadership skills, interpersonal relationships and real problem understanding were the most mentioned topics in the open-ended question in which the students were asked to mention other competencies developed during the activity.
- There was a high degree of students' commitment in the activity. Every group has visited their location and followed the instructor's suggestions properly. Also, presentations were delivered accordingly and instructions for the final lectures were followed.
- Two main limitations were noted in this assignment. Firstly, the deadlines were quite difficult to meet due to its conduction at the end of the semester. Secondly, the field works might have been accompanied by the

instructor. Both aspects are quite simple to modify in future PBL assignments.

- Regarding the survey, it can be emphasized that it was performed three months after the end of the semester, which may have some impact on students' perception. In addition, the survey was sent by the class instructor, which may have led to some discomfort in answering the questions honestly.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Fagner Alexandre Nunes de França: conceptualization, investigation, data curation, methodology, supervision, writing – original draft. Marcus Vinicius Melo de Lyra: conceptualization, methodology, data curation, writing – original draft. Matheus Gomes de Carvalho: methodology, writing – review & editing. Wagner José Opolski: methodology, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

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Teaching modern soil mechanics

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Article

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Critical state soil mechanics

Abstract

The important role of the critical state theory in the modern soil mechanics is undeniable. It is true that the number of soil mechanics courses that not cover this subject is progressively decreasing. However, when the critical state theory is introduced, this topic cannot be seen as a simple extension of the classic soil mechanics. On the contrary, it is essential that some significant differences between modern and classic soil mechanics are adequately clarified and understood. This subject is a relevant objective of this paper, besides the large benefits brought by the modern soil mechanics. This discipline, like the mechanics applied to other materials, is fundamentally a preliminary learning to prepare for the professional practice of geotechnical engineering. When the main objective is to teach methods to solve the engineering problems (foundations, excavations, embankments, tunnels, etc.), the matters transmitted to the students are sometimes focused on the geotechnical engineering methods, where, nevertheless, soil mechanics, naturally, has an irreplaceable role. It is true that a design is unique in itself. However, all designs must have in common the same theoretical principles of soil mechanics, regardless of the particularities of the geotechnical design. This cannot be neglected in the modern soil mechanics teaching. Brief ideas concerning where and how soil mechanics has been taught, is also introduced. The fundamentals about plastic design of geotechnical structures are highlighted. The article ends calling attention to the outstanding contribution of the critical state theory for a unified understanding of the soil behavior. Its pedagogic benefits are invaluable.

1. Introduction

After a short comment about the plasticity role in soil mechanics and to the limitations of elasticity concerning the description of the soil mechanical behavior, the link between the perfect-plasticity and the classic soil mechanics is characterized and exemplified. A brief reference to the role of finite element method on limit equilibrium analysis and on displacements evaluation is also presented. The tight relationship between modern plasticity and the modern soil mechanics has been taken into consideration. Failure soil criteria are reexamined, in light of classic and modern soil mechanics. Understanding of soil behavior according to the critical state theory is introduced and its contribution to modern soil mechanics is underlined, with a particular emphasis on the displacements prediction capacity. Finally, some considerations about the plastic design of geotechnical structures are presented.

2. Previous considerations

There are some basic assumptions, applicable to both classic soil mechanics (CSM) and critical state soil mechanics (*CSSM*) that deserve to be mentioned.

2.1 Continuum mechanics

Continuum mechanics, like in other branches of mechanics, is by far one of the underlying sciences on the case of soils. Modern theories that describe mechanical soil behavior considering, explicitly, the particulate nature of soils, do exist. But in nearly all geotechnical engineering applications, theoretical and practical, the soil is idealized as a continuum, i.e., a body that may be subdivided indefinitely without altering its character.

2.2 Effective stresses principle

The principle of effective stresses (Terzaghi, 1936), a fundamental concept for the establishment of soil mechanics itself, is obviously another basic assumption.

2.3 The soil material

It is necessary to make some considerations about this material. Currently, the material object of any mechanics is an archetype of the real material. So, a prerequisite in any design problem involving the real materials is the assumption of certain simplifying material properties to assist mathematical analysis (Chen & Baladi, 1985). In this

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case, the soil is considered a homogeneous mechanical mixture of two phases. One represents the structure of solid particles and the other constitutes the fluid water filling up the voids of the aggregate (the soil will always be regarded as saturated). The only forces among the particles are due to the effective stress. In practical terms it can be designated by saturated disturbed soil.

2.4 Disturbed and undisturbed soils

To justify the inevitable but powerful simplification just presented, some brief considerations resulting of the contrast between real and ideal soils must be pointed out. The particles of natural soils exhibit different degrees of structure, which may significantly influence the soil behavior. Ultimately, each natural soil could be considered a different material, but to bypass this troublesome allegation, it is necessary to make use of classifications, frames of reference, etc. To exemplify, the proposal for the use of mechanical characteristics of reconstituted (disturbed) clays as a basic frame of reference for interpreting the corresponding characteristics of natural sedimentary clays can be cited (Burland, 1990). The properties of reconstituted clays are termed intrinsic properties since they are inherent to the soil and independent of the natural state. Otherwise, the properties of natural clay differ from the intrinsic properties due to the influence of soil structure (fabric and bonding). The intrinsic properties provide a frame of reference for assessing the in-situ properties of natural clay and the influence of structure on its in situ properties.

3. Soil mechanics education, elasticity, and plasticity

The emphasis on plasticity issues in a text about the education on soil mechanics needs a justification. The aim of the paper is not to interfere with the course syllabus but remember that the theory of plasticity is an essential part of the education in soil mechanics. As it will be seen, the references to plasticity are also done to get a better understanding of the transition of the classic to the modern soil mechanics.

3.1 Linear elasticity in soil mechanics

Elasticity has sometimes been used successfully in classic soil mechanics to describe the general behavior of soil deformation under short-term working load conditions. Certainly, soil is by no means an elastic material. But it is attracting to assign values to a Young modulus (E) and to a Poisson's ratio (ν) and take profit of a large number of solutions for stresses and displacements due to the application of many types of loads to the surface of an elastic half-space that are available on catalogs of solutions (Poulos & Davis, 1974). Mainly due to the soil dilation phenomena, the elastic parameters largely used in soil mechanics are the bulk modulus (E) and shear modulus, (G) instead of E and ν.

The use of elasticity in the well-known one-dimensional consolidation theory (Terzaghi, 1925) must also be referred.

On the practice field, the elasticity application on the prediction of the foundations settlements due to vertical stress changes, whose reliability was demonstrated by Burland et al. (1977), is used to a great extent even today. This option can be a significant advantage when compared with the time and effort involved in obtaining numerical solutions that employ one of the numerous plasticity soil models available.

Nevertheless, elasticity fails to predict the behavior and strength of a soil-structure interaction problem near ultimate strength condition, because plastic deformation at this load level attains a dominating influence, while elastic deformation becomes of minor importance. This aspect strongly impairs any role of elasticity on the evaluation of structural safety through methods other than the maximum allowable stresses.

3.2 Perfect-plasticity and soil mechanics

The application of plasticity to soil mechanics begun more than 200 years ago, based on the celebrated contribution of Coulomb (1773). Until the 1950-60 decade, a lot of work concerning the rigid-perfectly plastic and the elastic-perfectly plastic models, most of them focused in metals, was accomplished and well understood. This knowledge field can be called classic plasticity.

But, by the time, not only the soil mechanics as a scientific discipline was consolidated, as well as a remarkable activity in the field of plasticity theory was in progress, with particular emphasis on the strain hardening (and strain softening) elastic-plastic models. This scientific work is called modern plasticity.

During the following text it will become clear that *CSM* is tightly associated with classic plasticity and *CSSM* is closely linked to modern plasticity.

3.2.1 The soil mechanics and classic plasticity

It can be admitted that despite the marked difference between metals and soils, the research into soil classic plasticity, notwithstanding its historical application to earth masses by Coulomb (op. cit.), arose as a result of investigations carried out on the mechanical behaviour of metals. For instance, the use, even in the present days, of the bearing capacity formula for continuous footings (Terzaghi, 1943), was inspired on the work about the use of slip lines theory applied to the metal indentation (Prandtl, 1921). Fundamental aspects of the theoretical background of classic plasticity, with reflex in soil mechanics, are the stability postulate and the associated flow rule (Drucker et al., 1952), and, above all, the important theorems of plastic collapse.

3.2.2 Limit analysis

As it is well known, the solution of any limit equilibrium problem can be obtained through the system formed by the equilibrium equations and the equation of the adopted failure criterion. This set of equations is normally known as basic equations. In cases where geometry and actions are simple, it is possible to obtain exact solutions only based on the Mohr circle. As a matter of fact, this circle is a graphic representation of the equilibrium conditions. If the failure condition (represented by two straight lines inclined and tangent to the Mohr circle) is added, a graphical representation of the basic equations is obtained and the necessary conditions to solve limit equilibrium problems exist (when geometry and actions are simple, as was already mentioned).

But the integration of these equations, taking into account the boundary conditions, is, analytically, unmanageable. This difficulty attracted the mathematicians to work hard in this area of the plasticity (in the same way as, some years before, they have done with the integration of the Laplace differential equation applied to seepage problems taking account complex boundary conditions). Once more, exact solutions were obtained only in relatively simple cases.

Therefore, it became common to use approximate methods, as is the case, for instance, of the numerical solutions proposed by Sokolovski (1960). He developed the theory of critical stress equilibrium. But since then no new methods or practical applications worth mentioning have been developed in this area.

Despite the simplicity of the strength expressions at failure, it is quite difficult to obtain exact solutions. So, standard methods used in geotechnical engineering involve simplifications. Two basic approaches exist: the bound methods and the limit equilibrium method.

3.2.3 The theorems of plastic collapse

Making use of these theorems of the perfect plasticity, it is possible, without satisfying all of equilibrium and compatibility conditions, to introduce important simplifications in the stability calculations (Davis & Selvadurai, 2002).

More in detail, to calculate an upper bound it is necessary to satisfy the conditions of compatibility and of the material properties (which govern the work done by the stresses in the soil) but nothing is said about the equilibrium conditions. On the other hand, to calculate a lower bound is mandatory to satisfy the conditions of equilibrium and the material properties (which determine the strength), but nothing is said about displacements or compatibility. This has important consequences on the procedures for safety evaluation of simple geotechnical structures.

3.2.4 Discontinuous equilibrium stress states

Contrary to what happens in elastic media, in the plastic media, the stresses do not impose any strain condition, so it is not necessary to verify the compatibility requirement of the elasticity. So, it is admissible to consider possible discontinuities in the stress fields of plastic equilibrium in order to obtain solutions that comply with the boundary conditions. Such discontinuities are characterized by abrupt changes of direction and on the value of the principal stresses. Then, the lower bound theorem allows the attainment of approximate solutions for a lot of classical problems of plasticity. In such cases it is simpler than any other type of solution, namely those that use numerical methods.

The most well-known methods derived from the theorems of plastic collapse, are those based on the Mohr representation, the numerical method due to Sokolovski (1960), the consideration of discontinuities on the stress field and the slip line theory. Correct solutions to the limiting earth pressure problems with given stresses on the boundaries were given for example by Sokolovski (op. cit.). Despite their very low use, these methods of analysis deserve to be referred to. All solutions that use the slip plane model neglected strain.

3.2.5 The method of the associated fields

In order to predict deformations using perfect plasticity, Serrano (1972) and James et al. (1972), among others, proposed a solution allowing the determination of the stress and strain for each point of the soil mass. It was imperative to equilibrate the resultant stress field, not only with the applied exterior actions but also with the internal stresses. Regarding de strain field, the boundary conditions and the internal kinematic compatibility need to be satisfied. Obviously, it was necessary to postulate a stress-strain law. However, this apparently promising way to obtain displacements of soil structures had no continuity. Since the beginning of years 70, the subject has lost any research and practical interest.

3.2.6 The limit equilibrium method

The limit equilibrium method is the most used to evaluate the stability of geotechnical structures. The method puts together characteristics of both the upper and lower bound theorems. The geometry of the slip surfaces must form a mechanism that will allow the collapse to occur (upper bound) and the overall conditions of equilibrium of forces on blocks within the mechanism must be satisfied (lower bound). The limit equilibrium method leads to correct solutions (there is no formal proof of this allegation) and is one of the reasons for the large use of the method, even in our days. This is also the case with the old wedge analysis methods of Coulomb and the Rankine (1857) method. A large number of computer programs for analysis of geotechnical structures that make use of the limit equilibrium method are available today.

3.2.7 Perfectly plasticity and dilation

One of the more distinctive mechanical properties of soil is dilation. This phenomenon, common to all particulate media, was already known from the 19th Century (Reynolds, 1885). This property is quantified through the angle of dilation, ψ, defined as the relation between the volumetric and deviator strain increment components $\left(\delta\varepsilon_v \text{ and } \delta\varepsilon_s\right)$ of the resultant deformation, $\delta\varepsilon$. It is then interesting to see how this important property can be integrated on the continuum mechanics and the elastic perfectly-plastic theories used in the classic soil mechanics.

A condition required to prove the bound theorems is that the material must be perfectly-plastic. This implies an associated flow rule, i.e., the increment of plastic strain must be normal to the yield function.

Figure 1 presents a yield function, which is also the failure envelope, corresponding to a drained loading of a soil.

According to the definition of ψ, at failure, it will be

$$\tan\psi_f = -\frac{\delta\varepsilon_v^p}{\delta\varepsilon_s^p} = \tan\phi_f' \quad (1)$$

As will be seen later on (when dealing with *CSSM*), a soil state at failure is constant, which also means that the volume is invariant. Consequently $\psi_f = 0$. But, according to the normality rule, $\delta\varepsilon_p$ must be normal to the yield function. This condition cannot be satisfied because, as previously proven, $\psi_f = \phi_f'$. This means that the plastic behavior during a drained test cannot be taken as perfectly plastic, at least if the yield and the plastic potential functions are identical. This is important due to the large use of the elastic-perfectly plastic non-associated Mohr-Coulomb models in geotechnical practice, even in our days.

These considerations merely mentioned the incompatibility between the perfectly-plastic model and dilation, which could install doubts about the use of dilation on elastic perfectly-plastic models. This subject will be clarified further below.

Consider a plastic potential function, G (different and possibly more adequate than the yield function,), as can be seen in Equation 2 (Wood, 2004)

$$G(\boldsymbol{\sigma}) = G(p', q) = q - \mathrm{M}^* p' + k = 0 \quad (2)$$

where $\boldsymbol{\sigma}$ is the stress tensor, k an arbitrary value which allows $G(p', q)$ to be defined at the current state stress and M^* is a soil property related to the dilation (see Figure 2). In this context and still in the perfectly plastic framework, the increment of plastic deformation complies with normality rule.

In practice, to use an elastic perfectly-plastic model, the elastic parameters $\left(E \text{ and } G\right)$ and the resistance, ϕ', must be determined. If the information regarding the yielding volume variation his needed, the dilation parameter, M^*, or ψ, is also required. All these parameters are constant.

In a drained loading context, if $\psi < 0$, the soil volume diminishes at constant rate. If $\psi > 0$, the soil volume increases at constant rate. This model is employed on the safety analysis of geotechnical structures. When an undrained loading is considered, the ψ value must be zero (Maranha & Maranha das Neves, 2009). In fact, if $\psi \neq 0$, the soil will never fail.

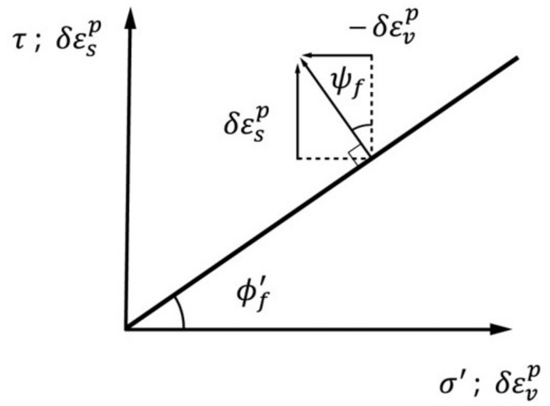

Figure 1. Plastic strain increment in a perfectly-plastic soil model (in the case of a drained loading).

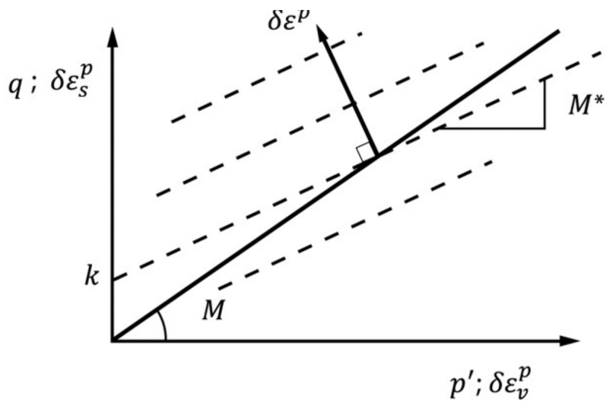

Figure 2. Plastic potential functions of an elastic perfectly plastic material, different of the yield function, and that observes the Mohr-Coulomb criterion.

4. The role of the finite element method on limit equilibrium analysis and on displacements evaluation

Practical results of the research on this area had occurred from 1970, and we cannot ignore their role on the prediction of the deformational behavior of geotechnical structures (Duncan, 1996).

4.1 Static stability and deformation analysis in geotechnical structures

The finite element method has been developed and adapted to these applications. Improvements on this approach followed the increasing availability of computers and related software. The finite element method was confirmed as the most widely used method of analysis of deformations on geotechnical design. Geotechnical engineers had long been aware of the limitations of the linear elastic analysis of stresses and strains in earth masses, and it was immediately apparent that the ability to consider nonlinear stress-strain behavior gave the finite element method great potential for use in geotechnical problems.

The finite element method allowed the calculation of deformations of soil structures before failure, considering non-linear behavior of the soil (with de elastic-perfect plastic model, before failure, only elastic strains, reversible, were obtained). This was a remarkable aspect as it allowed the analysis of the serviceability of a soil structure.

4.2 The incremental analysis and the new breath of elasticity concerning the serviceability limit states of geotechnical structures

The use of incremental analysis involved the simulation of the overall problem as a series of events, and to interpret each event as a simple linear problem. Nonlinear and stress-strain dependent behavior is modeled by changing the stiffness values assigned to each element during each increment of the analysis. Different stress-strain relationships were used, namely the hypoelastic approaches (Naylor et al., 1986; Maranha das Neves & Veiga Pinto, 1988).

Examining more in detail the impact of the use of finite element and finite differences methods in the geotechnical area is out of the scope of this paper. But the growing and useful influence of these numerical techniques on the applications to geotechnical engineering cannot be denied.

5. The classic soil mechanics

5.1 Generalities

As already pointed out, classic soil mechanics and plasticity are tightly connected. It must be highlighted the role of the plane and its omnipresence on the theory of the classic soil mechanics. Consequently, any role of the intermediate principal stress is omitted. But perfectly-plasticity may be profitably used since as it permits to take advantage of the powerful bound theorems. Nevertheless, its practical use is restricted to safety evaluations of geotechnical structures.

Today, excluding the use of the actual version of the Coulomb method, the Rankine method, the limit equilibrium method, as well as the use of the Mohr – Coulomb perfectly-plastic model (with or without dilation) on numerical safety evaluation of geotechnical structures, it must be recognized that the use of the classic plasticity in the soil engineering practice, is, in a certain way, modest. The main debility is its impossibility to predict the deformations of a geotechnical system under working loads, i.e., the evaluation of the potential serviceability limit states. Indeed, classical geotechnical education concentrates its attention on the determination of shear strength and on the failure of geotechnical structures, i.e., the evaluation of ultimate limit states (Wood, 2012).

5.2 Fundamental aspects of the classic soil mechanics not shared with the modern soil mechanics

There are other fundamental aspects that must be cited, though they are not shared with the modern soil mechanics. In particular, the use of the concept of true cohesion, the maintenance of the classical ideas of Terzaghi centred on an approach to the strength and stress-strain relationships as practically independent entities. Another feature is to think about clays and sands as soils that need to be dealt with in separate, and finally, the necessity of an *ad hoc* explanation of the concepts of drained and undrained behavior, as well as the concept of the undrained strength (Alonso, 2005). These topics will be appreciated later on when dealing with $CSSM$.

Another interesting point refers to the role of mineralogy and colloidal chemistry on the mechanical behavior of clays. More precisely, the role of inter-particle forces when they have dimensions lower than $1\mu m$. This was a subject widely and deeply developed in the soil mechanics textbooks, mainly in the decades 70-80. This is the case, for instance, of the well-known and appreciated books of Scott (1963) or Lambe & Whitman (1979). But in more recent publications, mainly those who include the critical states theory, the theme of the particle's mineralogy and inter-particle forces resulting of the surface chemistry is completely ignored. See for instance, Schofield & Wroth (1968), Bolton (1979), Wood (1990) and Atkinson (1993).

It is true that in geotechnical civil engineering and in some situations, these inter-particle forces may have a significant role, for instance those related with the occurrence of piping, scour, self-filtering etc. But nothing that could justify the relevance assigned to this type of forces in soil mechanics (Maranha das Neves, 2007).

6. The critical state soil mechanics and the modern plasticity

The emergence of the modern soil mechanics $(CSSM)$ is also a consequence of more recent developments in the plasticity theory. The results of these significant advances are called modern plasticity. In short, the coming in site of the $CSSM$ is also due to the modern plasticity, a fact that must be underlined by those who teach soil mechanics.

6.1 Work hardening plasticity

One of the major advances is the application of the elastic-plastic work hardening (and work softening) theory to soil and is due to Drucker et al. (1957). The innovation is based in the idea that the usual soil consolidation curve is a case of work hardening stress-strain relationship, as well as the successive yield envelopes, as those marked 1 and 2 in Figure 3. Another innovation concerns the isotropic normality consolidated condition, such as point A in Figure 3:

an increase in the mean effective stress causes yield so that the yield envelope must pass through point A'. The yield surface changes according a hardening law, usually based on the accumulated volumetric plastic work (Wroth, 1973).

6.2 The emergence of the critical state soil mechanics

In the last part of this paper, besides drawing your attention to the unique facets of the $CSSM$, the main aim is to make clear the differences between modern and classic soil mechanics. According to a highly impressive generic appreciation it can be said that the CSM is based in critical stresses while the $CSSM$ is based in critical states.

The family of soil models developed at Cambridge University (UK) resulted not only from the introduction of work hardening plasticity into soil mechanics, as well as from the important innovation that has been the concept of critical state, conceived by Roscoe et al. (1958).

A soil is said to be in a critical state when exhibits shear strains with invariance of q, p' and v. According to this concept, the critical state line (CSL) is the locus of the end condition (failure) of all shear paths, considering that soil remains homogeneous during those trajectories.

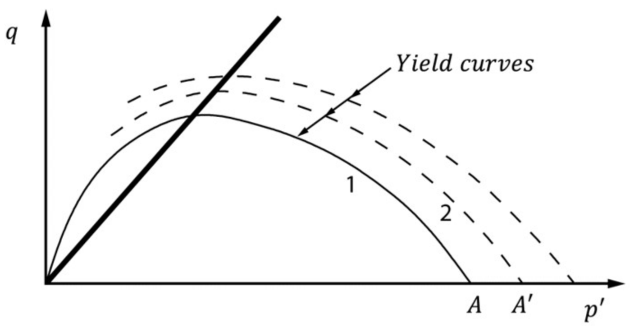

Figure 3. Possible yield surfaces produced by normal consolidation.

The failure criterion, according to the critical states, is defined not only in a stress plane q e p' (as in the CSM), but also considers the specific volume v. (Figure 4).

The failure criterion is defined by the Equations 3 and 4. The Equation 3, in the (q, p') plane, is

$$q = \mathrm{M}p' \tag{3}$$

and Equation 4, which represents the critical state line, CSL, in a (q, p', v) space, will be

$$v = \Gamma - \lambda \ln p' \tag{4}$$

where Γ is the v value at the CSL, for $p' = 1kPa$.

The Equation 5, not represented in Figure 4, is the unload-reload line in the $(v, \ln p')$ plane

$$v = \mathrm{N} - \kappa \ln p' \tag{5}$$

where κ is the slope of that line and N is the v value at the NCL for $p' = 1kPa$.

In this model, the elastic and plastic behavior is entirely specified by only four basic soil constants: $\lambda, \kappa, \mathrm{M}$ or ϕ' and Γ.

The CSL is the critical state locus. This line links together successive yield locus by connecting the points as C in the Figure 4.

It was first proven that the use of the Coulomb's failure envelope as a yield locus (Drucker et al., 1957) was mistaken. In reality this envelope is the locus of separate failure points (see Figure 5b).

The first model to make use of the work hardening plasticity in the context of the critical state theory was presented under the name of Cam-clay. The different limit surfaces in a (q, p', v) space, in addition to the CSL and to the NCL, are presented in Figure 6. The Cam-clay model diffusion in multiple variants, many concerning the use in practice, occurred in a short time. The use of numerical

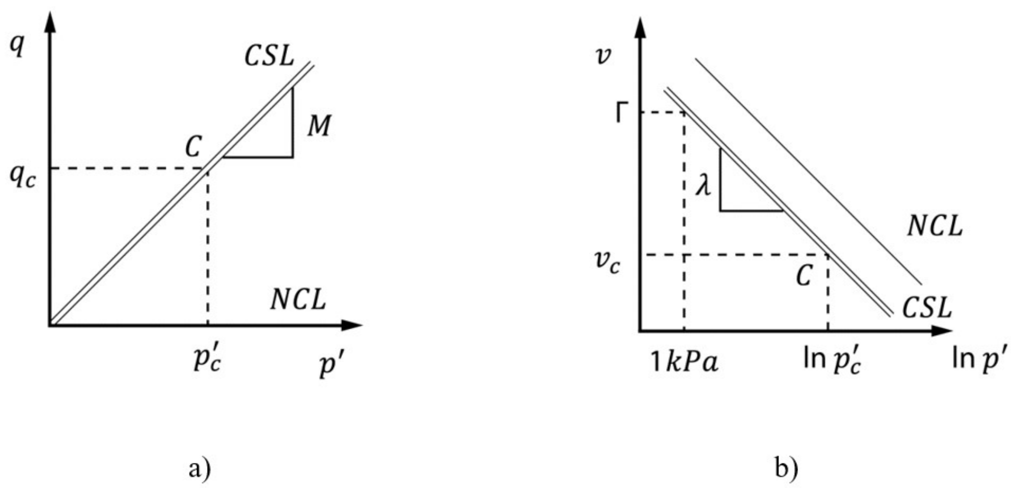

Figure 4. Critical state line (CSL) and normal compression line (NCL). (a) in the (q, p') plane; (b) in the $(v, \ln p')$ plane.

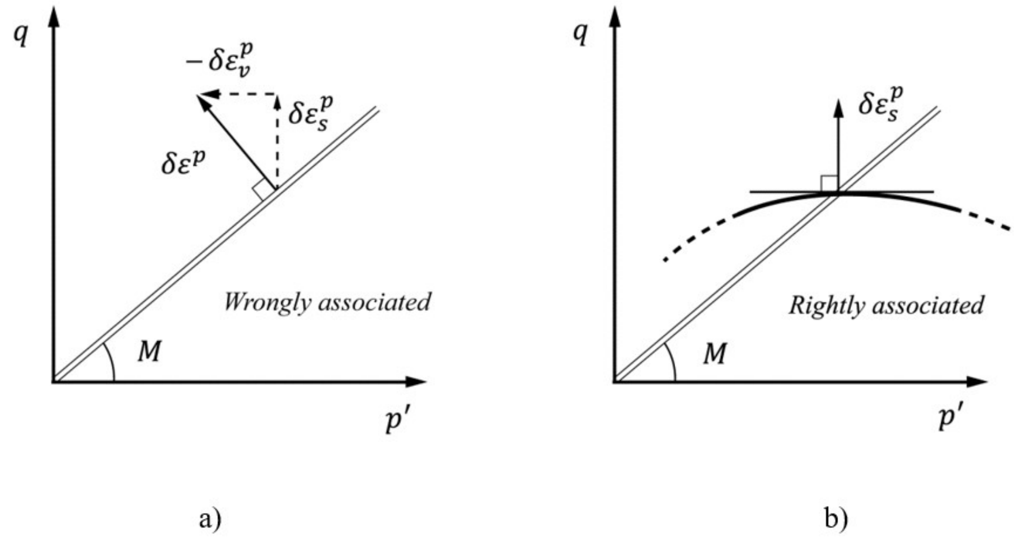

Figure 5. Associated flow for a soil at critical state. (a) wrongly associated; (b) rightly associated.

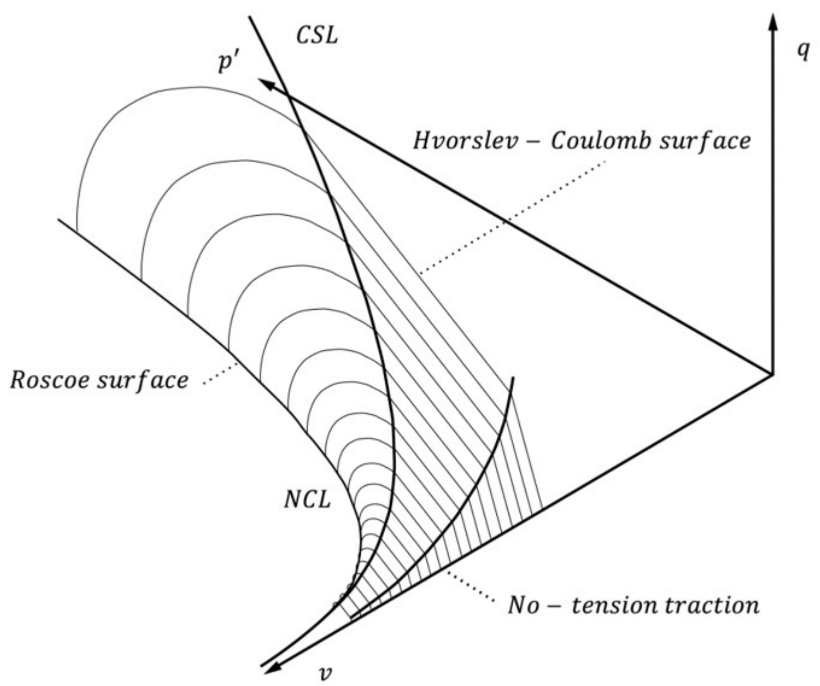

Figure 6. Limiting states surfaces in a (q, p', v) space, according to the Cam-clay model: Roscoe surface, Hvorslev-Coulomb surface and no-tension traction surface (adapted from Wood, 1990).

methods in modern soil mechanics began in the decade 70 (see for instance Naylor & Zienkiewicz, 1972; Naylor, 1975).

After a reexamination of the work of Hvorslev (1937), Roscoe et al. (1958) recognized the huge importance of the incorporation of voids ratio as an essential parameter on critical state theory, with natural reflexes on soil failure criteria. Thirty years later, Schofield & Wroth (1968), in a tribute to the author, named the limit states surface that connects *CSL* and the no-traction failure surface, as Hvorslev-Coulomb surface (see Figure 6).

This surface has the outstanding role of being a frontier between two contrasting disturbed soil behaviours. One, based on the Cam-clay model for isotropic soft soil placed on the *wet* side of the *CSL* during plastic yielding and flow, where the material is considered homogeneous, contractile and exhibits stable yielding (Schofield, 2006). The other disturbed soil behavior (localized on the *dry side*), is characterized by slip planes, indicating dilation and an unstable yielding.

6.3 The failure criteria reexamined

According to the CSM, adhesion, friction and cohesion are the strengths with which soil resists cracks or slip plane failure. It makes use of the failure criterion of Coulomb, which, on the failure plane, is represented by the Equation 6,

$$\left|\tau\right| \leq c' + \sigma' \tan\phi' \tag{6}$$

and, graphically, in Figure 7.

To have an idea of the deep marks of Coulomb's failure criterion in soil mechanics, it could be said that, for engineers, the classic soil mechanics is the wide set of design calculations and studies which are based on the Coulomb equation.

Equation 6 shows that c' has a constant value, so, independent of σ'. This parameter, also called "true cohesion" according Terzaghi, would result of the closeness of the mineral particles that interferes in the balance between the attractive forces of Van der Waals and the repelling forces originated in the double layer. As was already stated, this is not a plausible reason in the context of the $CSSM$. Once more, it must be underlined that this failure criterion is only defined in function of the state stress.

In a clear contrast, the $CSSM$ treats soil as a paste continuum. It explains how the strength of an unbonded aggregate of strong and stiff soil grains, depends on effective pressure σ' and on specific volume v. This puts into question the Coulomb resisting slip plane and the Terzaghi concepts of "true cohesion",σ', and of "true friction angle", ϕ'.

According the $CSSM$, the failure criterion, due to Taylor (1962), is radically different. It is based on energy concepts and equates the dilation input for the soil shear strength characterization. It uses the term interlocking to

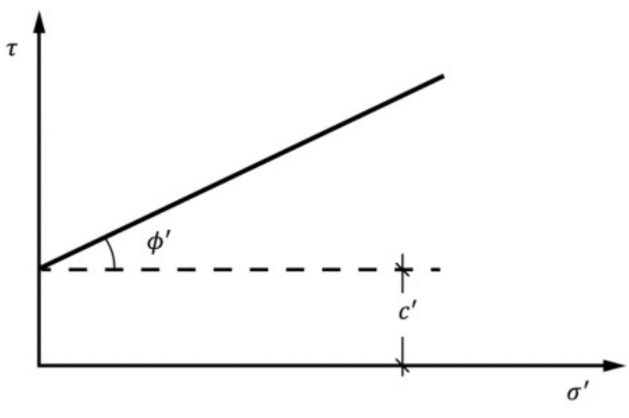

Figure 7. The Coulomb's failure criterion, Equation 6.

describe this important phenomenon. The Taylor's proposal is described by the Equation 7,

$$q\delta\varepsilon_s + p'\delta\varepsilon_v = \mathrm{M}p'\left|\delta\varepsilon_s\right| \tag{7}$$

According to this criterion, the applied energy is divided between the part stored (left side of Equation 7) and the part dissipated (right side). The dissipated energy depends on a frictional constant, M or ϕ', as a fundamental parameter in the theory.

It is important to point out that the volumetric change cannot produce work dissipation. This was intuited by Roscoe et al. (1958), but Thurairajah (1961) showed experimentally that the work absorbed internally is independent of the dilation rate. The occurrence of increments of volumetric strains in Equation 7 indicates that dilation has been taken into account to allow modeling of deformations.

6.3.1 Interlocking versus cohesion

It is evident that the definition of the shear strength in each of the criteria is a fundamental feature of the failure theory. Figure 8 shows the differences between both formulations and helps on the choice of which of them is the more appropriate (Schofield, 2006).

Taking into account these considerations, the peak strength that must be considered is the one suggested by Taylor (i. e., the sum of interlocking and the ultimate critical state drained friction) rather the peak strength recommended by the Coulomb criterion, always supported by Terzaghi (sum of the "true cohesion" and of the "true friction"). The first criterion is a fundamental concept of the $CSSM$ and the second one is inseparable of the CSM.

7. The over-consolidated soil behavior before failure

The interpretation of NC (or lightly OC) and OC soil behavior, is quite different, depending on which of the theories of CSM or $CSSM$, is based on. As was shown before, dilation is null at the critical state, so, the important role of interlocking has to do with the over-consolidated soil behavior before failure, particularly the peak stress states.

7.1 The interpretation according to the classic soil mechanics

As can be seen in Figure 9, the peak stresses are represented through the concept of effective cohesion, c'.

But the failure criterion, Equation 6, is only applicable to the situations where

$$\sigma' \leq \sigma_C^{'} \tag{8}$$

where $c_C^{'}$ is the pre-consolidation pressure. Some important limitations of this criterion are referred to in the next paragraph.

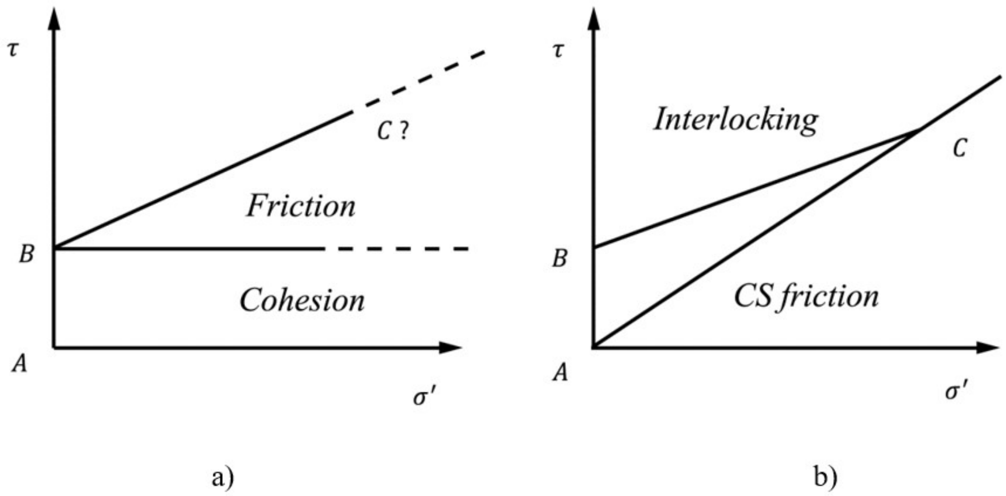

Figure 8. Alternative models for the peak strength of remolded, reconsolidated fine-grain soil: (a) according Coulomb; (b) according Taylor.

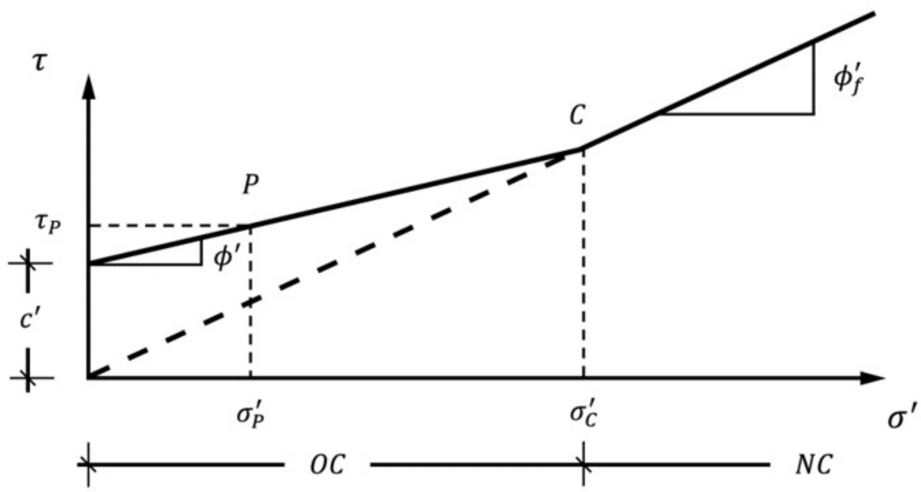

Figure 9. Peak strengths in *OC* soils, based on *CSM* theory. Interpretation in a (τ, σ') plane.

7.1.1 The true cohesion does exist in disturbed soil?

Even before the critical state theory appearance, the experimental work of Hvorslev (1937), reexamined by Schofield & Wroth (1968), showed that cohesion increases exponentially when the specific volume diminishes. This means that the Coulomb's equation, where c' is independent of the normal effective stress, is not verified. The same can be said about Terzaghi's opinion, that not only supported that invariance of σ', but also reinforced this concept by entitling it of true cohesion.

Besides, now in light of the critical state theory, is only obtained for those c' values two to three times lower than the pre-consolidation pressure (σ'_C, see Figure 9). This fact was not previously considered. The failure criterion also omits any information about the inexistence of c' at failure (critical state). And, if there were any "true cohesion" on the *dry side* of the CS line, it would also be seen on the *wet side*. Finally, c', for $\sigma' = 0$, was never measured, fact that cannot be ignored. All these reasons confirm that there is no "true cohesion" at all in re-consolidated disturbed soil (Schofield, 2001).

7.2 The interpretation according to the critical state soil mechanics

In Figure 10 is represented, in the planes (τ, σ') and (v, σ'), the failure criterion interpretation, based on the concept of Taylor and on the critical state theory. Obviously, c' doesn't exist.

The state W, located between the NCL and the CSL, when submitted to a shear stress (at σ' constant), displays a decrease of v during its path to W_C (critical state). The W states are NC or lightly OC and, as can be seen, pass by any peak shear stress located on the right of the CSL, (*wet soil*) they have a contractile behavior during the path $\overline{WW_C}$.

The D state, located on the left side of the CSL, (*dry soil*) are OC when submitted to a shear stress. It displays an increase of v during its path to D_c (critical state). The D states are OC and the shear stress evolves to a peak, D', before reaching the critical state, D_c, showing a positive dilation behavior.

During the shear path $\overline{DD'}$, the normal stress σ' is constant and has elastic behavior, the soil volume also remains constant. The change of volume occurs only during the path, $\overline{D'D_c}$ with a maximum at D' and zero at D_c.

Summing up, unlike the proposals of the CSM, soils only exhibit positive dilation for OC degrees higher than a certain threshold. This dilation behavior is responsible for the peak stresses that occur before the critical state is attained (the failure). Figure 11 intends to make evident the contribution of the dilation (interlocking) to the peak strength as well as its transient character.

The mentioned weaknesses from the CSM, are due to the use of a failure criterion defined only in a stress space. This inconvenient can be overcome by adding a parameter associated to the volumetric deformation as is the case of the Taylor's failure criterion, Equation 7. Furthermore, it will also allow the characterization of the states before the failure.

Dilation is a concept inseparable of the $CSSM$. As the volume is invariant at the critical state, its performance is mainly related with the behavior of OC soils before failure and specifically with the peak stress states.

This doesn't mean that CSM ignores the dilation phenomenon, but it must be considered in an *ad hoc* way, i. e., it is needed a previous indication of a drained or undrained condition. According to the $CSSM$ theory, the state localization in the (q, p', v) space is enough to quantify its volumetric behavior (or water pressure).

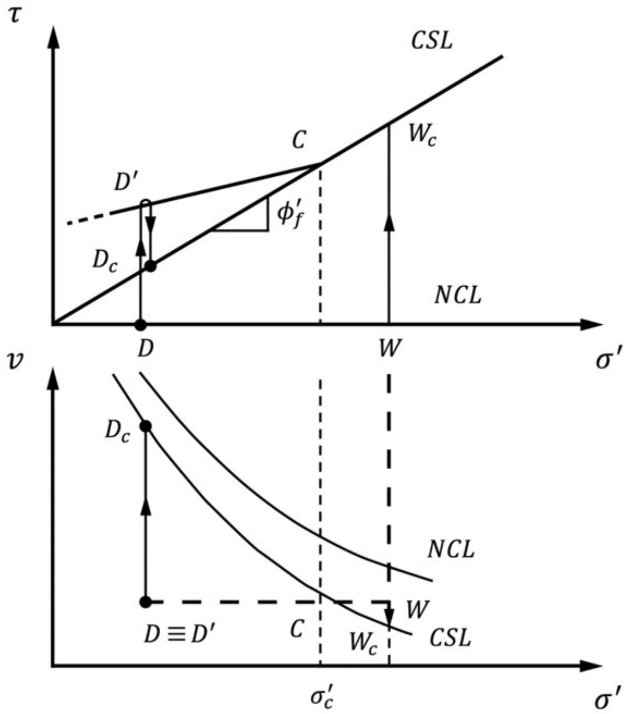

Figure 10. Peak strengths in *OC* soils, based on *CSSM* theory. Interpretation in a (τ, σ', v) space.

7.3 The *OC* soil behavior before failure according to the classic and critical state theories

On the application of the deviator stress to an OC soil, elastic and plastic volume changes occur simultaneously.

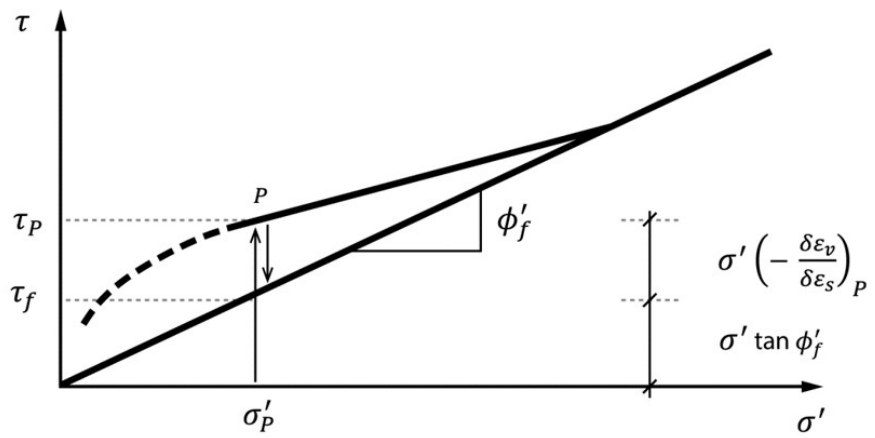

Figure 11. The peak shear strength, τ_P, has two different origins: friction, $\sigma' tan\phi'_f$ and interlocking, $\sigma'\left(-\dfrac{\delta\varepsilon_v}{\delta\varepsilon_s}\right)_P$.

When being tested, shortly after reaching peak deviator stress, the material deforms on planes or within thin zones, but the correspondent plastic expansions are hardly observed in the test boundary measurements (Parry & Amerasinghe, 1973).

7.3.1 According to the *CSM*

The *NC* soils don't have peak strengths and failure stresses are analyzed on the considered failure plane. Strains before or at failure cannot be obtained.

The *OC* soils exhibit peak strengths (peak values of c' or ϕ', or both) that can fall down to values corresponding to the failure envelope concerning the *NC* soil. Those last failure strength values, due to additional shear strains, can even fall to residual values. The slip plane model, mandatory in *CSM*, doesn't allow the prediction of all the successive forms of a specimen. A body can be divided into separate blocks moving apart from each other, or bulge and flow (Schofield, 2006). The analysis of equilibrium situations is always referred to a plane that, in this case, is a slip surface associated to the peak strength.

7.3.2 According to the *CSSM*

But following the *CSSM*, the *NC* soils are located on the *wet side* of the *CSL*. The material is considered homogeneous, and the soil state can be known before failure. In the state path to the *CSL*, the soil exhibits negative dilation, meaning that the soil plastic behavior is stable. Boundary displacements, originated by the integrated effects through the aggregate, can be observed and measured.

In the case of *OC* soils, the homogeneous character of the soil of the wet zone disappears once the peak strength is attained. Thenceforth, the soil exhibits positive dilation, which diminishes till zero at the *CSL*. In this phase soil plastic yielding behavior is unstable.

Note that a distinction has been made between the peak stress criterion in which the soil body is still considered to be a homogeneous continuum, and the Hvorslev-Coulomb equation for limiting equilibrium between two separate parts of an only just ruptured body. The Hvorslev-Coulomb surface specifies stress components only on the failure plane.

8. The high over-consolidated soils behavior

A soil can exhibit high *OC* behavior when, in an over-compacted state (low specific volume) and a low effective pressure, fails for very high values of the stress obliquity. In reality, under these conditions, the stress obliquity (q / p'), designated by η, can attain values near 3 (in the case of active equilibrium) or near $1,5$ (in the case of passive equilibrium). The soil behavior resulting of the conditions just described is characterized in the following paragraphs.

During the evolution of η from the critical state $(\eta = \mathrm{M})$ to $\eta \approx 3$ (or $\eta \approx 1,5$ for passive equilibrium), the soil begins to develop parallel slip planes, allowing the use of the limit equilibrium design methods, for instance. Note that at these states the global soil mass hydraulic conductivity is not affected.

But for $\eta \gg \mathrm{M}$, (near 3), the soil mass can even exhibit hydraulic fracture, piping, as well as fluidized rubble, phenomena that can happen, for instance, in embankment dams.

When dealing with natural undisturbed ground, which in reality is a soft rock with an aggregate structure (bonding and fabric), flow debris can occur and, at a first sight, this cannot be associated to soil embankments. However, the high *OC* disturbed soils, not only can fail along slip surfaces and exhibit tension cracks, but also break up into blocks of rubble. In this situation, if subjected to a high hydraulic gradient, it will flow as debris in a catastrophic failure.

9. Critical states soil mechanics education: where and how

Before some considerations about this matter it is necessary to make clear that the title of this paper may mislead the reader. In fact, it is not intended to discuss about pedagogy in soil mechanics in its different branches. It's a topic that deserves certainly great interest and there is a lot of information about this subject (Burland, 1989, 2008; Atkinson, 2008; Herl & Gesellmann, 2008, among many others). Nevertheless, some brief words about the soil mechanics education are pertinent.

9.1 The role of modern soil mechanics

There are recently well established theories in the field of soil mechanics that cannot be left to be taught. In many courses, predominantly undergraduate, these subjects are not yet contemplated in the syllabus of the soil mechanics discipline. Or they are simply added, but without explaining the contradictions that such information can originate. It's mandatory to take into account that some basic concepts that characterize modern soil mechanics, contradict in absolute those considered fundaments in classical soil mechanics. How to deal with this situation? The answer was already approached on this paper.

9.2 Critical states soil mechanics education in undergraduate and graduate courses

Another question that can be pointed out is the acceptable differences between syllabus of undergraduate and graduate courses regarding the critical states soil mechanics.

According to Burland (2008), the geotechnical education matters consist into three distinct but interlinked aspects that can be summarized in the following titles: a) the ground profile; b) the observed behavior and c) the use of appropriate models. All these three aspects can be influenced by a fourth one: the judgment based on empiricism and experience, or rather, "well-winnowed" experience (Burland, 1989).

The boundaries between these four aspects often became not clear and one or more of them are frequently neglected.

Regarding the three aspects previously mentioned, the undergraduate courses should mainly focus on the a) and b), while in the graduate courses, a particular attention should be given to c), where the critical states theory is included.

9.3 Differences between what is taught at the universities and what is used in the geotechnical practice

As early as 1983, Atkinson claimed that *CSSM* terminology became the "lingua franca" of soil mechanics. Nevertheless this rapid spreading wasn't followed by an equivalent expansion of the critical states concepts among the geotechnical professionals. The practical application of the critical states theory occurred mostly through the use of some commercial calculation programs embodying those theoretical concepts. Many of these programs employ very attractive models as they are not excessively complex and need only a reduced number of parameters. And, above all, they complain about the ability to determine deformations.

Nevertheless, many users are not yet familiar with the critical states theory taught in soil mechanics courses, making it difficult a correct interpretation of the program results. According Randolph (2005), the lack of comprehension is not due to the complexity of the concepts or the algebra, but rather about the understanding of the underlying message and the gap between the knowledge that many experienced engineers, academics and practitioners, actually have and the misleading language and teaching that permeate much of soil mechanics education.

To "know when one doesn't know", an extremely useful ability normally recognized to the engineers to have (May, 2008), may not be verified for the type of calculation programs that include critical states assumptions. This is one more reason to adopt a particular care when teaching with this kind of software in university courses.

10. Some brief considerations about plastic design of geotechnical structures

The plastic design methods involve the assessment to the strength of structures and are based on the assumption that the used materials have good ductile properties and can tolerate a certain permanent deformation.

These materials allow internal redistribution of structural forces, and if loads are slowly increased, their collapse values are predictable. The small imperfections of fabrication and construction of hyperstatic structures, which alter so markedly the elastic distribution of internal forces, have no effect on ultimate carrying capacity (Heyman, 1996).

As was already largely commented, the soil mechanics and plasticity were always deeply interconnected. But in modern soil mechanics, which incorporates the critical state concept, this link is even more evident. It wasn't by chance that the plastic design denomination, coming from the structural engineering, was also installed in geotechnical design.

Design of geotechnical structures should be based on plastic theory and on approximate methods of analysis by upper and lower bounds. As any other structure it cannot answer disproportionately to a small load increment. Or be at risk of progressive failure if it is not able to dissipate the required energy through the potential failure mechanisms. The *CSSM* concepts can be the guide to satisfy the plastic geotechnical design principles.

The most relevant aspect is the nature of the plastic flow that *NC* or lightly *OC* soils exhibit before failure. Being contractile, the associated volumetric deformations avoid a progressive collapse. This means a desirable stable structural behaviour.

The behaviour of disturbed soil will depend on the effective pressure on the aggregate of soil grains and the specific volume of the aggregate. If it is not over-compacted, it behaves as a ductile plastic material at the critical state effective pressure. But if over-compacted and lightly stressed, it exhibits the brittle behavior already described in 8.

The engineers should bring structural materials into a tough (avoiding fracture) and ductile state as far as possible. A plastic analysis on a critical state basis will emphasize the benefits of ductility in geotechnical structures (Schofield, 2005).

A debate concerning zoned embankment dams took place on the decades 1960-80, concerning the benefits (or not) of ductility in the behavior of these structures. Instead of heavy compaction and a water content lower than the optimum - that strengthens and hardens the soil - the construction using light compaction and water content at the optimum or slightly higher – which favours the soil ductility – were recommended (Maranha das Neves, 1991). The actual plastic design theory came to bring the scientific basis to justify the previous recommendations, mainly based on experience and structural observation.

11. Conclusion

It is unacceptable nowadays that the theory of critical states is completely excluded from soil mechanics syllabus of civil engineering courses. Sometimes some principles of the *CSSM* are attached, trying what can be considered as a simple refreshment of the *CSM*. But one cannot simply add to the *CSM* a few brief notes about the modern soil mechanics. On the contrary, the importance of the introduced topic and the contradictions that arise in relation between a certain fundamental aspects of the classic programme needs a profound clarification. Finally, as this paper also contemplates the soil mechanics education, the unified understanding of the soil behaviour must be considered one of the outstanding consequences of the critical state soil mechanics launching.

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List of symbols

e	void ratio
p'	octahedral effective stress
q	deviator stress
CSL	critical state line
CSM	classic soil mechanics
$CSSM$	critical state soil mechanics
E	Young modulus
F	yield function
G	plastic potential function; stiffness modulus
K	bulk modulus
M	frictional constant
M^*	dilation parameter
N	v value at the normal compression line for $p' = 1kPa$
NCL	normal consolidation line
NC	normally consolidated
OC	overconsolidated
$\delta\varepsilon$	strain increment
ε_s^p	plastic shear strain
ε_v^p	plastic volumetric strain
η	stress obliquity
κ	gradient of unload-reload compression curve on $(v, \ln p')$ plane; swelling index, (C_s)
λ	NCL gradient; compression index,
ν	Poisson ratio
v	specific volume,
$\boldsymbol{\sigma}$	stress tensor
σ'	normal effective stress
σ_C'	pre-consolidation stress
τ	shear stress
ψ	dilation parameter
Γ	$v$value at the critical state for $p' = 1kPa$

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The development and evaluation of an educational board game on basic geotechnical soil characterization

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Article

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Abstract

This paper discusses the potential of gamification as a tool for teaching and learning in geotechnical engineering. Gamification involves incorporating elements of gameplay such as challenges, rewards, competition, and cooperation into teaching and learning environments to make the process more interactive and engaging. Although gamification is widely used in many fields, it is still relatively new in geotechnical engineering. This paper presents the 'Soil Character' board game developed by the GeoFUN group as an example of successful gamification in geotechnical engineering education. The game focuses on basic soil characterization, including soil classification systems, index properties, and geotechnical characterization tests such as sieving, sedimentation, and Atterberg limits. The paper provides background information on the development of the game, and a description of the game components. The online Portuguese version of the game was tested with eight civil engineering undergraduate students who had successfully undertaken the introductory soil mechanics module. Student's satisfaction in terms of game design, rules, and gameplay was measured via a questionnaire. Results of the questionnaires showed that the game was well evaluated in all aspects. Student volunteers reported that they felt very motivated, and that they wished they had been able to play the game when they were learning the topic. Thus, results presented in this paper suggest that gamification has the potential to make geotechnical engineering education more interactive and engaging. Exploring the effectiveness of the game in various contexts and with diverse student populations constitutes a key direction for our future research.

1. Introduction

Introductory soil mechanics courses underpin key concepts of Geotechnical Engineering and commonly involve several topics that can be complex to students. As a result, students often struggle, particularly with theoretical content, which can be presented in a repetitive and tedious manner through traditional teaching methods. Meanwhile, lecturers also face difficulties, even when adapting their teaching methods, in motivating students to engage with and learn the content.

As in any other engineering discipline, laboratory experiments are an important part of geotechnical engineering education (Bhathal, 2011; Feisel & Rosa, 2005; Magin & Kanapathipillai, 2000), as they provide students with hands-on experience and reinforce theoretical concepts. However, there are several challenges in implementing effective soil mechanics lab practices in undergraduate curriculum.

One of the challenges is the cost and availability of equipment and materials. Many universities may not have access to the latest equipment or may not have sufficient funding to purchase expensive equipment (Nyemba et al., 2017). This can limit the types of experiments that can be conducted in the lab, which can in turn limit the students' exposure to different types of soils and testing methods.

Then, a related challenge is dealing with the mismatch between the number of equipment available and the number of students. The shortage of equipment and resources can lead to reduced opportunities for hands-on learning experiences (Magin & Kanapathipillai, 2000), where demonstrations are chosen over "one student-one equipment" approach. This can result in a suboptimal student experience and a reduced ability to develop the practical skills necessary for success in geotechnical engineering. In addition, the limited access to equipment can make it difficult for students to develop an understanding of the limitations and challenges of the testing methods, which is critical for the accurate interpretation of geotechnical data.

Furthermore, soil mechanics lab experiments can be time-consuming and require a significant amount of preparation

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and setup. This can be challenging for lecturers who are already balancing teaching responsibilities with other research and administrative duties (Jaksa et al., 2016; Tight, 2016; Lai et al., 2014). Then, there is the challenge of engaging and motivating students during lab experiments. Some students may find the experiments boring or repetitive and may not fully understand the relevance of the experiments to their future careers in geotechnical engineering (Edward, 2002).

In this context, Nordstrom & Korpelainen (2011) demonstrated that unconventional teaching tools are effective in promoting deep learning of scientific knowledge and various skills associated with scientific disciplines to engineering students. One of the unconventional approaches is the use of gamification as a tool for teaching and learning, which according to Subhash & Cudney (2018), is considered an excellent option for didactic complement in the classroom as they encourage competition and teamwork, facilitate socialization, and arouse students' interest, promoting playful learning. Gamification offers the opportunity to lecturers to cater to different learning styles (Buckley & Doyle 2017) by incorporating visual, auditory, and kinesthetic elements into the learning process.

Despite the very limited use, successful implementations of games in the geotechnical context such as the GeoExplorer (Bennett et al., 2017; Bennett et al., 2020), Rockbowl (rock mechanics quiz held during the Brazilian Conference on Soil Mechanics and Geotechnical Engineering – COBRAMSEG, since 2014) and Geobowl (similar to Rockbowl but in general Geotechnical Engineering context, held during the Geotechnical Engineering Seminar of Rio Grande do Sul – GEORS in Brazil, since 2017), demonstrated the potential of gamification to the geotechnical community.

Thus, gamification has the potential to address some of the challenges associated with soil mechanics. The interactive and engaging learning experience can be particularly beneficial for lab-related content, as students may be more motivated to participate and learn if they are presented with a challenge or a goal to achieve.

In addition, gamification can provide a low-cost and accessible complement to traditional soil mechanics lab experiments. While not a replacement for hands-on lab experience, gamification can be used as a supplementary tool to reinforce theoretical concepts and provide a more engaging learning experience.

Games, whether physical or virtual, on mobile phones or computers, are part of the daily lives of most young people in university age. According to Moran (2015), the younger generation, who are accustomed to playing games, find the language of challenges, rewards, competition, and cooperation attractive and easily comprehensible, highlighting the usability of such methodologies in the teaching process.

Thus, this paper presents the development and evaluation of an educational board game on geotechnical soil characterization testing called 'Soil Character'. The game was developed by the GeoFUN group and focuses on soil characterization. The game was designed to be used as a supplementary tool for undergraduate students taking modules on soil mechanics, and to provide a more interactive and engaging learning experience. The learning objectives of the Soil Character board game are to:

- Introduce students to the different soil classification systems, including the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System;
- Teach students the basic principles of soil index properties;
- Introduce students to the different geotechnical characterization tests, including sieving, sedimentation, and Atterberg limits;
- Provide students with a fun and engaging way to learn soil characterization.

In this paper, the background and motivation for the development of the Soil Character board game are discussed. The game and the game components are described and then the results of a survey conducted with undergraduate students who tested the online Portuguese version of the game (known in Portuguese as "Show Solo") as well as the moderation team are presented. Finally, enlightened by the findings of the surveys, the potential of gamification as a tool for teaching and learning in geotechnical engineering is discussed.

2. Materials and methods

This work was divided into three main stages: the design and development of the game itself; the application of the game; and evaluation of the play tests.

2.1 Design and development of Soil Character

This game is part of a series developed by the GeoFUN Group, aiming to promote interactivity within geotechnical classrooms. The GeoFUN group is a dynamic team of lecturers and researchers from Brazilian and UK higher education institutions, dedicated to exploring the exciting intersection of geotechnical engineering and game development. This game was developed in Portuguese by two undergraduate students from Universidade Federal de Roraima (UFRR) in Brazil closely supervised by two GeoFUN lecturers.

The first stage of this project was defining the game's theme. For that, the team involved considered several key questions, such as whether it would aid in learning Soil Mechanics and whether students typically struggle with the subject matter when taught traditionally. They also assessed whether the chosen theme was broad enough to be effectively explored within a didactic board game. Once these questions were answered, the decision on the theme became more objective.

This game was the first developed by the group, and naturally it focused on bringing the fundamentals of soil mechanics into perspective, mainly focusing on laboratory tests, since equipment is not always available for individual practices. A challenge was to incorporate both information that adhere to both Brazilian and international standards.

Once the content was established, various styles of games were considered. Since the development of the game started during the COVID pandemic it was important to the team to focus on board games that could be adapted to digital formats, while remaining relevant to the chosen theme. Extensive research was carried out on existing games in the market, both didactic and non-didactic, to identify the most suitable format and dynamics.

Following the idea's conception, the team proceeded to create the game, including the design of the board, development of rules, and formulation of questions for the cards used. These questions were a blend of theoretical and practical knowledge, intended to incite student's curiosity. Once the physical game was finalized, the team promptly created an online version using Google Slides for diagramming.

2.2 Application of Soil Character – playtest

Since the game was developed during the pandemic period, the playtest took place remotely. Eight undergraduate civil engineering students from Universidade Federal de Roraima (UFRR) in Brazil tested the Portuguese version of the game (known in Portuguese as "Show Solo"). All students had already successfully undertaken the introductory soil mechanics module. The GeoFUN group moderate the play test and split the students into two groups of four, who played the game simultaneously in separate virtual rooms.

At the beginning of the test, the volunteers took some time to read the rules, followed by a Q&A session with the GeoFUN team to clarify the game's process. Then the game was played. At the end of the test, all players and moderators completed a game evaluation questionnaire.

2.3 Game evaluation questionnaire

To evaluate the effectiveness of the game, two questionnaires were developed. One questionnaire (Q1) was given to the student volunteers who participated in the play test, while the other (Q2) was given to GeoFUN moderators who facilitated the test. The Q1 questionnaire aimed to assess the design, rules, dynamics, questions, and content of the game as well as the student's overall satisfaction with the experience. On the other hand, the Q2 questionnaire aimed to assess the moderators' perceptions of the experience.

Table 1 outlines the questions of Q1 covering each aspect of the game. The answers were measured using a

Table 1. Aspects and questions analyzed in Q1 questionnaire.

Aspects analyzed in the game	Statements
(a) About the design	1. I like the board design.
	2. I like the design of the cards.
	3. The appearance of the game is attractive and harmonious.
	4. Game design connects with subject matter.
(b) About the rules and dynamics of the game	5. Written explanation of game rules is clear and easy to understand.
	6. The time allotted for the game was appropriate.
	7. I found the game tiring.
	8. I found the game boring.
	9. The proposed challenges made the game more fun and challenging.
(c) About the questions and content covered	10. The way the questions were divided made the game too complicated.
	11. The questions on the topic addressed were very easy.
	12. The game had so much information that it left me confused, making it difficult to identify and remember important points.
	13. The game content will be useful to me.
	14. I was able to relate game content to things I saw, did or thought.
	15. The content addressed complements subjects seen in the classroom.
(d) Satisfaction	16. The game made me want to learn more about the subject.
	17. After playing, I can better understand the theme presented in the game.
	18. After playing, I can remember more information related to the theme presented in the game.
	19. Getting the right answers and completing the challenges gave me a sense of accomplishment.
	20. The game kept me motivated to keep playing.
	21. Overall, I found the game boring.
	22. This game was not challenging for me.
	23. I will recommend the game to others.
	24. I would play this game again.
(e) Additional comments	25. Additional comments.

five-point scale ranging from “I completely agree” to “I completely disagree”.

Regarding Q2 questionnaire, its purpose was to monitor and document the impressions of the test from the perspective of the game developers. This questionnaire was similar to Q1 questionnaire but focusing on the observations of those who moderated the testing process. Table 2 presents the aspects and questions examined. Once all data was compiled, the game was evaluated, and the developers deliberated on any necessary modifications. Since the feedback was overall positive, no major alterations were deemed necessary. At this stage, an English version was also produced.

3. Results and discussions

3.1 Soil Character game

3.1.1 Game components and number of players

The game can be played by 2 to 4 players. It is composed of the Board (Figure 1), 4 pawns, 48 “Your choice”, 32 “Is it true?” and 27 “Mystery” Cards. Figure 2 shows the design of the “Your choice” and “Is it true?” cards. As these cards

Table 2. Aspects and questions analyzed in Q2 questionnaire.

Aspects analyzed in the game	Statements
(a) About the design	1. Volunteers appeared to approve of game design.
(b) About the rules and dynamics of the game	2. Volunteers easily understood the rules of the game.
	3. Volunteers had no difficulty using the platform chosen for the online version of the game.
	4. Volunteers looked bored.
	5. The time allotted for the game was appropriate.
(c) About the questions and content covered	6. Volunteers in general did not have great difficulties with the questions.
	7. The degree of difficulty of the questions seemed about right – not too hard and not too easy.
	8. Volunteers understood most of the questions.
	9. Volunteers seemed motivated throughout the game.

Figure 1. Board with pawns in black square (top left corner of image).

contain technical questions, Tables 3 and 4 bring examples of their contents, respectively. Meanwhile, the "Mystery" cards introduce a fun component to the game with random rewards and punishments. Figure 3 presents three examples of this card deck.

The "Your choice" cards (Table 3) feature multiple choice questions with four options. This set of cards can be associated with the lower levels of Bloom's Taxonomy - remembering and understanding (Bloom, 1956). These cards require the players to recall facts, concepts, and information related to the theme of the game. The players must choose the correct option from four alternatives, which tests their comprehension of the material.

The "Is it true?" cards (Table 4) are true or false questions. These cards are more challenging than the previous set, even though they have a 50% chance of success. This deck can be associated with the higher levels of Bloom's Taxonomy - analyzing and evaluating (Bloom, 1956). These cards require the player to evaluate the truthfulness of statements related to the theme of the game, which involves higher-order cognitive skills such as analysis and evaluation. The foundational content of these questions, for both decks of cards, is derived from established sources in the field, notably Knappett & Craig (2019), a widely recognized textbook in soil mechanics. Finally, the "Mystery" cards (Figure 3), bring an element of unpredictability and fun to the game, as they may offer rewards or punishments without any associated action.

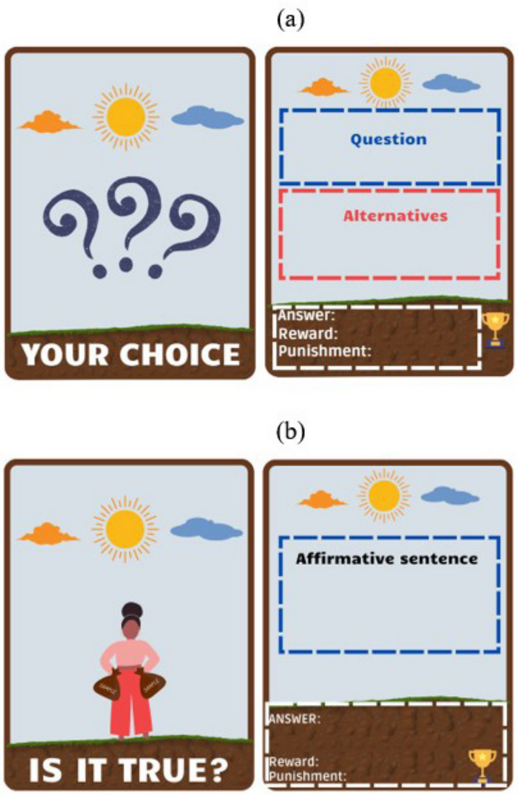

Figure 2. Cards design: (a) "Your choice" and (b) "Is it true?".

3.1.2 Playing order

Players must decide among themselves which pawn color they will use and the order in which they will play.

3.1.3 How to win

The player who first reaches the final square, "The end", of the board wins the game.

3.1.4 How to play

The squares on the board are stamped with the symbol of each card deck. During the game, players must turn over cards from the decks corresponding to the squares they landed on. Each card contains a reward if the player gets the answer right or a punishment if the player misses the answer.

In the first-round players must always draw a card from the "Your choice" deck. If the player correctly answers the question asked, his/her avatar must fulfill the reward indicated on the card; otherwise, the player must remain at the start, passing the turn to the next participant.

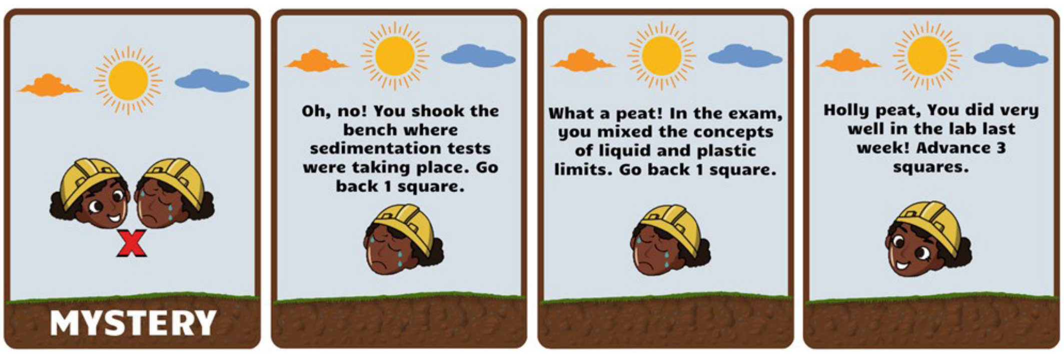

Figure 3. Examples of "Mystery" cards.

Table 3. Sample of questions of "Your choice" cards.

Question	Alternatives	Answer	Reward/ Punishment
How is it called the water content at which fine-grained soils change from a semi-solid to a solid state?	a) Liquid limit b) Plastic limit c) Shrinkage limit d) Atterberg limit	C	Advance 4 squares/ Stay where you are
You're in charge of finding the dry unit weight of a soil sample, for that you'll need the weight of solids and:	a) Volume of voids b) Total volume c) Volume of solids d) Volume of water	B	Advance 3 squares/ Skip next round
According to the Unified Soil Classification System (USCS), how it is classified a material in which more than 50% of the particles are retained on sieve 200 (0.075 mm) and less than 50% of the coarse fraction are retained in sieve 4 (4.75 mm)?	a) Gravel b) Sand c) Organic Silt d) Peat	B	Advance 2 squares/ Stay where you are
Which of the following is not presented as a percentage?	a) Water content b) Porosity c) Degree of saturation d) Void ratio	D	Advance 3 squares/ Go back 1 square
What is the particle size test used for materials passing the 200 sieve (0.075 mm)?	a) Sieving b) Flocculation c) Sedimentation d) Gradation	C	Advance 3 squares/ Go back 1 square
The relationship between porosity (n) and the void ratio (e) is given by:	a) $1 + n = 1/(1 + e)$ b) $1 - n = 1/(1 + e)$ c) $n = 1/e$ d) $n = e/(1 + e)$	D	Advance 5 squares/ Stay where you are
In the Highway Classification System (HRB), what percentage passing the #200 sieve is used to classify silt and clay-type materials?	a) 50 b) 35 c) 45 d) 60	B	Advance 3 squares/ Skip next round
The percentage of soil retained in each sieve, in the sieving test, is obtained by measuring:	a) Total mass b) Total weight c) Soil density d) Total volume	A	Advance 2 squares/ Go back 2 square
If the porosity of a soil sample is 20%, what is its void ratio?	a) 0.30 b) 0.27 c) 0.28 d) 0.25	D	Advance 6 squares/ Stay where you are
What is the name of the device commonly used to obtain the liquid limit of a soil material?	a) Darcy's device b) Casagrande's device c) Bernoulli's device d) None the above	B	Advance 3 squares/ Go back 1 square

Table 4. Samples questions of "Is it true?" cards.

Affirmative sentence	Answer	Reward/ Punishment
The Atterberg Limits are: Plasticity Limit, Liquid Limit and Shrinkage Limit.	True	Advance 2 squares/Go back 1 square
The following parameters can be obtained through laboratory tests: moisture content, specific gravity and dry unit weight.	True	Advance 4 squares/Go back 2 square
According to the Unified Soil Classification System (USCS), a soil in which more than 50% of the particles are retained in the 200 sieve (0.075 mm) is classified as coarse.	True	Advance 3 squares/Skip next round
Sieving is carried out by placing the various sieves one above the other in descending order of their openings from top to bottom.	True	Advance 3 squares/Stay where you are
The weight of voids in a soil is equal to the weight of water.	True	Advance 4 squares/Go back 1 square
The soil void ratio is given as a percentage.	False. Void ratio is dimensionless and given as fraction.	Advance 3 squares/Skip next round
According to the Unified Soil Classification System (USCS), when coarse soil (G, S) has low compressibility (L), it is classified as GL.	False. L cannot complement G or S.	Advance 4 squares/Stay where you are
When the soil is fully saturated, there are no voids present in it.	False. Voids are filled with water.	Advance 2 squares/Go back 3 square
Experimentally, the Liquid Limit corresponds to the moisture at which the soil closes a certain groove under the impact of 15 blows.	False. 25 blows.	Advance 5 squares/Skip next round

3.1.5 Online version

As previously mentioned, after finalizing the entire concept of the physical game, an online version was developed. The online version of Google Slides was used, so players could simultaneously access a page, through a link.

Six slides were produced: one for the cover of the game; one for the rules; one for the board; and 3 slides for the cards: "Your choice", "Is it true?" and "Mystery" cards, respectively (Figure 4).

One of the challenges in adapting the physical game to an online version was how to prevent the answers of the card questions from being exposed to all players. To address this, a tag was placed over the answer section of the card, and a background grid guide was added to help organize the pile of cards (Figure 5). Another challenge faced by the team was how to recreate the natural player interactions, such as teasing, banter, and discussions, that occur during board game play. To solve this, a video call via Google Meet was utilized. The use of these two tools demonstrated that the online play could be both interactive and easily accessible without requiring the download of any additional applications. In fact, the entire process could be accessed using just two links.

3.2 Questionnaire analysis

The data representing the feedback collected from students who play-tested the Soil Character educational board game is presented in Figure 6. The responses of the students are a useful indicator of the effectiveness of the game in terms of both its design and educational value.

The responses of questions regarding the game design (questions 1 to 4 - Figure 6a) show that the board design, card design, and overall appearance of the game were well-liked by most of the students. This is an excellent indicator of the game's success in terms of its visual appeal, which can have a significant impact on a player's engagement with the game.

Regarding rules and game dynamics, responses 5 and 6 (Figure 6b) indicate that the written explanation of the game rules was generally clear and easy to understand, and that the time allotted for the game was appropriate. These are positive indicators of the game's usability and playability. Responses 7 and 8 (Figure 6b) indicate that the game was not found to be tiring or boring by the majority of students, which is a positive sign that the game was engaging and enjoyable. Response 9 (Figure 6b) shows that the proposed challenges made the game more fun and challenging, which is a positive indicator of the game's ability to maintain a player's interest.

In terms of questions and content, response 10 (Figure 6c) indicates that the way questions were divided did not make the game too complicated, which is a positive sign that the game's structure was effective in facilitating gameplay. Response 11 (Figure 6c) indicates that students did not find the questions on the topic addressed to be too easy, which suggests that the level of difficulty was appropriate. Response 12 (Figure 6c) shows that the game content did not leave students confused, which is a positive indicator that the game's educational content was well-organized and presented effectively. Responses 13 to 15 (Figure 6c) show that students found the game content to be useful and complementary to subjects seen in the classroom, which is a positive indicator of the game's educational value.

Figure 4. Slides used on the online version of the game.

Figure 5. Online version solution: (a) question revealed with tag over answer, reward and punishment section; (b) answer, reward and punishment of the card in question revealed.

Lastly regarding students' satisfaction, responses 16 to 18 (Figure 6d) indicate that students generally found the game to be effective in facilitating learning and retention of information related to the game's theme. Response 19 (Figure 6d) shows that completing challenges gave students a sense of accomplishment, which is a positive sign that the game's structure was effective in rewarding players for their progress. Responses 20 to 24 (Figure 6d) show that the game was motivating, enjoyable, and challenging for most students, and that they would recommend the game to others and play it again themselves.

Student's additional comments are presented in Table 5. It is evident that the game was well-received by the students, and it provided a unique and entertaining learning

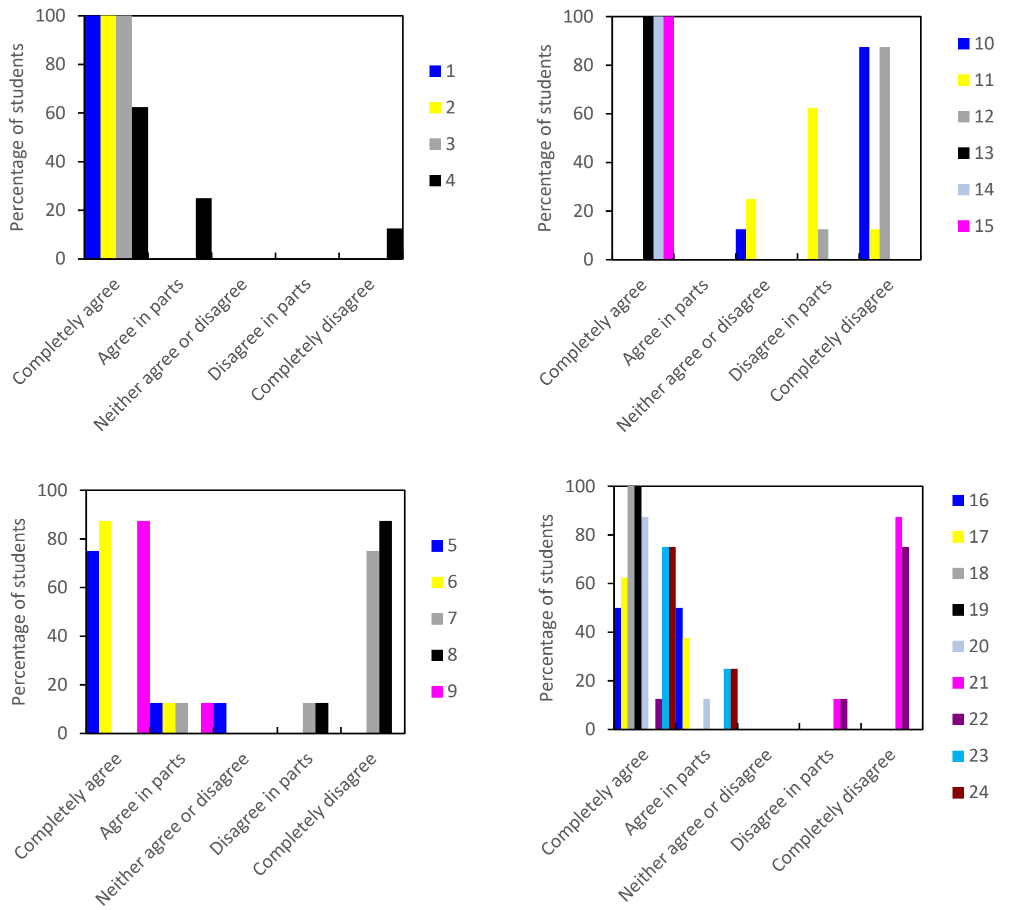

Figure 6. Q1 questionnaire results: (a) about design (1-4), (b) rules and game dynamics (5-9), (c) questions and content (10-15), and (d) satisfaction (16-24).

Table 5. Q1 questionnaire results: Additional comments.

Student	Additional comments
Student 1 (Group 1)	No comments
Student 2 (Group 1)	*"Very entertaining and also adds knowledge without giving the feeling that we are taking a test."*
Student 3 (Group 1)	*"I loved the opportunity to be able to play and I enjoyed the game a lot, both in terms of design and content. It was a great learning experience."*
Student 4 (Group 1)	*"There could be a variation between easy and difficult questions, which would give more chances for those who are behind to advance and for those who are in front to either go back or stay put. Congratulations to everyone involved, the game is very entertaining, and the design is beautiful!"*
Student 5 (Group 2)	No comments
Student 6 (Group 2)	No comments
Student 7 (Group 2)	*"Very well-made game. Congratulations on the idea:)"*
Student 8 (Group 2)	*"One of the questions was confusing regarding washing the passing material in the 4.5mm sieve, in the grain size distribution test. The game is very dynamic, and the design is fun, a unique and motivating experience that is also very entertaining."*

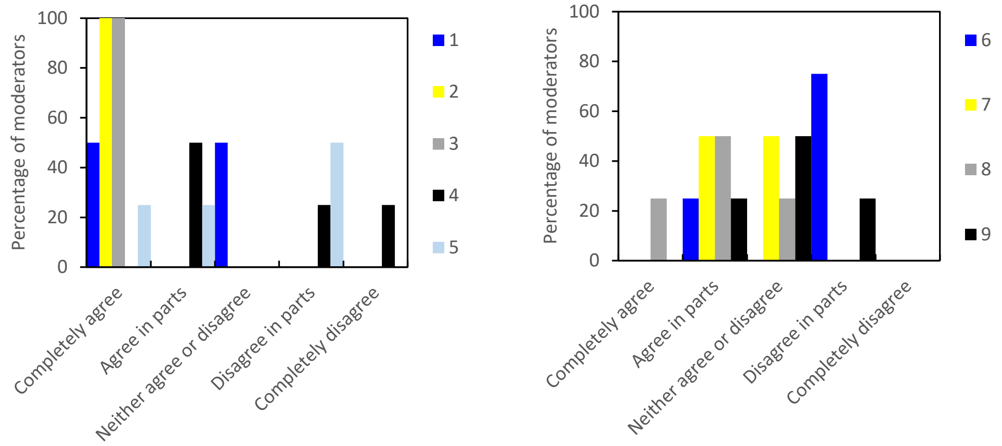

Figure 7. Q2 questionnaire results: (a) about design, rules, and game dynamics (1-5), and (b) questions, content, and satisfaction (6-9).

experience. Only two suggestions were made. The first one (Student 4 – Group 1) regarding mixing the level of difficulty of the cards can be easily addressed by shuffling the card. The second suggestion (Student 8 – Group 2) was dealt with by the team – the question was properly revised and modified accordingly. Overall, the data suggests that the game was successful in terms of its visual design, usability, engagement, and educational value.

Figure 7 shows the results of Q2 questionnaire. Data collected during the playtest shows some interesting findings regarding the moderators' perception of students' experience with the game. Based on the data provided, the moderators had mixed perceptions of the students' play testing, particularly in relation to the design and content of the game.

In terms of the game design (Figure 7a – question 1), half of the moderators completely agreed that the volunteers approved of it, while the other half had neutral opinions. On the other hand, moderators had more positive perceptions regarding the rules and dynamics of the game. All of the moderators completely agreed that volunteers easily understood the rules of the game (Figure 7a – question 2), and that there were no difficulties in using the online platform chosen for the game (Figure 7a – question 3). These are positive findings as they indicate that the game's instructions were clear and concise, and the online platform was user-friendly and easy to navigate and had not interfered with the experience.

In terms of volunteers' engagement with the game, half of the moderators somewhat agreed that the volunteers looked bored during the game (Figure 7a – question 4). This could indicate that the game did not fully capture the interest or attention of all participants, which could be a concern for the overall effectiveness of the game in promoting learning. However, this perception was not substantiated by the students' feedback (Q1: question 8 - Figure 6b and question 21 - Figure 6d).

In terms of the questions and content covered, the moderators' perceptions were mixed. While 75% of moderators disagreed in parts that volunteers did not have great difficulties with the questions, half of them agreed that the level of difficulty of the questions seemed about right (Figure 7b – question 6). Moderators also had mixed perceptions of volunteers' understanding of the questions, with 50% agreeing in parts, 25% agreeing completely, and 25% disagreeing in parts (Figure 7b – question 7). Lastly, moderators were divided on the volunteers' motivation throughout the game (Figure 7b – questions 8 and 9).

The mixed perceptions among the moderators could be associated with their different backgrounds and expectations. The fact that half of the moderators were undergraduate students while the other half were lecturers suggests that they may have had distinct expectations of what the game should be like and how the volunteers should have responded to it. For example, the undergraduate students may have been more attuned to the volunteers' perspective and may have had different expectations of what makes a game engaging and fun. Meanwhile, the lecturers may have had higher standards for the quality and educational value of the game. This difference in expectations could have contributed to the mixed perceptions among the moderators, particularly in relation to the design and content of the game. It would be interesting to explore these differences in expectations further and consider how they might influence the design and implementation of future educational games.

After the playtest and the analysis of the questionnaires followed by a slight refinement of the game, the physical and online versions of the Soil Character game were also translated to English.

4. Conclusion

This paper investigated the potential use of gamification as a tool for teaching and learning in geotechnical engineering. The Soil Character board game developed by the GeoFUN group provides an effective example of gamification, incorporating game mechanics and social learning to enhance student engagement and motivation in learning soil characterization.

The evaluation of the game with eight civil engineering undergraduate students showed high levels of satisfaction with the game design, rules, and gameplay. The feedback collected from the students indicates that the game was well-liked, engaging, and effective in promoting learning. Most students found the game to be motivating, enjoyable, and challenging, and they would recommend it to others and play it again themselves. These findings suggest that the game was successful in achieving its intended goals and was well-received by the target audience of students. On the other hand, the moderators' perceptions were more mixed, particularly in relation to the design and content of the game. The mixed perceptions among the moderators could be explained by their different backgrounds and expectations since half of them were undergraduate students while the other half were lecturers.

These findings suggest that gamification can be a valuable tool in making geotechnical engineering education more interactive and engaging. The Soil Character board game can be used as a supplementary teaching tool in soil mechanics courses, as well as being adapted to other fields of engineering and science that involve complex concepts and terminology. Further research is needed to explore the effectiveness of the game in different contexts and with different student populations.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Mariana Ramos Chrusciak: conceptualization, visualization, validation, investigation, methodology, formal analysis, supervision, writing – original draft, writing – review & editing. Hingred Karoline Magalhães da Luz: conceptualization, data curation, visualization investigation, methodology. Rebeca Dias de Souza: conceptualization, visualization. Bruna de Carvalho Faria Lima Lopes: conceptualization, visualization, validation, investigation, methodology, formal analysis, supervision, project administration, writing – original draft, writing – review & editing

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

e	void ratio
n	porosity
AASHTO	American Association of State Highway and Transportation Officials
COBRAMSEG	Brazilian Conference on Soil Mechanics and Geotechnical Engineering
G	gravel
GEORS	Geotechnical Engineering Seminar of Rio Grande do Sul
HRB	Highway Classification System
L	Low compressibility
S	Sand
UFRR	Universidade Federal de Roraima
UK	United Kingdom
USCS	Unified Soil Classification System

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Digital tools used on the teaching-learning process in geotechnical engineering

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Article

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Information and communication technologies
Teaching-learning process
Geotechnical engineering
Digital tools
Software
Geotechnical engineering education

Abstract

This article presents the incorporation of information and communication technologies on the teaching-learning process of geotechnical engineering to improve the quality of education and provide practical knowledge to civil engineering students. The content of this paper is divided into three main modules, which are: Treatment of laboratory tests results, Slope stability and Rock mass stability. For this, some software were used, including 2D limit equilibrium stability analysis, stability analysis of rock wedges and a dynamic mathematics, to obtain and analyze soil shear strength parameters, among others. Furthermore, a digital tool was developed to analyze the results gathered in compaction, one-dimensional consolidation, and direct soil shear tests, in order to clarify the relationship between theoretical concepts and practical results of the tests and analyses and to help students on doubts, in addition to increase their interest and motivation to perform the complete interpretation of the collected data. The activities were conducted in classes of geotechnical disciplines of the undergraduate course in Civil Engineering at the Federal University of Viçosa, aiming to promote active learning and improve teaching quality. Based on the results of an applied feedback questionnaire, it was observed that most students were satisfied with the resources used in the classroom, demonstrating that the implemented digital tools work as a didactic instrument that facilitates learning and comprehension of practical problems, in addition to enabling the resolution of several geotechnical engineering problems much more quickly and efficiently.

1. Introduction

Quality education is one of the Sustainable Development Goals of the United Nations 2030 Agenda (United Nations, 2023), which aims to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. In this sense, digital technologies have been recognized as a fundamental tool to achieve this goal, providing an excellent opportunity to assist students in establishing connections between the theoretical concepts studied and practical problems (Haleem et al., 2022).

Geotechnical Engineering involves problems of significant complexity, which require a solid understanding of theoretical concepts to support high-quality engineering projects. Therefore, the use of digital tools in the teaching-learning process on geotechnical engineering is becoming increasingly important. Through specialized software, it is possible to carry out more accurate and elaborated analyses, simulating situations that would be much more laborious without the aid of these tools and would require more time and resources. Furthermore, digital tools can help to prepare students for the geotechnical industry, by providing them with practical skills that are highly valued by employers.

In this context, the implementation of some interactive digital tools has been proposed to assist undergraduate students in geotechnical disciplines of the Civil Engineering course at the Federal University of Viçosa in order to assist the students to perform, analyze, and interpret results related to different laboratory tests, slopes stability studies and rock masses characterization and analyses, and flow studies.

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From this experience, it will be discussed whether this approach could contribute to the improvement of students' learning, promoting a deeper understanding of the concepts studied in the classroom, in addition to developing skills in the use of digital technologies applied to geotechnical engineering. Finally, the perceptions of students regarding the use of these tools will be presented, obtained through a feedback questionnaire.

2. Materials and methods

Table 1 presents the geotechnical disciplines of the Civil Engineering undergraduate course in which digital tools were applied, their regular semester of offering and the syllabus for each one.

2.1 Treatment of laboratory tests results

Performing laboratory tests is essential for understanding the properties of materials used in geotechnical works, enabling the prediction of soil and rock behavior when subjected to various field conditions. In addition, the correct interpretation of these tests is crucial for the precise characterization of materials, allowing the choice of appropriate parameters for the project.

Thus, in order to facilitate the understanding and application of the concepts studied in the disciplines, a practical approach with demonstrations of the procedures was proposed. For this, the use of two main software was implemented: Microsoft *Excel*® and *GeoGebra*, a free software.

Excel was applied more widely in the "Soil Mechanics I" course to exemplify concepts, facilitate calculations, and demonstrate more quickly some correlations between soil physical index parameters. In addition, its use was essential in laboratory classes in the "Soil Mechanics I and II" courses, where it became a very useful tool for teaching the processing of data obtained from tests such as Consolidation, Direct Shear, and Triaxial Tests.

GeoGebra was primarily used to promote interaction with graphical solutions to define equations that would typically be difficult to visualize and draw in the classroom, such as the Mohr-Coulomb diagram, the graphical determination of soil shear strength parameters, and the determination of normal and tangential stresses on the failure plane. Its use was added to slide presentations and to the classic blackboard drawing tools in which only static scenarios could be demonstrated, which limit teaching to pre-defined situations in lesson planning, making it difficult to adapt to questions that can arise in the classroom. The objective was to make the solutions already in use more visual and interactive, so that students could have greater interest, focus, and understanding of the presented concepts.

Furthermore, encompassing the teaching of several of the previously listed topics, a custom application was developed with joint effort from students and professors, named "Soil Physical Indexes". This application was developed in Adobe® Flash Professional CS5 language and ActionScript® code, and although considered simple compared to commercial software, it contributed for a practical and friendly learning environment to be created. Content related to theory, definitions of concepts, animated examples, exercises and demonstrations of practices in laboratories were implemented on it. This application was designed to be made available to students of the Civil Engineering course at the Federal University of Viçosa, acting as a study tool for them. This tool brings together in one single place the possibility of reviewing and applying concepts seen in the classroom, with the possibility of doing exercises of different levels of difficulty and checking the results.

Table 1. Disciplines in which digital tools were applied.

Discipline	Semester	Discipline syllabus
Engineering Geology	4th	Main geological phenomena. Stratigraphy. Structural geology. Geological-geotechnical properties of geological formations. Weathering. Technological properties of rocks. Underground investigation. Hydrogeology. Tunnel geology. Dam geology.
Soil Mechanics I	5th	Soil mechanics and engineering. The soil from an engineering perspective. Index properties of soils. Soil structures. Classification and identification of soils. Stresses acting on a soil mass. Soil permeability. Compaction.
Soil Mechanics II	6th	Water flow through soils. Soil compressibility and consolidation. Shear resistance of soils.
Earthworks	9th	Exploration and soil sampling for geotechnical projects. Slope stability and retaining structures in soils. Retaining structures. Earth pressure on support structures. Stability of retaining structures. Lowering of the water table.
Earth and rockfill dams	Optative	Introduction. Dams. General aspects. Earth and rockfill dams. Small earth dams. Geological investigations. Geotechnics of foundations. Study of materials to be used in construction. Laboratory tests for design purposes. 'In situ' tests on the dam body. Percolation in earth and earth-rockfill dams. Slope stability analysis. Monitoring during construction and operation. Understanding seismic effects.
Introduction to Rock Mechanics	Optative	Concepts in rock mechanics. Minerals, classification, weathering and index properties of rocks. Strength and deformability properties of rocks, discontinuity and rock masses. Flow in rock masses. Slope stability. Rheological behavior of rocks. Underground excavations. Instrumentation and monitoring.

2.2 Slope stability

Performing slope stability analysis is fundamental in several applications in Geotechnical Engineering. Therefore, it is extremely important that the student understands both the theoretical content involved in the solutions, as well as the functionalities of slope stability analysis software, which will be essential in their professional practice.

Thus, during the classes of the disciplines “Earthworks” and “Earth and Rockfill Dams” of the Civil Engineering course at the Federal University of Viçosa, software for slope stability analysis using the Limit Equilibrium Method and for percolation analysis through computer simulations were used to illustrate theoretical concepts, to present practical exercises to solve real problems, and to develop geotechnical projects using these software tools. For this purpose, the *Slide2* software from Rocscience® and *Slope/W* and *Seep/W* from the *GeoStudio* package by Seequent® were used.

Initially, in the introductory part of the discipline “Earthworks”, contents regarding landslides were explained, involving the main types of landslides and its possible causes. Afterward, the types of failure and the main methods used for slope stability analysis, in terms of strength and permeability, were addressed. From this, the professor instructed the students on the most commonly used slope stability software, explaining in detail the functioning and use of these programs. During the classes, the student version of the *Slope/W* and *Seep/W* software from the *GeoStudio* package, which is available for free download on the Seequent® website, was used. In addition, a UFV’s student license for the *Slide2* software from Rocscience® was provided to each student in the course, and it was up to the student to choose which software to use for the activities, according to their preference.

In order to demonstrate the practical use of the softwares for slope stability analysis, in addition to aid in the understanding and memorizing of theoretical concepts, several exercises were proposed. Among them, the analysis of stability of a partially saturated heterogeneous slope was performed to determine the potential surface of failure and the global safety factor using deterministic methods based on the limit equilibrium, such as those proposed by Bishop (1954), Spencer (1967), and Morgenstern & Price (1965). The objective of this activity was to evaluate whether the simplified Bishop method, which only considers the effect of normal forces between slices and satisfies the moment equilibrium, provides similar results to the Spencer and Morgenstern & Price methods, which consider the effect of normal and shear forces between slices and satisfy the equations of statics related to moment and force equilibrium.

In addition, another important activity proposed was the performance of percolation analysis of a retaining wall with a vertical drainage system, in order to better visualize the drainage behavior inside the soil mass with the retaining structure. To carry out this activity, the student could choose which software to use to perform the analysis, according to their preference. Furthermore, in the final part of the “Earthworks” discipline, an evaluation was proposed regarding the feasibility of constructing a gabion retaining wall to contain a certain soil mass. In this evaluation, the lateral earth pressures should be calculated, as well as the global stability analysis of the wall-soil system, using one of the analysis methods based on the limit equilibrium theory and a slope stability program of the student’s preference.

In the discipline “Earth and Rockfill Dams”, the same software mentioned earlier were also used. Initially, theoretical concepts related to dam construction were discussed, including aspects related to compacted embankments, shear strength, percolation, drainage systems, among others. After exposing all the theoretical content, a dam inspection project was proposed for a dam located in the state of Minas Gerais, Brazil, including a technical visit and the preparation of a technical report containing stability and percolation analyses of the dam. To carry out these analyses, a slope stability software of the student’s choice was used.

2.3 Rock mass stability

Just as the stability analysis of soil slopes, stability analysis of rock masses is an essential activity to be carried out in many geotechnical projects, such as dams, open-pit and underground mine slopes, tunnels, highways, foundations, and several other applications.

Software for stability analysis of rock masses are powerful tools to predict material behavior under field conditions. One of the widely used techniques to perform this prediction is the kinematic analysis based on stereographic projection. This technique allows the analysis of the orientation of fractures and faults present in rocks, through angular relationships between lines and planes in space, using a projection of a sphere onto a plane (Marques & Vargas Júnior, 2022), enabling the identification of fracturing patterns that may affect the stability of the rock mass.

Therefore, the software *Dips* from Rocscience® and the free software *Stereonet* were used in the “Engineering Geology” course of the Civil Engineering course at the Federal University of Viçosa, to predict possible planar, toppling or wedge failures in rock masses. In addition, the Rocscience® software *Rocplane*, *Swedge*, *Unwedge* and *Toppling* were used in the “Introduction to Rock Mechanics” discipline to evaluate the stability of discontinuity planes in rock masses using the Limit Equilibrium Method.

The “Engineering Geology” course was divided into two types of classes, theoretical and practical. During the theoretical classes, contents were covered regarding structural geology, geological-geotechnical properties of geological formations, factors that influence the behavior of rocks, and various applications in geotechnical works. In the practical classes, concepts about geological maps and sections, as well as stereographic projection were studied.

On the practical classes several exercises of plotting planes, lines and poles were done using the Schmidt-Lambert net with equal-area projection, based on the information that characterizes the attitude of each plane. From this, the professor of the discipline instructed the students on the most widely used stereographic projection analysis and kinematic analysis software, teaching in detail the operation and use of these programs. During the classes, the *Stereonet* software, which is available for free download on the internet, was used. In addition, a student license to use the *Dips* software from the Rocscience® company was provided to each student of the course, leaving it up to them to choose which software to use for the proposed activities.

With the objective of demonstrating the practical use of stereographic projection, in addition to helping the understanding and consolidation of the theoretical concepts studied, a project was proposed to evaluate the feasibility of constructing a highway, whose route required cutting through a fractured rock mass to overcome a certain elevation. For this purpose, data on the attitudes of 74 discontinuities planes obtained from a real geological mapping were provided, as well as two possible cutting plans for the construction of the road, so that students could evaluate the possible types of failure for each proposed slope and determine the ideal option. To perform these analyses, a stereographic projection analysis software of the student's choice was required.

In the "Introduction to Rock Mechanics" course, concepts were addressed regarding the main fields of application, including topics on geomechanical classification, rock alterability, flow in rock masses, rock excavations, and stability analysis of rock slopes, among other important aspects. In order to present the concepts related to rock mass stability more clearly, several activities were proposed to evaluate the possibility of planar, toppling, and surface and underground wedge-type failures using *RocPlane*, *RocTopple*, *Swedge*, and *UnWedge* software, respectively. In these activities, students had to assess the stability of the rock masses under study, and if they did not meet the necessary safety factors, a stabilization solution for the mass should be proposed.

2.4 Feedback questionnaire

In order to obtain an overview of the impacts of the implementation of digital tools in the teaching-learning process, an electronic questionnaire was developed for the Civil Engineering undergraduate students who have already taken disciplines in the area of Geotechnics. Thus, through this questionnaire, students were able to anonymously report their individual evaluation on how the use of these digital tools has impacted their learning process.

3. Analysis and results

3.1 Treatment of laboratory tests results

Figure 1 and Figure 2 show the interface of the "Soil Physical Indexes" application developed at the Civil Engineering Department of Viçosa Federal University and used in the "Soil Mechanics I" discipline. The example shown portrays the verification of the soil physical indexes calculated in two specific exercises of the course.

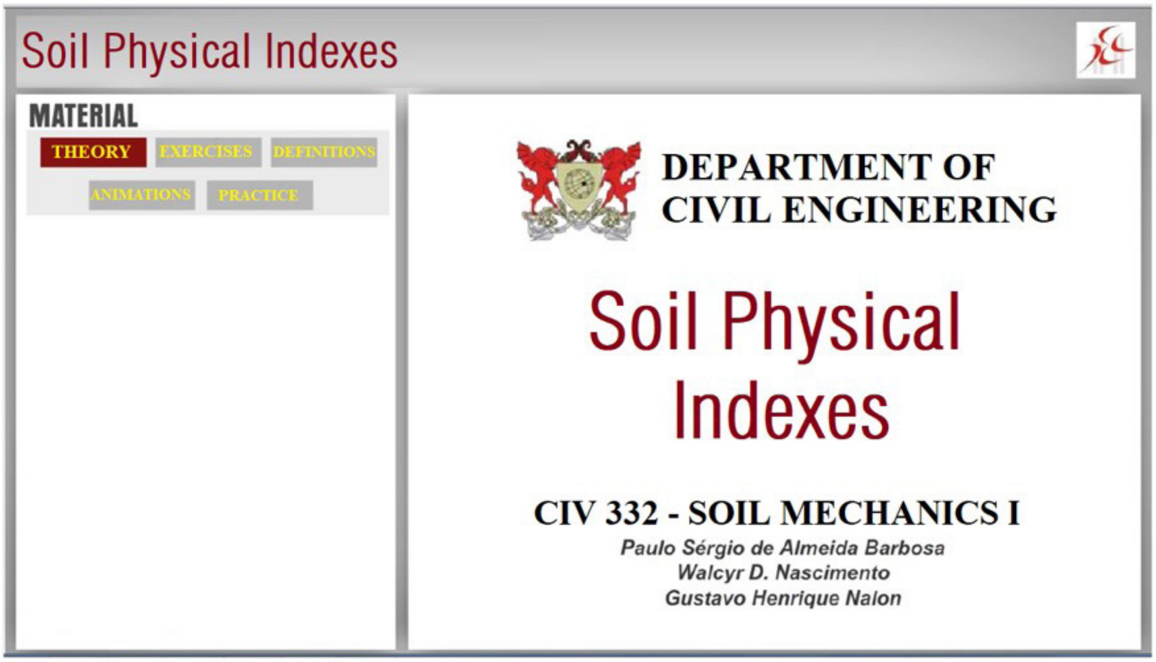


Figure 1. Application interface with available features. Adapted from Nalon et al. (2013).

The use of the resources of this application has proved to be a very important tool to help the fixation of the knowledge of the soil physical indices, since after the classes, the students were able to revise, exercise, check and often solve doubts about the themes studied. In addition, this tool also helped explain and review the subjects covered in practical classes, as shown in Figure 3.

Figure 4 shows two graphs generated from data obtained in a direct shear test, with pre-consolidation stresses of 50, 100, and 200 kPa, aiming to illustrate the process of interpreting the results of laboratory tests in Excel, in the discipline of "Soil Mechanics II". From the visualization of these graphs, it was possible to guide students through the interpretation of each element, such as the inclination of the lines, deformation stages, and failure stresses of the samples, as well as to correlate them with the preconsolidation stresses. This graphical resource, when used in various tests, samples, and soil types, demonstrates the different situations that future professionals may face.

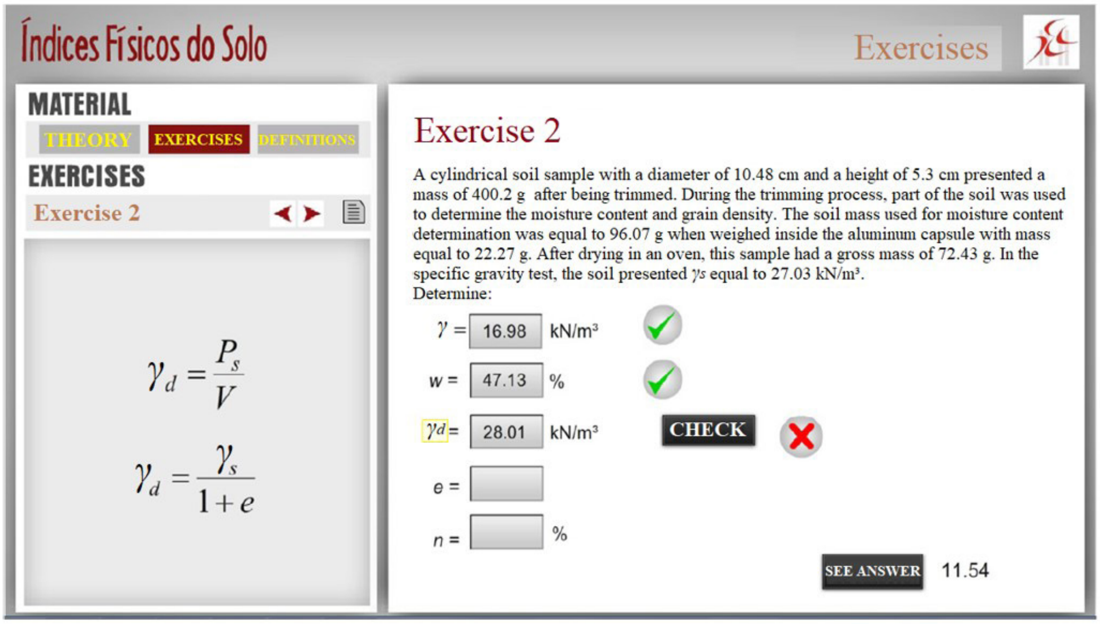


Figure 2. Application exercises functionality. Adapted from Nalon et al. (2013).

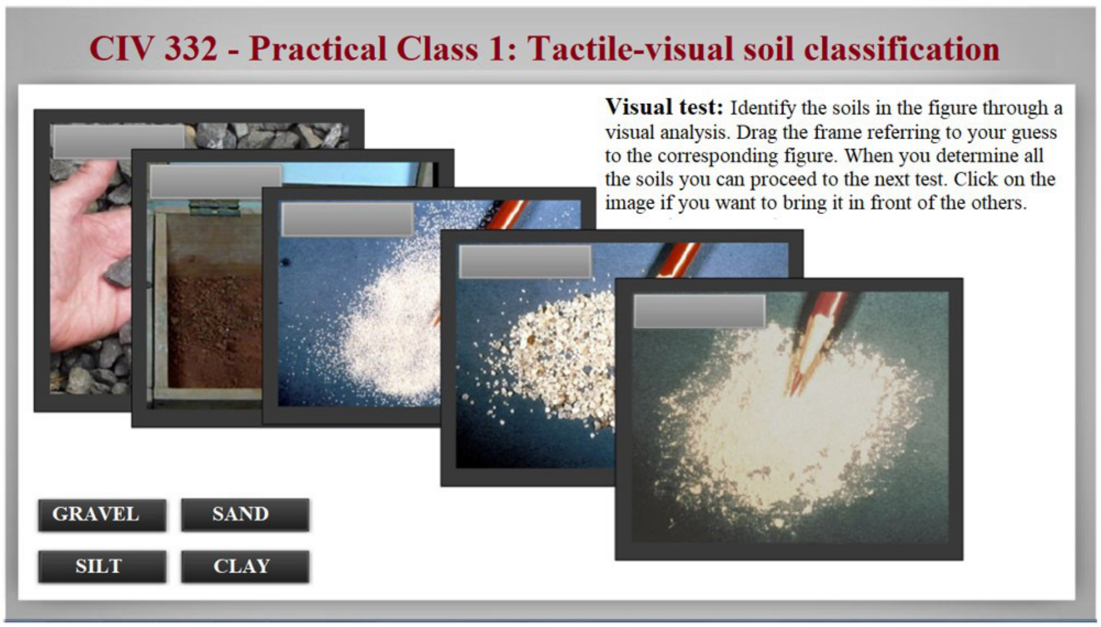
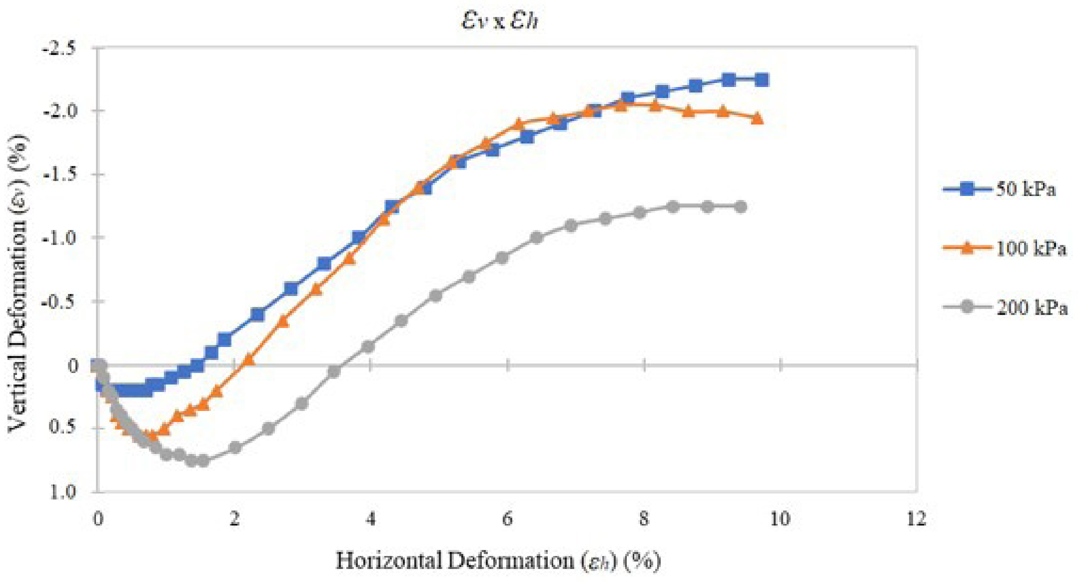


Figure 3. Animation of lab practice functionality. Adapted from Nalon et al. (2013).

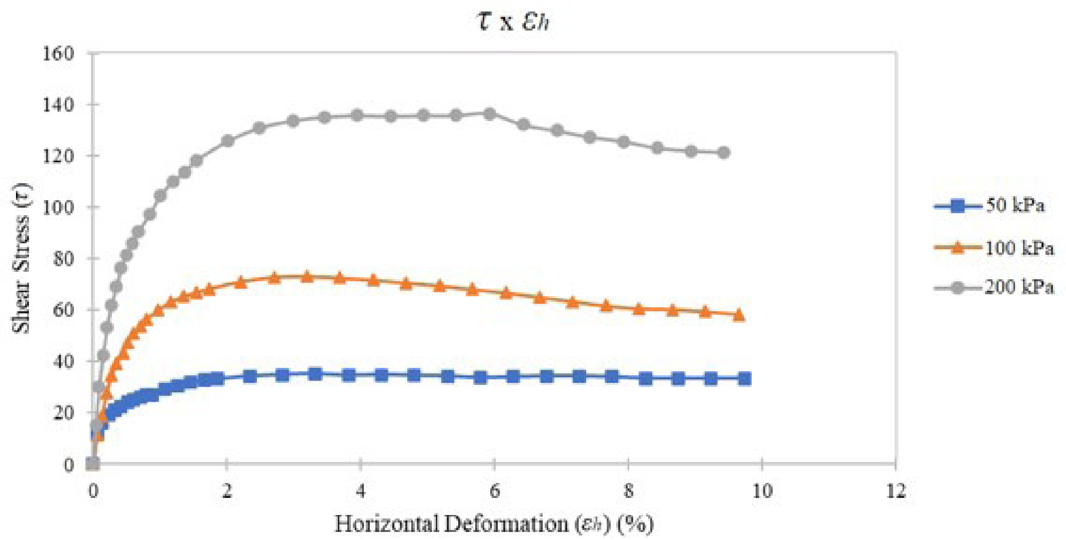
Thus, the contribution of this tool in refining and interpreting laboratory tests data could be observed, exercising an easy and practical way to provide data recording, graphical representation, and obtaining useful parameters for future analyses.

Figure 5 shows some useful results obtained in tests such as direct shear in the *GeoGebra* graphical solution. The bars shown above the graph represent sliders of soil parameter values, which, once changed, modify the graph format, illustrating the correlation between them.

This tool represented a means by which the professor of the discipline "Soil Mechanics II" could demonstrate in a more visual way the Mohr-Coulomb diagram, the determination of soil shear strength, and stress trajectories. Moreover, it was very useful in helping students to better visualize the theoretical concepts related to this subject, contributing to the improvement of the teaching-learning process.



(a)



(b)

Figure 4. Example of data interpretation from a Direct Shear test: curves of (a) vertical deformation x horizontal deformation and (b) shear stress x horizontal deformation.

3.2 Slope stability

Figure 6 presents the result of the stability analysis proposed in the "Earthworks" course for a partially saturated heterogeneous slope, with the determination of the position of the potential circular failure surface and the indication of the global safety factor obtained by deterministic methods based on the limit equilibrium theory, such as those proposed by Bishop (1954), Spencer (1967), and Morgenstern & Price (1965). The fictitious heterogeneous slope was composed of two soil types and a bedrock foundation. The strength parameters provided for the materials are shown in the table presented in Figure 6, considering the Mohr-Coulomb failure criterion for soils 1 and 2 and infinite strength for the rocky layer. The analysis presented was performed in the *Slide2* software from Rocscience®.

The accomplishment of this activity was important for the practical demonstration of the application of the concepts studied, helping in the understanding and fixation of the contents. Thus, the students were able to verify that, despite the simplifications adopted in the simplified Bishop analysis method, it provides very accurate values of the factor of safety for circular failure surfaces, coinciding with the values obtained by the Spencer and Morgenstern & Price methods.

Figure 7 presents the results of the stability analysis proposed in the "Earthworks" course for one of the suggested geometries for the construction of a gabion retaining wall, with the determination of the circular potential failure surface and indication of the global factor of safety obtained by deterministic methods based on the limit equilibrium theory, such as those proposed by Bishop (1954), Spencer (1967), and Morgenstern & Price (1965). The material strength parameters follow the Mohr-Coulomb failure criterion and are presented in the same figure. For the gabion wall, high strength parameters were considered so that the failure surface would not cross the wall, and the global stability analysis corresponded to the soil-wall system. The analysis was performed using the *Slide2*® software. Additionally, it was found that for the evaluated situation, the factor of safety is satisfactory, being greater than 1.5.

Figure 8 shows the results of the percolation analysis proposed for a retaining wall with a vertical drainage system, performed using the *Slide2*®. In this analysis, it was possible to observe the flow network inside the soil mass, containing the water table surface, the flow lines, and the equipotential lines with the total loads presented in the legend, considering a situation where the soil mass is fully saturated.

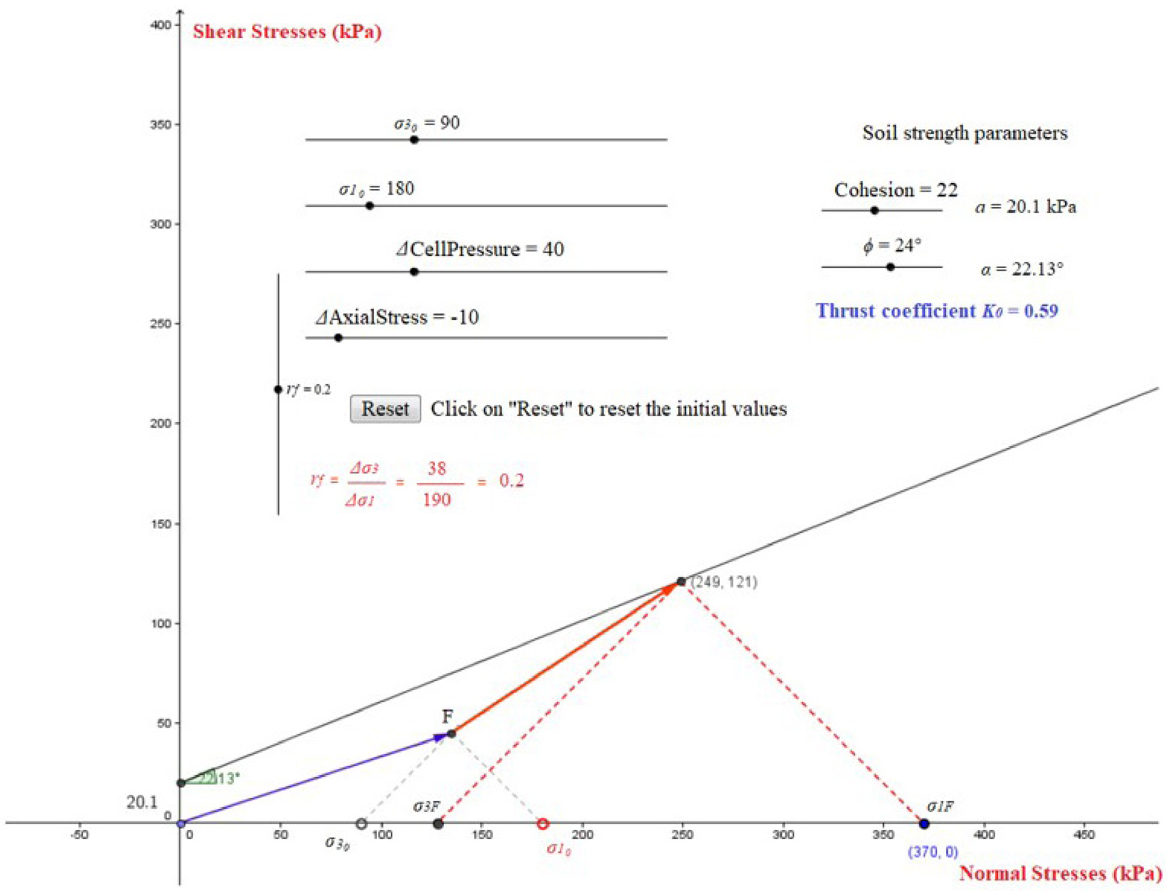


Figure 5. Application of soil stress trajectory. Adapted from Nalon et al. (2012).

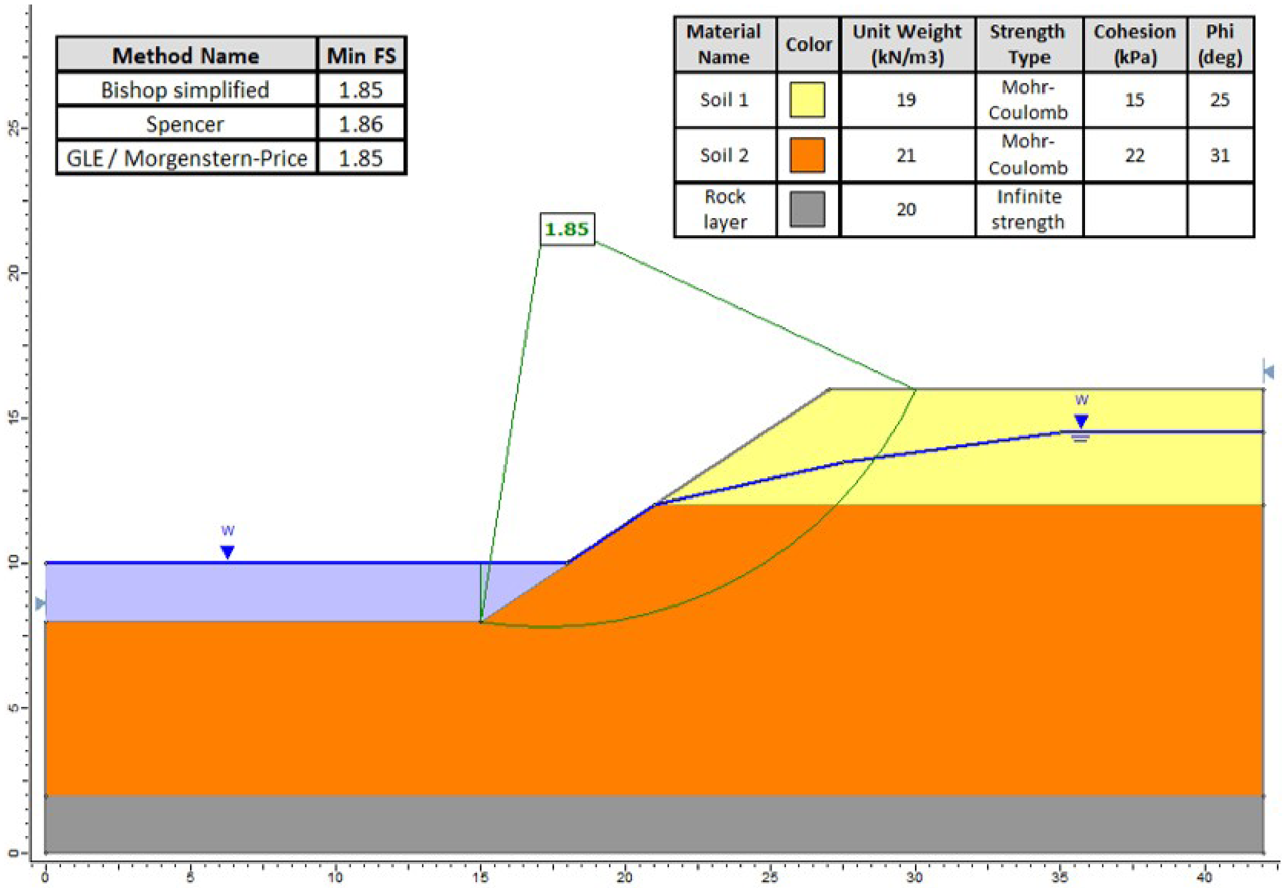


Figure 6. Stability analysis of a partially saturated heterogeneous slope.

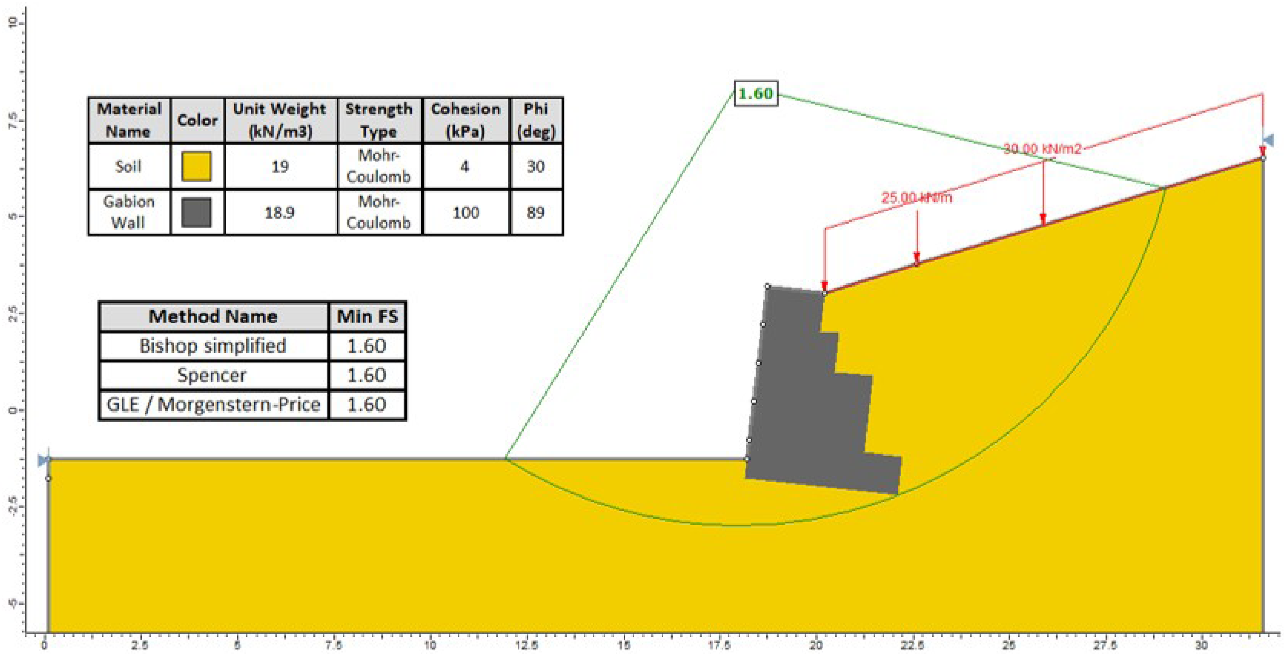


Figure 7. Stability analysis of a gabion retaining wall.

From the performance of these activities the students were able to visualize some practical applications of the concepts presented, as well as learn how to develop important evaluations in geotechnical projects. In addition, through the software, it was possible to simulate different scenarios of stability and percolation analysis, varying parameters such as wall geometry, material properties and overloads, in order to evaluate the performance of the structure under different conditions.

Figure 9a presents the stability analysis proposed in the discipline “Earth and Rockfill Dams”, carried out after the technical visit of the students to a dam site, indicating the factor of safety of circular potential failure surface obtained by the simplified Bishop method. Figure 9b presents the percolation analysis of the same dam, indicating equipotential surfaces. The stability and percolation analyses were performed considering a normal operating condition, with the reservoir at its operational level. The strength and permeability parameters of the materials that constitute the dam are presented in Figure 9. The analyses presented were carried out using the *Slide2*®. Furthermore, it was possible to verify that, for the evaluated situation, the global factor of safety is satisfactory, being greater than 1.5.

The completion of this work allowed the students to obtain a deeper understanding of the dam behavior in terms of strength and permeability, providing a clearer and broader understanding of the subject matter. This activity has contributed significantly to the development of essential skills for professional practice in the geotechnical engineering field, allowing for the acquisition of fundamental knowledge.

Therefore, through the use of digital tools in the disciplines “Earthworks” and “Earth Dams and Rockfill”, students were able to understand in a clearer, practical and more dynamic way the resolution of geotechnical problems, in addition to developing essential technical skills for the execution of projects in geotechnical engineering.

In this way, it is concluded that the use of these digital technologies greatly favors the teaching-learning process, allowing students to have access to actual tools commonly used in the industry. Furthermore, the use of these tools makes it possible to carry out accurate analyzes of the stability of slopes and other geotechnical structures, resulting in significant savings in time and resources.

3.3 Rock mass stability

For the proposed work in the “Engineering Geology” course, 74 discontinuities obtained through geological mapping could be grouped into three families (1m, 2m, and 3m), as shown in Figure 10. This plotting was constructed from discontinuities attitude data, using the Schmidt-Lambert network with equiarea projection, in the Rocscience® *Dips* software.

Figure 11 shows the attitudes of the three families of fractures and the two possible cutting planes (1 and 2) proposed for the construction of the highway. In addition, the lines of intersection between each family of fractures are presented, which were necessary information for carrying out the kinematic analyzes, in order to assess whether there could be any possibility of planar, wedge or toppling failure for the proposed geometry. Based on the analyses performed on the example in question, it was found that the two suggested slopes are equally unstable, and another slope with different attitudes should be proposed to meet the safety criteria against planar, wedge, and toppling failures.

Through the completion of this activity, the students had the opportunity to learn about the functioning of kinematic analysis software, in addition to visualizing in practice the concepts studied in the discipline, developing the sensitivity to evaluate how parameters such as plane direction, plane inclination, and discontinuity dip direction can influence the stability of a rock mass.

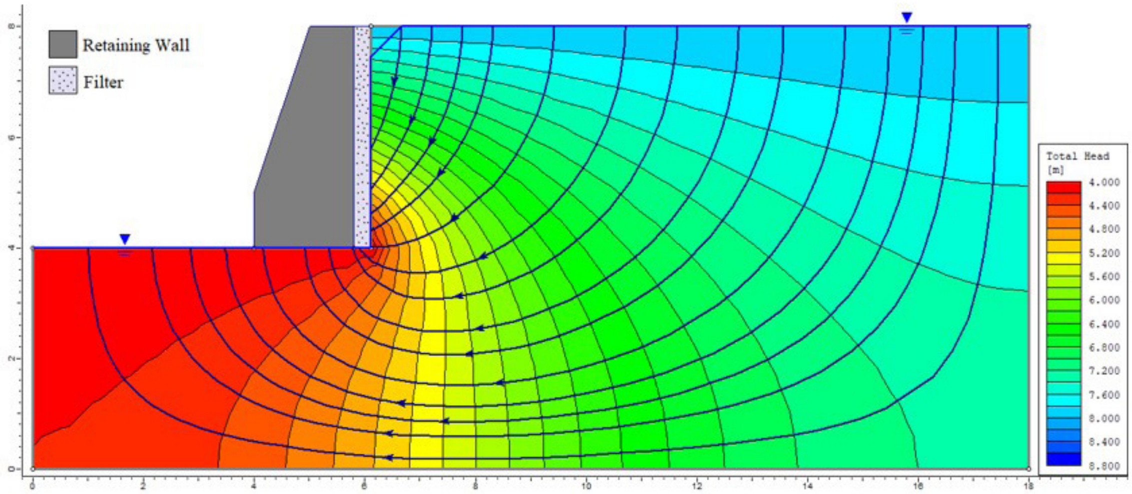


Figure 8. Percolation analysis in a soil massif, detailing the flow network.

In the "Introduction to Rock Mechanics" course several activities were proposed, but for illustrative purposes, Figure 12 presents an analysis of planar rupture stability in a fictitious rock mass, using the Limit Equilibrium Method through *RocPlane®*.

As observed in the image, the safety factor was not satisfactory, requiring the proposal of a solution to this problem. Thus, a possible alternative proposed by the students is presented in Figure 13, using rock bolts to increase the resistance of the rock mass, achieving an acceptable safety factor, greater than 1.5.

The use of these digital tools in the disciplines of "Engineering Geology" and " Introduction to Rock Mechanics" provided students with a deeper understanding of the application of the studied contents, generating a practical experience closer to the challenges that can be found in some engineering projects.

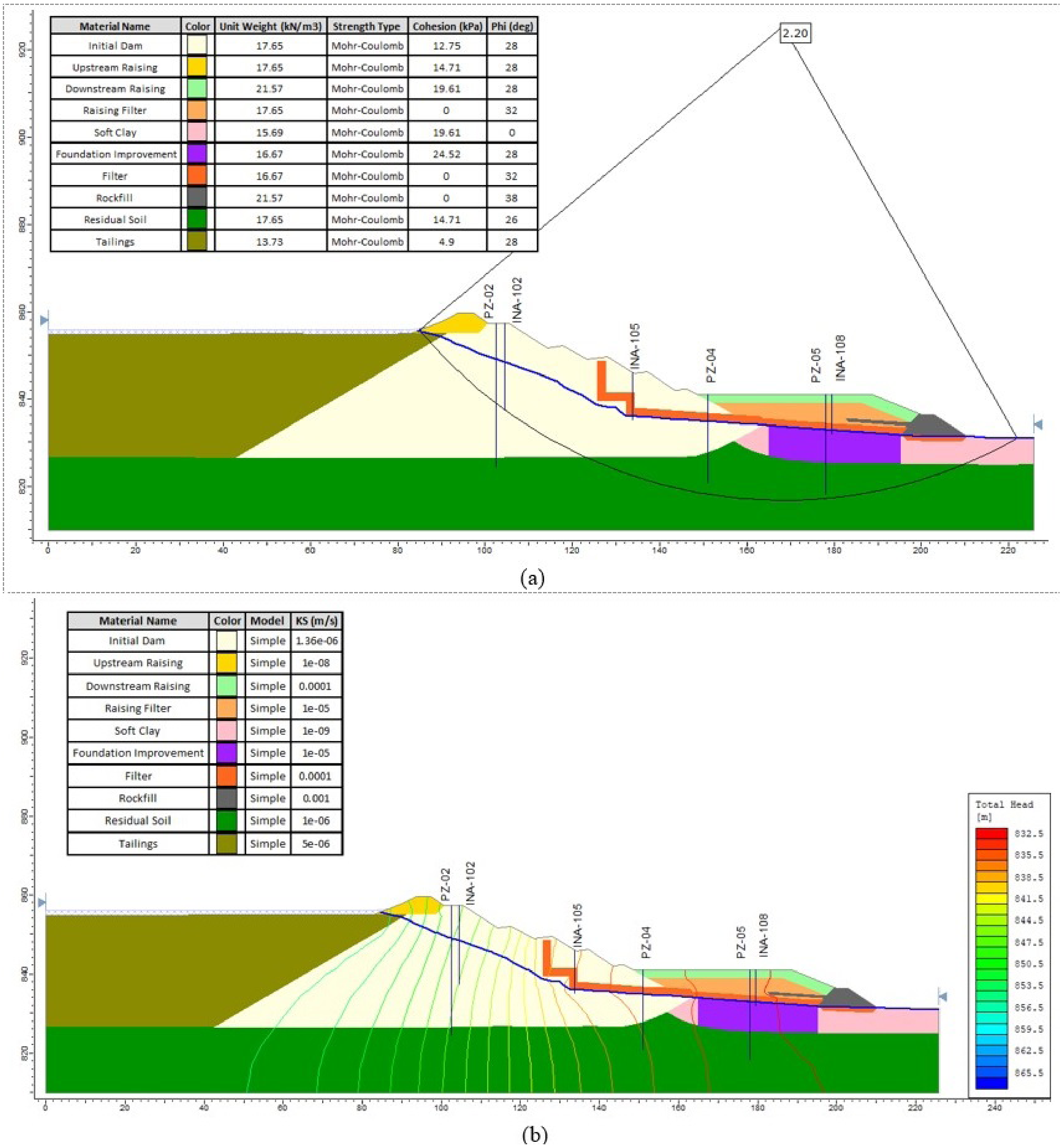
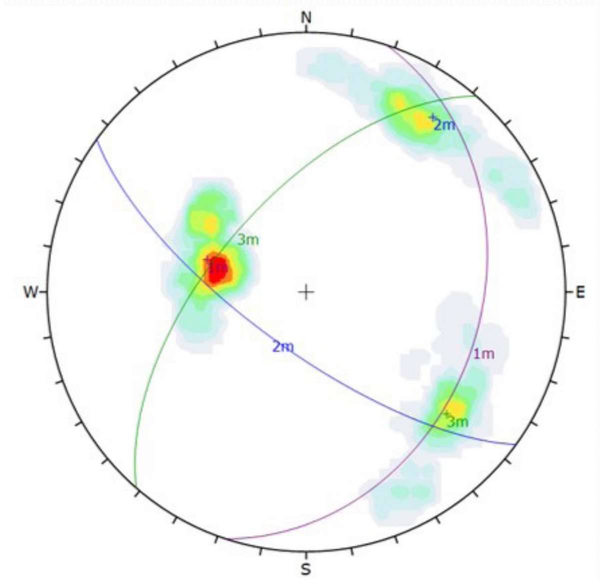
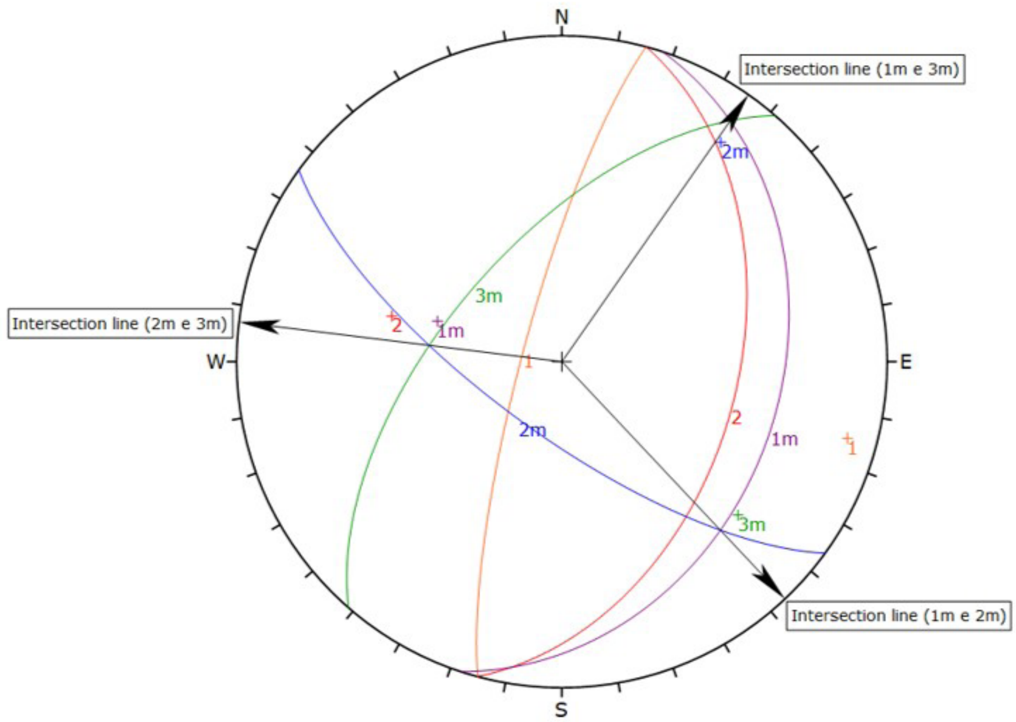


Figure 9. Analyzes of: (a) stability and (b) percolation of a dam.



Color	Density Concentrations
	0.00 - 1.40
	1.40 - 2.80
	2.80 - 4.20
	4.20 - 5.60
	5.60 - 7.00
	7.00 - 8.40
	8.40 - 9.80
	9.80 - 11.20
	11.20 - 12.60
	12.60 - 14.00
Contour Data	Pole Vectors
Maximum Density	13.51%
Contour Distribution	Schmidt
Counting Circle Size	1.0%
Plot Mode	Pole Vectors
Vector Count	74 (74 Entries)
Hemisphere	Lower
Projection	Equal Area

Figure 10. Representation of discontinuities grouped into families.



	Color	Dip	Dip Direction	Label
User Planes				
1		80	285	
2		45	105	
Mean Set Planes				
1m		33	108	
2m		72	216	
3m		61	311	

Figure 11. Plotting the attitudes of the cutting planes and fracture families.

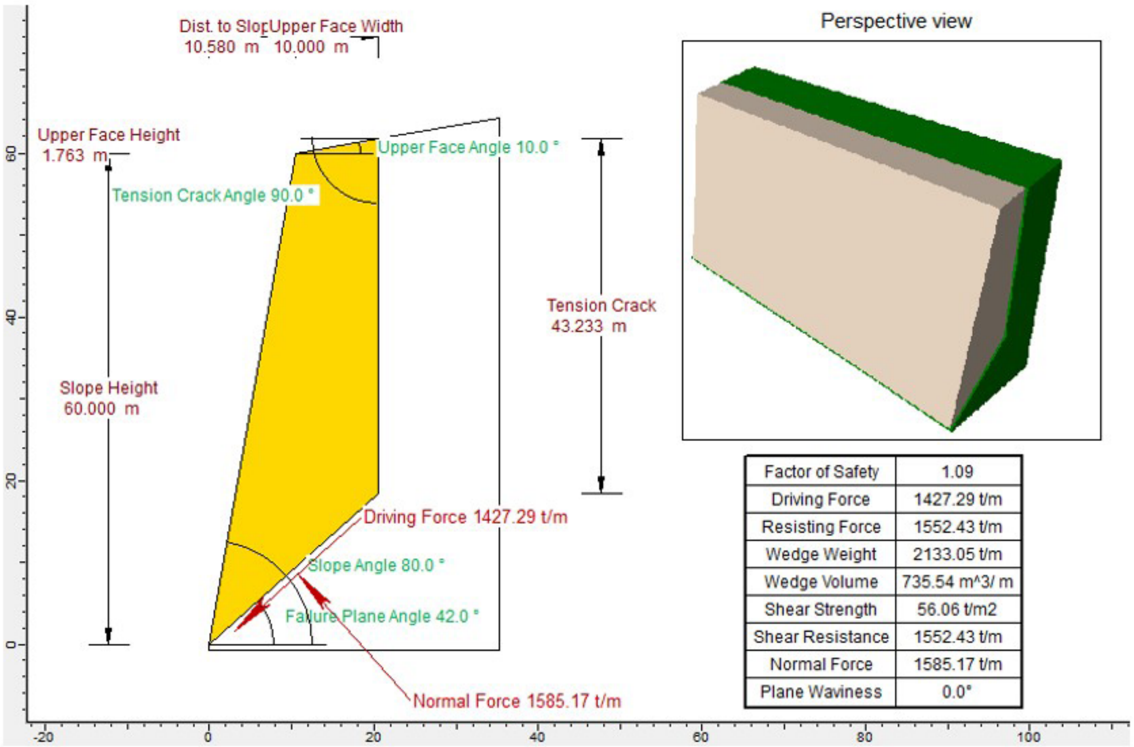


Figure 12. Planar rupture stability analysis in a rock mass.

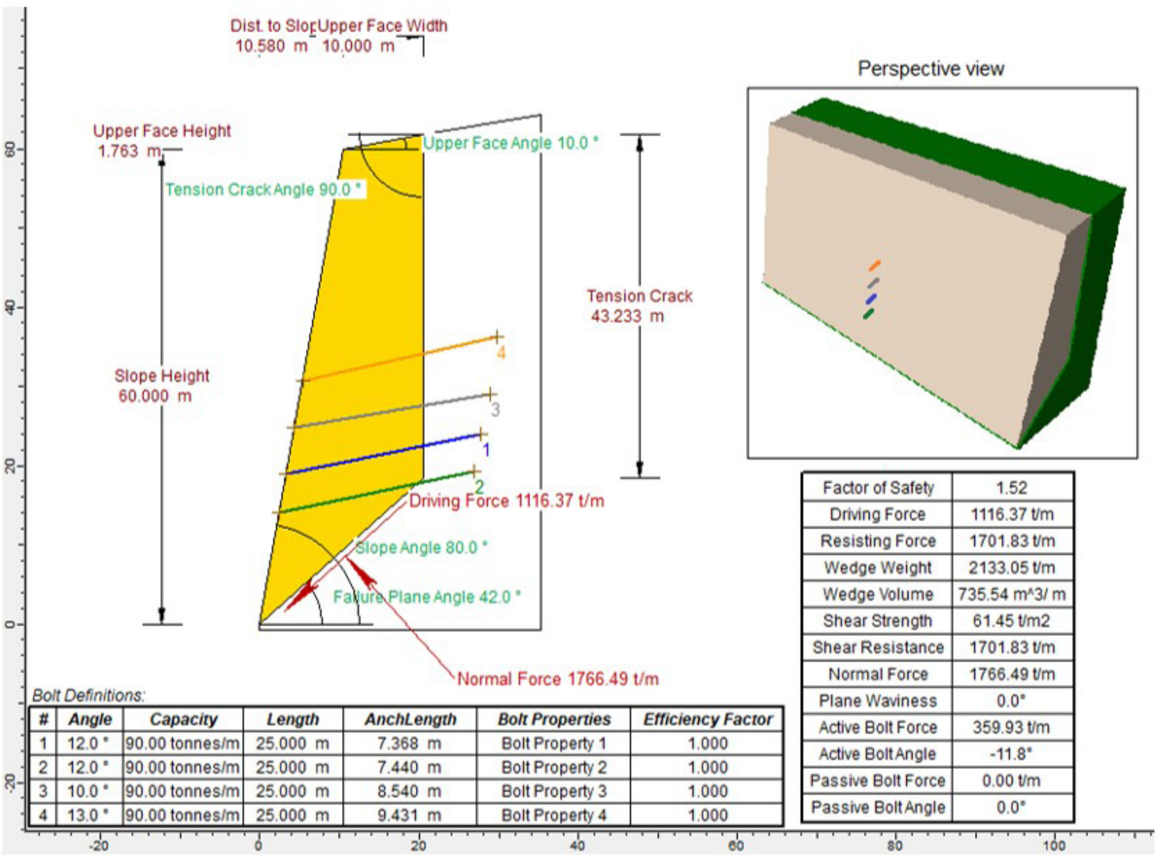


Figure 13. Planar rupture stability analysis in a rock mass with bolts.

Moreover, the use of these software programs allowed for three-dimensional visualization and rapid obtaining of results for the analyses and the optimization of the slopes design in an easy and real manner. Thus, the application of these technologies in the teaching of geotechnics can significantly contribute to the formation of more qualified and prepared professionals to face the challenges of the industry.

3.4 Feedback questionnaire

Based on the feedback questionnaire results, it was found that most students stated that the use of digital tools contributed to their learning in the Geotechnical Engineering disciplines. Among the responses recorded, students affirmed that this practice made the application of studied contents more visible, making the analyses and exercises more efficient, and contributed to the development of skills such as logical reasoning, critical thinking, and problem-solving.

When questioned about the software used, the students highlighted the help of *Excel* and *GeoGebra* in file preparation and analysis, as well as the use of analysis software such as *Slide2*, *Slope/W*, *Seep/W*, and *Dips*, which provide a practical and realistic application of the studied concepts, contributing to better preparation of students for the employment market.

Students were also asked about their perception of a hypothetical situation in which the courses did not use digital tools, and how this could affect their learning process. According to the students, the understanding of contents would be impaired by the difficulty in visualizing and analyzing the information, requiring much more time to understand the problem, and to carry out the activities and facing greater challenges to the treatment of data from laboratory tests.

In addition, the subject teachers and the course coordination stated that they have been monitoring the professional performance of graduates. It has been observed that the skills resulting from the use of these computational tools have been a distinctive factor in the hiring and performance of these professionals by engineering project companies in the fields of Geotechnics and Structures.

Furthermore, as suggestions, some students pointed out the importance of spreading the use of software in other Geotechnical Engineering disciplines, in order to further expand the benefits of their use in the learning process.

4. Conclusion

Based on the topics covered in this paper, it was possible to conclude that the use of softwares and other digital tools in the teaching-learning process in geotechnical engineering is a very important and efficient strategy, promoting active and dynamic learning and a deeper understanding of the theoretical and practical concepts studied.

The use of the “Soil Physical Indexes” application, used in the “Soil Mechanics I” course, allowed students to review and exercise the knowledge learned during the classes. In addition, the use of some tools on Excel for the “Soil Mechanics II” discipline was very important for interpreting results of direct shear tests, while *GeoGebra* contributed to better visualization of the Mohr-Coulomb diagram and for determining the soil shear strength. The use of these tools made it possible to demonstrate the influence of changing values in certain equations in a more effective way, saving the time that would be required with manual calculations.

In the disciplines “Earthworks” and “Earth and Rockfill Dams”, the use of slope stability software enabled the learning of stability and percolation analysis in slopes, earthworks with containment structures, and earth and rockfill dams. These technical skills developed are essential for conducting real projects in geotechnical engineering and are widely used in the market, providing better preparation for students to work in the industry.

The use of kinematic and rock mass stability analysis software in the courses “Engineering Geology” and “Introduction to Rock Mechanics” allowed for the evaluation of the orientation of fractures present in the analyzed rock masses, with three-dimensional visualization of the analyses and obtaining results more efficiently. Additionally, the proposed activities enabled students to suggest possible engineering solutions for cases where the safety factor was not satisfactory, depicting a very common situation in the practice of geotechnical engineering.

The results obtained through the feedback questionnaire applied to the students indicated that the use of digital tools in Geotechnical education significantly contributed to the students’ learning process. According to the collected responses, the software used helped to make the application of the studied concepts more visible and improved the students’ skills. Furthermore, the students pointed out that the lack of these tools could impair their understanding of the contents, increasing the time required to perform the activities. As a suggestion, some students highlighted the importance of spreading the use of software to other disciplines in the area of Geotechnics.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors’ contributions

Carolina Crissafe dos Santos Lemos: conceptualization, data curation, visualization, writing – original draft. Luiz Otávio Fontes Dias: conceptualization, data curation, visualization, writing – original draft. Paulo Sérgio de Almeida Barbosa: software, supervision, validation, writing – review & editing. Eduardo Antonio Gomes Marques: supervision, validation, writing – review & editing. Roberto Lopes Ferraz: supervision, validation, writing – review & editing. Gustavo Henrique Nalon: methodology, software.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

a	Rupture envelope intercept
e	Void ratio
n	Porosity
r_f	Loading ratio
w	Moisture content
INA	Water level indicator
K	Thrust coefficient
P_s	Dry sample weight
PZ	Piezometer
UFV	Federal University of Viçosa
V	Total sample volume
α	Rupture envelope inclination angle
Δ	Variation
ε_h	Horizontal deformation
ε_v	Vertical deformation
ϕ	Angle of friction
γ	Natural specific weight
γ_d	Dry apparent specific weight
γ_s	Specific weight of grains
σ_1	Major principal stress
σ_3	Minor principal stress
τ	Shear stress

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Forks in the road: decisions that have shaped and will shape the teaching and practice of geotechnical engineering

Rodrigo Salgado[1#]

Article

Keywords
Piles
Geotechnical engineering
Education
Mohr-Coulomb and Tresca yield criterion
Dilatancy
Critical state soil mechanics
Machine learning
Discrete Element Method
Artificial Intelligence
Offshore wind energy

Abstract

Geotechnical engineering spans a wide range of applications, including tunnels, foundations, dams, and retaining structures. It deals with a material known to be difficult to model: a particulate material whose mechanical response is affected by all three invariants of the stress tensor, by loading rate, by density and by fabric. New problems and greater complexity in old problems have come about with the effects of climate change. Progress in certain technologies—notably artificial intelligence—also defines the new landscape in which geotechnical engineers must operate. This paper focuses on mechanics-based geotechnical engineering applications. The paper reviews some of the major decisions that were made by the engineers and researchers who developed geotechnical engineering to the point at which it was an identifiable separate discipline and the consequences that these decisions have had on the development of the discipline and on its teaching. The paper identifies some key modelling choices that were made that have had an undeservedly disproportionate impact on the teaching and practice of geotechnical engineering. The focus of the paper is therefore on these decisions and choices, and what should be taught in their place today. Challenges that future geotechnical engineers may face, as well tools that will be available to them, are also discussed in the context of what should be taught in undergraduate and graduate courses.

1. Empiricism, science and geotechnical design

1.1 The pre-science days

Construction in, on or with soil is nothing new: we have been building structures of the most varied types for millennia. One might infer from this that geotechnical engineering, which is the engineering of structures or systems of which soil is an integral part, would be a settled subject. However, the fact that we can design and construct does not mean that we do these things as well as we could, and it does not mean that the models that we use in analysis and design are correct.

In any type of activity, improved processes and products result from trial and error, but only up to a point. This attempt to arrive at better ways of doing things without a full understanding of the factors at play and their interrelationships is known to us as empiricism, and progress can at times be painful. An interesting twist in how both individuals and populations learn and add to knowledge in an empirical manner resulted from the development of the World Wide Web, the internet, and smart search engines. The combination of these three technologies, and the access by a large fraction of the Earth's population to them has given people much more access to knowledge and the possibility of experimenting with knowledge they find online, keeping what works, and discarding what does not. Whereas individuals in their daily lives and people working in the trades have benefited from the rapidly accumulating body of easily accessible specialized knowledge, it is possible to argue that the same is not true of a profession, which geotechnical engineering is. There are two reasons for this. One, common to all professions, is that new knowledge and its transmission are curated with a higher level of formality in professions. For a profession like geotechnical engineering, another reason for this is that, at least for the more challenging projects, the engineering profession today must rely on science, and science cannot be found or taught or developed so easily and so loosely. There is a method to science, and not to rely on science would take us back a hundred years, when results in terms of economy and safety were far from satisfactory.

There is a common misconception that all engineering done before the advent of science was conservatively done. The inference seems to be common-sensical, because it would be natural to proceed cautiously when one does not know very well what one is doing, i.e., when one is proceeding by trial and error. Ancient structures, with their robust pillars and

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arches, also convey this impression that we have always built conservatively. However, that has not necessarily been so. While cases of serious engineering failures would not have appeared in geotechnical scientific journals – because they, as such, did not exist before the first half of the 20th century – we can still learn about how things could go wrong in the pre-science days of geotechnical engineering by referring, for example, to court decisions. An interesting case is that of *Stees v. Leonard*. Here is an excerpt of a pertinent part:

> The action was brought to recover damages for a failure of defendants to erect and complete a building on a lot of plaintiffs, on Minnesota street, between Third and Fourth streets, in the city of St. Paul, which, by an agreement under seal between them and plaintiffs, the defendants had agreed to build, erect, and complete, according to plans and specifications annexed to and made part of the agreement. The defendants commenced the construction of the building, and had carried it to the height of three stories, when it *fell to the ground*. The next year, 1869, they began again and *carried it to the same height as before, when it again fell to the ground*, whereupon defendants refused to perform the contract. Stees v. Leonard, 20 Minn. 494, 449 (Minnesota Supreme Court, 1874) [emphasis added].

There are other cases like this recorded in court proceedings that show the inadequacy of a trial-and-error approach, which lacks a basis on the underlying science. The number of events is most certainly a multiple of those we can learn about from consulting such records. Starting a geotechnical engineering course with a case history like this and following that with a discussion of the scientific method gives students an appreciation for what the subject is about, its importance, and why science matters.

1.2 The development of the science

The scientific method is the formulation of a hypothesis about some question or problem and then the idealization and execution of experiments to validate the hypothesis. If the hypothesis is properly validated, we have a model, which we can then use to guide further scientific inquiry or the development of engineering design methods.

Until the early 20th century, all that anyone working with soil and rock could count on was empirical knowledge. It was not until scientists like Philipp Forchheimer (whom his student, Karl Terzaghi, later emulated in many respects) started seeking to frame some flow problems as boundary-value problems (Goodman, 1999) that the science of soil mechanics started coming into form. It was a natural step to go from flow problems to consolidation theory, in which flow is coupled with deformation, and that development is credited as the birth of soil mechanics. Although Terzaghi's one-dimensional consolidation theory was imperfect (see Goodman (1999), Salgado (2008), or Salgado (2022b) for an account of why that is so and of the sad events involving Terzaghi and Forchheimer) its flaws were not fatal to its application to a range of practical problems, and it was by no means a misstep. It will not be discussed further in the present paper.

Once consolidation theory was in place, the same general approach—looking for the science to underpin design methods in the incipient engineering discipline that we now call geotechnical engineering—was followed for other problems. Bearing capacity theory, as an example, follows from work done during the industrial revolution on metal indentation (Prandtl, 1920, 1921; Reissner, 1924). This path was by no means easy. Faced with hurdles, the pioneers took detours and made decisions that have had significant implications for how geotechnical engineering is practiced and how it is taught at universities even today.

1.3 Structure of the paper

This paper examines how these difficulties and resulting decisions, many related to how to model the mechanical response of soil, have shaped the development of the discipline and its teaching. Understanding of soil mechanics is vastly superior today. The paper puts forth some ideas regarding key content that should be taught at the undergraduate and graduate level that is consistent with current understanding and that—contrary to opinions sometimes expressed—is easily learned by students. Due to space limitations, the paper covers only three of the fundamental model choices that shaped soil mechanics and geotechnical engineering, but there are more.

The three topics addressed are the use of the Mohr-Coulomb and Tresca yield criteria to model soil shear strength, the use of an associated flow rule with these models, and the neglect of shear strain localization. These choices have guided the development of the discipline and have led to a significant body of work. Among topics not covered are the reliance of analyses on infinitesimal strains, the neglect of fabric effects on material response, and the use of total-stress undrained analyses in clays.

A final topic is the decisions and choices that we, as subject matter experts, are making now and the possible impact that teaching decisions relating to these choices may have on the future of the discipline. This relates, in particular, to the themes that are currently being identified by many researchers as the future of geotechnical engineering: artificial intelligence and analysis of soil as a particulate medium (i.e., a "micro" as opposed to a "macro" approach). But I also briefly discuss three additional timely topics as they relate to geotechnical engineering: mining tailings, climate change and offshore wind energy.

2. The original sin: soil as a Mohr-Coulomb material and clay as a "cohesive" material

2.1 Background

Traditionally, soil, although a particulate material, has been treated as a continuum—a solid, to be more precise.

Solids—when plastic—may experience plastic deformation when their shear strength is exceeded. This strength may depend on the normal effective stress on the eventual plane of shearing, or it may be independent of it. The first type of shear strength is known as frictional; the second type, as cohesive.

To understand why, today, students learn that there are two types of soils—“cohesionless soils” and “cohesive soils”—we must travel back to the 1950s, when the science of soil mechanics was in development. After a relatively successful study of 1D consolidation using the coupling of deformation with flow, Terzaghi and co-workers set about dealing with problems involving shear strength, such as the calculation of the bearing capacity of foundations.

The state of the mechanics of foundations at the time was fundamentally this: little progress had been made in the practice of foundation engineering in the preceding century. We discussed earlier the case of *Stees v. Leonard*, in which a contractor tried, not once, but twice, to erect a building on soil that could not support it. In the lawsuit that followed, they misidentified the cause of the problem, which was a bearing capacity problem, as the existence of “quick sand” at the site. But, even as the understanding that one must design against bearing capacity “failures”—i.e., bearing capacity ultimate limit states—started forming, the means to calculate this bearing capacity lagged behind.

The practice of foundation engineering was to try to build based on prior experience, an experience that was often not applicable to the conditions at hand. In this environment, in which scientific knowledge hardly existed, it is not surprising that Terzaghi believed that “[…] [b]ecause of the unavoidable uncertainties involved in the fundamental assumptions of the theories and in the numerical values of the soil constants, simplicity is of much greater importance than accuracy” (Terzaghi & Peck, 1967, p. 153). This thinking permeated much of Terzaghi’s work at the time, and it is therefore no surprise that he also believed that “[…] [i]n spite of the apparent simplicity of their general characteristics, the mechanical properties of real sands and clays are so complex that a rigorous mathematical analysis of their behavior is impossible” (Terzaghi, 1943, p. 5).

We now know that there are three things that are incorrect in Terzaghi’s two statements. First, simplicity and accuracy are not necessarily antithetical. Something can be both simple and inaccurate, and *vice versa*. To state that something simple but inaccurate is superior to something not simple but accurate does not appear sensible. Second, the mechanical properties of sand and clay are not even apparently simple. Refer to Figure 1 and Figure 2 for stress-strain plots for sand and clay sheared under drained and undrained conditions in triaxial compression. The stress q in the figures is the Mises shear stress (a multiple of the octahedral shear stress). Without an understanding of the mechanics of these soils, it is impossible to make sense of transitions and reversals between contractive and dilative response, of the existence of a peak shear stress to normal effective stress ratio, of the existence of a critical state, or of the transition to a residual strength at large shear strains and sufficiently large normal effective stresses for clays. Lastly, the final part of Terzaghi’s second statement is also (today) incorrect, because researchers are developing fairly rigorous relationships for modeling soil behavior. Monotonic mechanical response is not considered today a challenge to model (see e.g., Chakraborty et al., 2013b; Dafalias & Herrmann, 1986; Li & Dafalias, 2000; Loukidis & Salgado, 2009b; Manzari & Dafalias, 1997; Woo & Salgado, 2015). Figure 1 and Figure 2 show simulations done using an advanced constitutive model that clearly match the experimental response quite well.

Faced with what he deemed an impossibility, it is not surprising that Terzaghi proposed the concepts of an “ideal sand”—a linear elastic, perfectly plastic Mohr-Coulomb type of material with non-zero friction angle and $c = 0$—and an “ideal clay” —a linear elastic, perfectly plastic material following a Tresca yield criterion (Terzaghi, 1943). Terzaghi referred to this material as a “cohesive” material, a term that survives to this day. As to sand, engineers soon started assuming non-zero cohesion also for sand, deviating from the original “ideal sand” concept that Terzaghi had advanced.

So the Mohr-Coulomb yield criterion (Figure 3a) would be used for sand, and the Tresca yield criterion (Figure 3b) would be used for clay. The only way to understand this postulation is to assume that Terzaghi observed increasing strengths for sand tested at increasing confining stresses under drained conditions, but constant strength for clay with increasing *total stresses* when samples were tested under undrained conditions. Based on this limited set of observations, Terzaghi postulated behaviors for soil that are not real. To this, Schofield (1988) later referred as “Terzaghi’s error.” This criticism is tempered by the recognition that the “ideal clay” model turned out to be an effective basis to build a body of analysis for problems involving saturated clay, and that even erroneous models of soil behavior were better than the crude form of knowledge available in those days. Additionally, the greater harm concerning sands was the subsequent use of a Mohr-Coulomb material with nonzero cohesion for sand, rather than the original ideal sand concept. Consequently, some viable theories have evolved from these simple “ideal” soil models, but the failure to accurately describe the sources of shear strength in soils remained.

2.2 The error

We have argued that Terzaghi’s “ideal sand” and “ideal clay” models led to an erroneous description of soil behavior. This is true even if one is simply interested in calculating shear strengths and has no interest in realistically simulating any other aspects of behavior. But why is it so? For the answer, we look to plasticity theory.

Perhaps nothing has been as damaging to the teaching of soil mechanics than the notion that soil can generally be considered

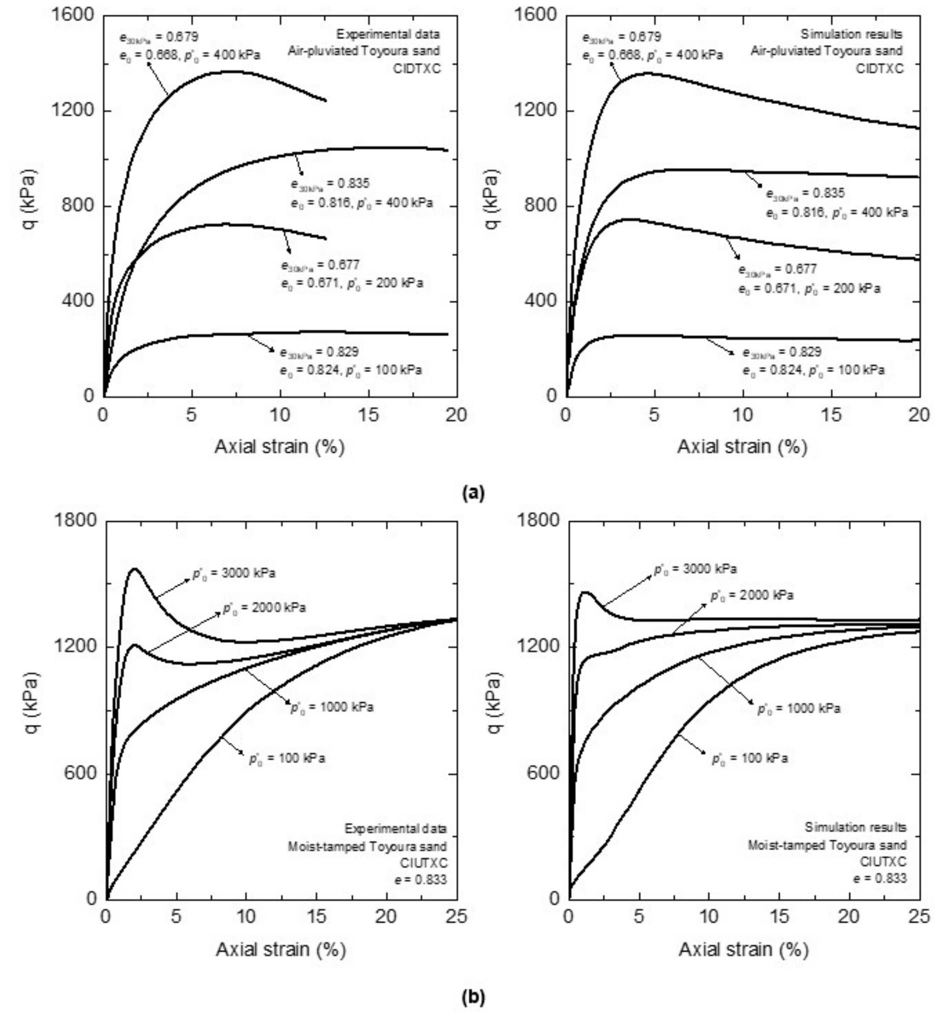


Figure 1. Results of triaxial compression tests performed on sands (left) and respective simulations (right): (a) drained; (b) undrained (Woo & Salgado, 2015).

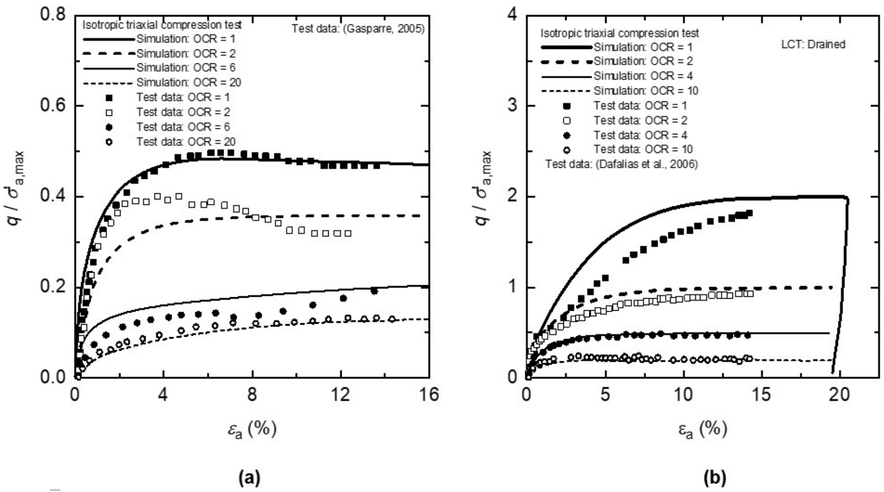


Figure 2. Results of triaxial compression tests performed on clays: (a) undrained (b) drained (Chakraborty et al., 2013b; Dafalias et al., 2006; Gasparre, 2005).

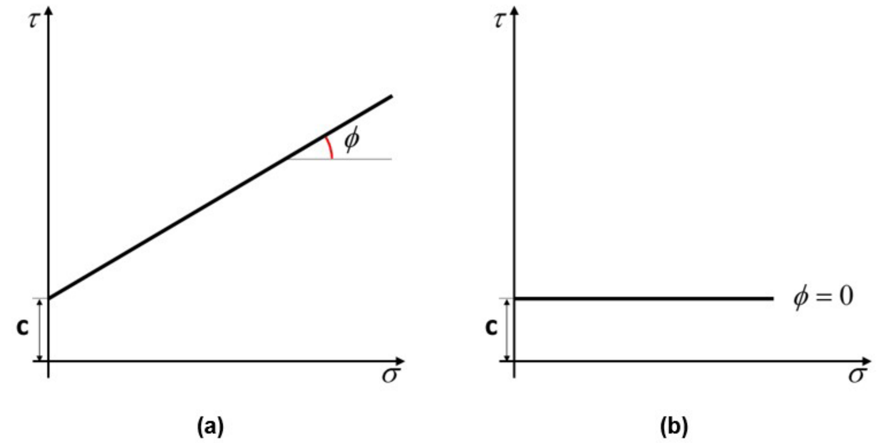


Figure 3. Relationship between normal and shear stresses for (a) a Mohr-Coulomb material, idealized in the 1950s as an "ideal sand" if *c*= 0 and (b) a Tresca material, idealized in the 1950s as an "ideal clay".

to follow the Mohr-Coulomb yield criterion. A material that follows the Mohr-Coulomb yield criterion experiences plastic strains only when the stress state satisfies the relationship:

$$F = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3)\sin\phi - 2c\cos\phi = 0 \quad (1)$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively. The function F of stresses is referred to as the yield function, and $F = 0$ is referred to as the yield criterion. The parameters ϕ and c are the friction angle and the cohesion, respectively, of the material. Terzaghi's ideal sand has non-zero ϕ and $c = 0$, and the ideal clay has zero ϕ. As discussed earlier, in later work, engineers abandoned the original concept of zero c in sand and started using nonzero c and ϕ to describe sand. No explanation was provided for the source of what should amount to a frictional strength component and a stress-independent (frictionless or cohesive) strength component. What this step left both educators and practitioners with was a model that was not based on an understanding of soil behaviour, since ϕ and c were the starting point of the analysis, that is, the model fundamental parameters.

Unfortunate implications of this paradigm were the misunderstanding that clean, uncemented sands could have non-zero c, and that clays had a constant c, a result directly implied by the "ideal clay" model. Initially, educators taught students that a set of tests had to be done at more or less the "appropriate" level of effective stresses, and straight-line fits to the corresponding data points would yield the correct values of ϕ and c. This presented a variety of questions, one of which regarded the applicable level of effective stress for a problem in which the soil experiences a wide range of stress levels, as in the bearing capacity problem. In some of these problems, stresses can be as high as several or even tens of megapascals. Clearly, performing shear strength tests at these elevated stress levels was not realistic.

Fortunately, even as Terzaghi made these influential choices, others (e.g., Taylor, 1948) were attempting to understand what the real sources of shear strength were. Taylor laid the foundation for what would later be known as critical-state soil mechanics. In this framework for the mechanics of soil, soil is a frictional material capable of volume change; a second source of shear strength results from this dilative response.

2.3 What should be taught instead

What emanated from the studies of Roscoe et al. (1958), Schofield (2006), Taylor (1948) and others was the understanding that soil is always a frictional material. In the absence of cementation, a fully saturated or completely dry soil derives its strength exclusively from friction if under sufficiently high confining stress and/or sufficiently low density (see, e.g., Salgado 2022b). Although beyond the scope of this paper, current understanding of the mechanical response of unsaturated soil also points to suction being translated into a greater effective stress, with correspondingly greater frictional strength. If either density is sufficiently high or effective stress is sufficiently low, soil also derives its strength from dilatancy.

It follows that, whether teaching at the graduate or undergraduate level, we should teach our students that soil takes its strength from two sources: friction and dilatancy. It is essential to stress that unstructured soil (soil without cementation or any source of extraneous cohesion) is frictional, lacking cohesion. A good starting point for this discussion is plastic deformation in the absence of any tendency to change volume: the so-called critical state. Surprisingly, based on anecdotal evidence, this is a concept to which undergraduate students are often not exposed. The concept is, however, easy to teach. The easiest way to teach it is to show students that the critical state is simply a purely frictional state. At critical state, the soil derives its strength from the frictional strength between soil particles, there being no other source of shear strength. And frictional strength only exists in the presence of non-zero effective normal stress.

It is sometimes surprising to students who have somehow learned otherwise that even clays are purely frictional materials. An example that can be used to get this last point across is that of a clay deposit forming at the bottom of a lake (Salgado, 2022b). It is easy for students to understand that the soil right at the surface of the bottom of the lake, composed of particles that have recently deposited out of water, lacks shear strength. The reason for that is that the clay there is essentially a slurry: it is under zero effective stress and has a very high void ratio. In the absence of nonzero normal effective stress, that clay has zero shear strength because it is a frictional material. An example for sand that can be given, to which undergraduate students can easily relate, is that someone picking up some sand on the beach can easily manipulate the soil, for it lacks strength, and it lacks strength because it is under nearly zero normal effective stress.

The other component of shear strength is due to dilatancy, which can best be explained by referring to a figure such as Figure 4, which shows that spherical particles that are closely packed must separate in the direction normal to that of shearing. This separation must occur against an existing normal effective stress, which requires work to be done. Where does the work come from? From the applied shear stress. So, the applied shear stress must overcome not only frictional strength to cause the material to deform plastically, but also this confining stress opposing the required soil dilation.

These two concepts are easy for students to understand. This basic understanding of the physical processes underlying shear strength development in soil can then be used throughout their course of study of geotechnical engineering applications (retaining structures, foundations, slopes and other structures), and should effectively inoculate them against the flawed concepts of "cohesive" or "cohesive-frictional" soils. From that point on, students will understand that soils are truly potentially dilative, frictional materials.

At the undergraduate level, one of the easiest ways to teach how dilatancy works is to use the Bolton (1986) friction angle calculation framework for sands. This work has been extensively referred to and has been extended to apply to sands with fines (see, e.g., Carraro et al., 2009; Salgado et al., 2000) and sands at low confining stresses (Chakraborty & Salgado, 2010). Concisely, for a sand, the peak friction angle ϕ_p is written as the summation of a critical-state friction angle ϕ_c and an angle due to dilatancy:

$$\phi_p = \phi_c + A_\psi I_R \tag{2}$$

where A_Ψ is a parameter in Bolton's equation having value of 3 for triaxial conditions and 5 for plain-strain conditions, and I_R is the relative dilatancy index given by:

$$I_R = I_D (Q - \ln p') - R \tag{3}$$

where I_D is relative density, p' is the mean effective stress and *Q and R* are fitting parameters.

This is essentially the approach that I follow in my geotechnical engineering text (Salgado, 2022b). In the introductory soil mechanics course, I follow a Socratic approach in in-person sessions combined with a variety of content delivery methods (such as reading assignments, video lectures and problem-solving sessions) and assessment methods (including quizzes; laboratory reports and laboratory quizzes; exams; and a term project). The use of the Socratic sessions in which everyone participates during the semester allows verification that the students have been able to learn these concepts quite well.

At the Ph.D. level, one must go much beyond this. It is important then to cover constitutive modeling (mainly the most recent models, such as bounding-surface or two-surface models) and particle-based methods.

3. Compounding the original sin: reliance on the associated flow rule

3.1 Background

The teaching of geotechnical engineering tends to emphasize stresses, but strains are just as much a part of the solution to any boundary-value problem in geomechanics. The only exposure that students seem to get to strains is through stress-strain plots typically shown or obtained in the laboratory and through the coverage of consolidation. A standard discussion surrounds the facts that loose sands

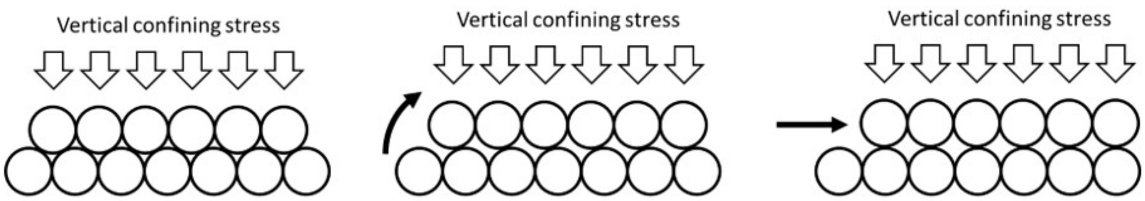


Figure 4. Particle climbing action for densely arranged particles (Salgado, 2022b).

contract or dilate less than dense sands and that dense sands may contract initially, but then end up being ultimately dilative. Strains are typically not linked back to stresses with any rigor, and that is sometimes true even at the graduate level. Yet, this link is crucial to the modeling of the mechanical response of soil.

The relationship is rather obvious to students in the context of elasticity. There is a general sense that application of a stress increment leads to a strain increment, and that its removal returns the body to its original configuration. When it comes to plasticity, matters turn more complex.

The rate of the plastic strain tensor in classical plasticity models is obtained from the plastic flow rule:

$$\dot{\varepsilon}_{ij}^{p} = \dot{\lambda}\frac{\partial G}{\partial \sigma_{ij}} \tag{4}$$

where i and j are indices taking values 1, 2 or 3; σ_{ij} are the six components of the (symmetric) stress tensor; $\dot{\lambda}$ is the plastic multiplier; and G is the plastic potential, a function of the stress tensor:

$$G = G(\sigma) \tag{5}$$

Given that there are six independent stress components, Equation 4 states that the plastic strain increments or rates are determined by a six-dimensional surface defined by Equation 5. The meaning of the term $\partial G/\partial \sigma_{ij}$ is that of a gradient in that space. This can best be visualized if we represent the stress tensor using its three principal stresses, in which case we are able to represent these equations in 3-dimensional space (see Figure 5). The gradient can then be visualized as being normal to the 3-dimensional surface defined by Equation 5. This visualization of a 6-dimensional process in 3-dimensional space can only be taken so far, as discussed by Woo & Salgado (2014).

If the gradient is aligned with the σ_1 axis, for example, that means that only the ε_1 strain component will change, with $\dot{\varepsilon}_2 = \dot{\varepsilon}_3 = 0$. So $\partial G/\partial \sigma_{ij}$ determines the proportion or ratio between each pair of strain rate components.

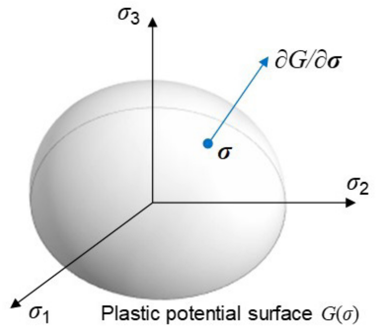


Figure 5. Plastic potential surface represented in principal stress space and its stress gradient, which enters the formulations of the flow rule.

In metal plasticity, which developed considerably during the industrial revolution, it was observed that there was no plastic volume change during plastic deformation. Although we don't show this here, this leads to the result that plastic strain rate is normal to the yield surface given by Equation 1 if plastic strain rates are plotted in the same space (with a separate scale) as stresses. This led to the adoption of what we now call an associated flow rule for the plastic strain rate, where F is used as the plastic potential:

$$\dot{\varepsilon}_{ij}^{p} = \dot{\lambda}\frac{\partial F}{\partial \sigma_{ij}} \tag{6}$$

If we are working with clays using total stresses in undrained loading simulations, we are in effect using Terzaghi's "ideal clay" model. There is then no volumetric strain, and Equation 6 is applicable. In drained simulations or effective-stress simulations, an associated flow rule does not apply. This can be observed by performing experiments and observing the lack of normality between the plastic strain rate and the yield surface. However, it is important to understand what the fundamental error of use of an associated flow rule is in those cases.

3.2 The error

A material undergoing plastic deformation (yielding), in contrast with only elastic deformation, dissipates energy. We can think of energy dissipation as the energy that has to be expended to change the material internally (i.e., to permanently deform it in some manner). The rate of plastic energy dissipation D_p per unit volume for infinitesimal-strain plasticity is given by:

$$D_p = \sigma_{ij}\dot{\varepsilon}_{ij}^{p} \tag{7}$$

where σ_{ij} is the stress, and $\dot{\varepsilon}_{ij}^{p}$ is the time rate of plastic strain.

Taking Equation 1 and Equation 6 into Equation 7, we obtain the following for the rate of plastic dissipation:

$$D_p = \dot{\lambda}[2c\cos\phi] \tag{8}$$

What Equation 8 tells us is that the rate of plastic energy dissipation is entirely due to the existence of a cohesion c. If $c = 0$, then no energy is dissipated during plastic flow. If we think of sand in realistic terms, it has no cohesion. So Equation 8 is telling us that the shearing of sand does not require energy dissipation, which we know to be incorrect. This result is also baffling to the typical graduate student. How can a cohesive-frictional material—that is what a Mohr-Coulomb material is supposed to be—dissipate no energy upon plastic deformation when $c = 0$? Is friction not intricately linked to energy dissipation?

The inescapable conclusion is that the use of the Mohr-Coulomb yield criterion with an associated flow rule to model real soils in effective-stress analysis is simply wrong. Sand, loaded under drained conditions, which corresponds to the vast majority of applications involving sands, cannot be modeled with a Mohr-Coulomb model even as an approximation, unless a flow rule that is not associated is used. Unfortunately, drained analysis with a Mohr-Coulomb material and an associated flow rule is what a large body of work in geotechnical engineering is based on. This is the content that many geotechnical engineering students get in the classroom, likely without elaboration about the limitations of the concepts.

3.3 What must be taught instead

If one must use the Mohr-Coulomb model, it is important not to teach any of the theories in which an associated flow rule was assumed and, where needed, stress that the flow rule for a Mohr-Coulomb material cannot be associated if realism is to be achieved. This difference is far from just conceptual, with important numerical consequences.

Consider, for example, the bearing capacity problem in sand. The unit bearing capacity q_{bL} in sand can be seen as the summation of two terms:

$$q_{bL} = q_0 N_q + \frac{1}{2}\gamma B N_\gamma \tag{9}$$

where q_0 = overburden stress, γ = unit weight, and N_q and N_γ are bearing capacity factors. We ignore any depth correction factor that might be incorporated into Equation 9 for the purposes of the discussion that follows. The classical equations for the two bearing capacity factors are:

$$N_\gamma = 1.5\left(N_q - 1\right) tan\ \phi \tag{10}$$

and

$$N_q = \frac{1+\sin\phi}{1-\sin\phi} e^{\pi \tan\phi} \tag{11}$$

Equation 10 is due to Brinch Hansen (1970), who proposed it based on results from the method of characteristics. The method of characteristics assumes an associated flow rule, as does most of the work published using limit analysis. We now know that these two equations cannot be correct, for sand does not follow an associated flow rule. How innacurate are the results? We can answer this by referring to the equations proposed by Loukidis & Salgado (2009a) for a sand with a non-associated flow rule:

$$N_q = \frac{1+\sin\phi}{1-\sin\phi} e^{J(\phi,\psi)\pi \tan\phi} \tag{12}$$

and

$$N_\gamma = \left(N_q - 1\right)\tan(1.34\phi) \tag{13}$$

where J is a function given by

$$J(\phi,\psi) = 1 - \tan\phi\left[\tan(0.8(\phi-\psi))\right]^{2.5} \tag{14}$$

and ψ is the dilatancy angle.

The dilatancy angle in simple shear loading is defined as:

$$\sin\psi = -\frac{\dot{\varepsilon}_{\mathrm{v}}}{\dot{\gamma}_{\max}} \tag{15}$$

where $\dot{\varepsilon}_v$ is the time rate of volumetric strain and $\dot{\gamma}_{\max}$ is the rate of the maximum shear strain.

The dilatancy angle is a measure of how much volumetric strain results from shearing of the material. A flow rule associated with the Mohr-Coulomb yield function leads to $\psi = \phi$. It is more realistic for sands to assume $\psi < \phi$. This would correspond to a non-associated flow rule. Figure 6 illustrates the impact that the choice of an associated instead of a non-associated flow rule has on engineering computations related to the bearing capacity problem. The figure shows value of N_γ resulting from realistic pairings of ψ and ϕ and from $\psi = \phi$. Values for $\psi = \phi$ significantly exceed values for $\psi < \phi$.

How much difference does the choice of flow rule make in the calculation of the bearing capacity of a footing? Let us consider the bearing capacity factors and the limit bearing capacity q_{bL} of strip footings calculated using the two sets of equations. As an example, we take a friction angle ϕ = 45°; dilatancy angle ψ = 45° and 18°; and unit weight of sand = 19 kN/m^3. Table 1 presents the computed bearing capacity factors—N_γ and N_q—and the bearing capacity q_{bL} of two strip

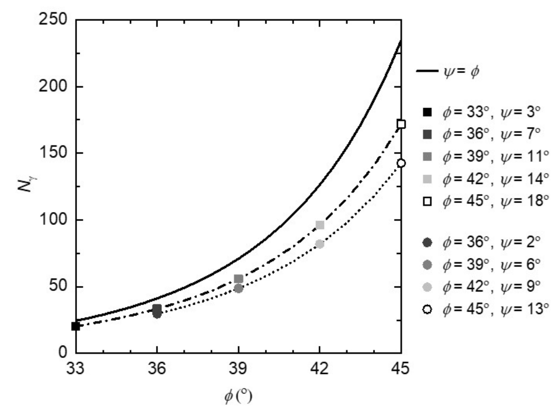


Figure 6. Comparison of values of bearing capacity factor N_γ calculated based on the assumption of associated flow ($\psi = \phi$) with values calculated based on non-associated flow ($\psi < \phi$).

Table 1. Effect of flow rule non-associativity on bearing capacity of strip footings: results of calculations using Equations 12 and 13.

Flow rule	ϕ (°)	ψ (°)	N_q	N_γ	q_{bL} (kN/m²)			
					embedment = 0 m		embedment = 1 m	
					B = 1 m	B = 2 m	B = 1 m	B = 2 m
Associated	45	45	135	235	2230	4459	4792	7022
Non-associated		18	99	172	1631	3262	3511	5142

footings with width B = 1 m and 2 m, with an embedment of 0 m and 1 m, with the depth factor on the overburden term of the bearing capacity equation neglected.

The resulting bearing capacity for footing on the surface of a deposit of the material following the associated flow rule is 37% greater than that calculated for a material following the non-associated flow rule. This very significant overestimation of the bearing capacity of a strip footing resulting from use of the associated flow rule is an error that is unconservative. Given the nature of shallow foundation design, with serviceability controlling in the majority of design cases, this error is not as consequential to final design as it otherwise would be.

This simple example, for one of the classical problems of soil mechanics, illustrates the level of error resulting from use of theories based on a Mohr-Coulomb material following an associated flow rule. Ideally, these would not be taught but for providing historical perspective. The teaching of methods of analysis and design that rely on realistic soil models would be the best approach, and it is possible in many instances. Failing that, whenever the Mohr-Coulomb yield criterion is used, it must be used with a non-associated flow rule.

Lastly, use of a non-associated flow rule does not heal the defects of a model relying on the Mohr-Coulomb yield criterion. The model is still exceedingly simple—having constant ϕ and ψ—and will not be realistic for calculations requiring a higher degree of realism. In such cases, use of a more sophisticated constitutive model is required.

4. Shear strain localization and its implications

4.1 Background

In undergraduate laboratory classes, students typically see or perform triaxial tests on dense sand specimens; they observe the resulting "failure plane" that eventually develops through the specimen. In most classrooms, that observation leads to nothing more, but it should. That is the best time to make a number of crucial points that are today essential for a well-rounded geotechnical engineer to understand.

The first important point regarding that "failure plane" is that it is not a plane at all. The second is that "failure" is too vague a term, and it confuses students to use it. It is better to speak of what has happened as the shearing of the sand or, if one is especially attached to the word, as a shear "failure" of the sand specimen. Back to the first point, today it is possible to show to students videos taken of the shearing of sand. In videos of the shearing of sands, we can clearly see that a band of particles, with thickness of the order of 5 to as many as 10 particle diameters, is what constitutes that "plane." The "plane" is what we know today as a shear band.

Shear bands in soil have been studied as early as the 1970s (Vardoulakis et al., 1978). It is however very important to teach students this for the following reason: a plane is an abstraction from which no pattern of soil behavior can be inferred, but a band, containing a number of soil particles, has a behavior that results from the interactions of the particles in it. This interaction of particles in the band directly produces the constitutive behavior of the soil. Once students understand this, it is much easier for them to understand how shaft resistance develops along a pile or why the pressure on a retaining wall is what it is.

The localization of shearing in a band results from the mechanical behavior of soil: from the softening, i.e., loss of shear strength that occurs with the progression of shearing. With continuing shearing, the soil will tend to weaken at the location where this process first starts, shear strain then localizes there, sparing regions surrounding the band of further deformation. It is vital to understand this process because any simulations that we attempt of boundary-value problems involving such materials depend on correctly capturing the width of the shear bands. Mechanicians speak of the "length scale" of the material as determinative or intrinsically linked to the material behavior.

Shear bands are also seen in soils following a Mohr-Coulomb yield criterion with c = 0 if they also follow a non-associated flow rule. This is closely linked to the fact that, in these materials, plastic energy does dissipate—due to friction—once plastic shearing starts. It is then natural for shearing to continue where it started instead of diffusing to surrounding regions, because that would require greater plastic energy dissipation.

Shear band thickness depends on essentially two factors: (1) soil particle size, and (2) the boundary conditions for the shear band (that is, does it form entirely within the soil or at an interface between the soil and a structural element). If the interface is rough, the shear band thickness will be of the order of the thickness that forms entirely within soil; however, if the interface is smooth, there is no shear band that forms along the interface: there is only clean sliding of the interface with respect to the soil (Tehrani et al., 2016; Tovar-Valencia et al., 2018). Images of strain localization can be collected through an exposed (transparent) window that allows visualization of soil during loading or, for small specimens, through X-Ray CT (e.g., Desrues et al., 2018). In approximate terms, shear bands in sand are of the order of 5 times the mean particle size for rough interfaces (Tehrani et al., 2016; Tovar-Valencia et al., 2018) to the order of 10 times the mean particle size for shear bands entirely contained in soil (Alshibli & Sture, 1999).

The simplest examples of localization and its impact on the solution of a boundary-value problem can be seen in the context of axially loaded piles, for which localization is known *a priori* to occur along the pile shaft (Han et al., 2017, 2018; Loukidis & Salgado, 2008; Salgado et al., 2017). Figure 7 shows the results of finite element analyses of an axially loaded pile in sand modelled using an advanced constitutive model in terms of the ratio K of the lateral effective stress on the pile shaft to the initial (free-field) vertical effective stress during shearing (Loukidis & Salgado, 2009b).

Knowing K from a battery of finite element analyses, we can compute pile limit unit shaft resistance q_{sL} using:

$$q_{sL} = K\sigma'_v \tan\delta \tag{16}$$

where δ = friction angle of the pile-soil interface. It is seen in the figure that the shaft resistance calculated for a pile depends on the width of the finite elements used immediately next to the pile. As the finite element simulation progresses, shear strain localizes next to the pile in that "column" of elements. Consequently, the shear stress along the pile shaft at any given level of pile settlement depends on the response of that band of soil and how it responds to shearing. Pre-knowledge of what the shear band thickness is in a soil allows the correct calculation of the shaft resistance of the pile. The alternative is more difficult: use of a constitutive model and computational method that inherently have the correct length scale so that the correct final shear band pattern and thickness will emerge.

Pile loading is far from the only problem in which shear strain localization is observed. On the contrary, it is pervasive. It appears in slope failures, behind retaining walls, beneath footings and in other applications at loading stages that would correspond to ultimate limit states or even serviceability limit states (Salgado, 2022b). Shear bands also insure that the critical state is often reached in boundary-value problems of interest, because shear strains in them can be quite large even if boundary displacements are not.

4.2 The shortcoming of not considering shear strain localization

Students are often inundated with coverage of "elastic soil" or elasto-plastic soil following the Mohr-Coulomb or Tresca yield criteria. These are often observed in naïve use of commercial finite element software. An interesting illustration of how analyses using either an elastic soil model or an elasto-plastic soil model without realistic representation of shear strength, strain softening and strain localization fall short comes again from foundation engineering.

Traditional models of pile group interaction relied on modeling soil as an elastic material that transferred stresses between piles in a pile group (Poulos, 1968; Randolph & Wroth, 1979). This work was groundbreaking in highlighting for the first time the interaction between piles in a pile group and the capacity of that group, but led to pile interaction and

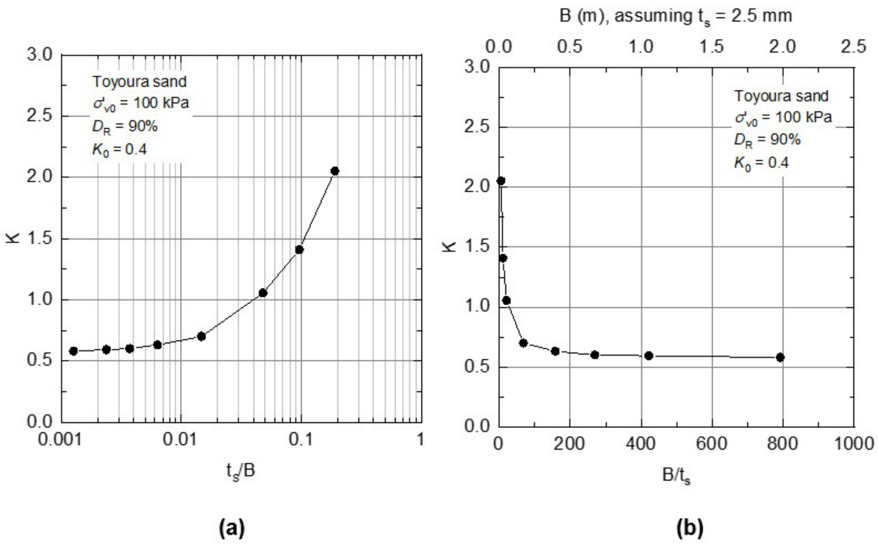


Figure 7. Effect of ratio of shear band thickness t_s to pile diameter B on the ratio K used in the computation of shaft resistance (Salgado et al., 2017): (a) K vs. t_s/B and (b) K vs. B/t_s.

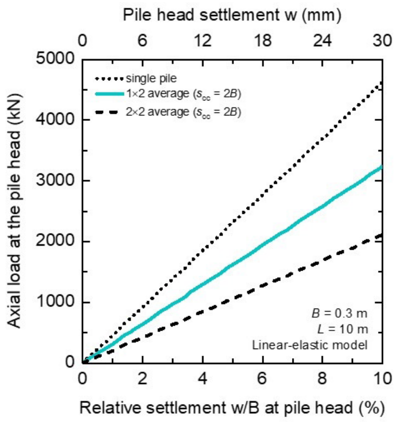
group efficiency coefficients that are unrealistic because the models did not account for strain localization, which significantly reduces interaction between neighboring piles (Han et al., 2019). Figure 8 shows the significant difference in pile interaction within a group and group efficiency resulting from finite element analyses assuming a linear elastic soil, an elasto-plastic soil with a Mohr-Coulomb yield criterion, and a realistic sand model with an appropriately fine finite element mesh. These results show clearly that shear strain localization cannot be ignored if we desire accurate, realistic solutions to geotechnical boundary-value problems.

As a final illustration of the importance of capturing shear strain localization correctly, consider again the bearing capacity problem discussed earlier. Assume that a student or engineer decides to use a modern method of analysis or a commercial computational package to perform calculations for the same problem we discussed earlier. Table 2 shows results for calculations using SNAC (Abbo & Sloan, 2000), OptumG2 (Krabbenhoft et al., 2015) and the material point method (MPM) (Bisht & Salgado, 2018; Woo & Salgado, 2018). The values shown in the table are in reasonable agreement because consistent size for the mesh elements were chosen in these calculations. The SNAC and OptumG2 analyses were done using 15-node triangles with 12-point Gauss quadrature. The MPM analyses were done using Q4 elements with an initial number of material points per element equal to 4 and a B-bar scheme. The MPM analysis with the smallest element size e = 0.025m has approximately the same Gauss point density as the SNAC analysis, and the match between the two is evident. However, use of a coarser mesh, whether in SNAC, OPTUM or MPM would produce higher values of bearing capacity. For example, in the table, MPM with the smallest element size e = 0.1m yields a bearing capacity of 3055 kPa instead of 2241 kPa. This results from the fact that strain localization can only take place to the degree that the mass is discretized. A coarse mesh will lead to thick shear bands and a stiffer response.

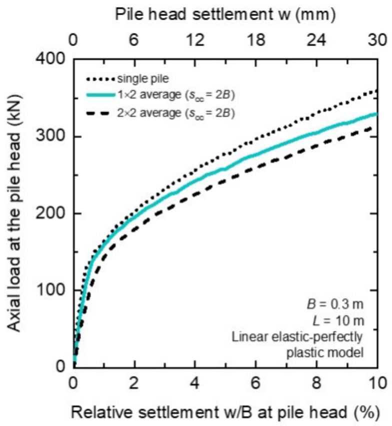
4.3 What should be taught instead

Students should be acquainted with realistic stress-strain relationships under various loading paths, both drained and undrained, and should be provided with the opportunity to understand the role density, initial effective stress, dilatancy, and fabric evolution have in shaping these relationships. When exposed to problems in which shear strain localization occurs, and therefore the stress-strain history before localization is determinative of soil response, it is important to explain this and provide students with solutions and design methods based on analyses that do take localization into consideration.

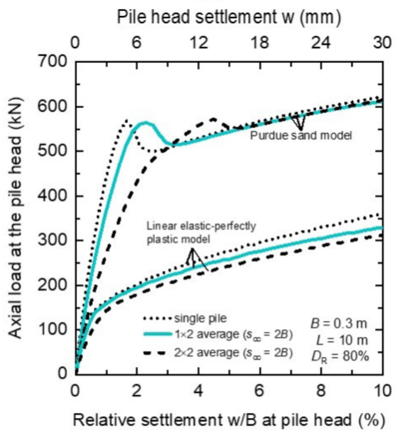
Taking piles again as an example, teaching an analysis that ignores the shear strain localization along the pile shaft will be ineffective in that the value of pile shaft resistance cannot be calculated with any accuracy using such an analysis. Thus, one could teach using directly the results of analysis for piles in sand (e.g., Han et al., 2017; Loukidis & Salgado, 2008) or clay (e.g., Basu et al., 2014;



(a)



(b)



(c)

Figure 8. Load-settlement curves obtained from analyses using: (a) a linear-elastic model; (b) a linearly elastic-perfectly plastic model with the Mohr-Coulomb yield criterion; and (c) the Purdue sand model and the linearly elastic-perfectly plastic model with the Mohr-Coulomb yield criterion (Han et al., 2019).

Table 2. Strip footing bearing capacity computed using different numerical schemes and element sizes.

Flow rule	ϕ (°)	ψ (°)	q_{bL} (kN/m^2) (embedment = 0 m, B = 1 m)				
			SNAC	OptumG2	MPM		
					e = 0.1 m	e = 0.05 m	e = 0.025 m
Associated	45	45	2230	2307	3055	2301	2241
Non-associated	45	18	1631	1646	1924	1650	1611

Chakraborty et al., 2013a) that do account for localization and realistic soil response. For undergraduates, the teaching might consist of presenting the equations, explaining why they were formulated with those particular forms, and then having the students apply the equations directly to design problems. At the graduate level, one could go beyond that, and ask the student to read the papers, reproduce results and apply them to more challenging design problems.

As a final illustration of how strain localization can be included in our teaching, we turn again to the pile group example. It is advantageous to introduce students to these problems using the classical papers assuming linear elastic soil (Poulos, 1968; Randolph & Wroth, 1979), which facilitate understanding of the concepts of group pile interaction and group efficiency, but then share with them new results (Han et al., 2019; Salgado et al., 2017) that show that the interaction between the piles is considerably reduced when shear strains localize along the shafts of the piles.

5. Looking for a future: the modeling of soil as a particulate medium, artificial intelligence, and the pressing challenges of a world under stress

We have so far focused on past decisions that influenced the teaching and practice of geotechnical engineering. These decisions came out of research that focused on how to solve the problems found in the practice of geotechnical engineering. The thrust of past efforts has been to develop the science of soil mechanics: how to model soil as a material and how to solve the boundary-value problems of soil mechanics.

In the last 10-15 years, the volume of research in two areas—particulate mechanics and artificial intelligence applications to geotechnical engineering—has increased considerably. In particulate mechanics, soil is not viewed as a solid, but as a collection of particles. The emphasis is on describing particle interactions and letting these interactions, and possibly any mechanical effects on the particles themselves (such as crushing or breakage), determine the behavior of the overall particle assemblage. The main analysis tool used for this is the Discrete Element Method (DEM) (Cundall & Strack, 1979). The enthusiasm with DEM has led to very optimistic statements about its role in the future of geotechnical engineering. We will briefly examine the current viability of DEM as an analysis tool and potential implications of its adoption in both teaching and practice.

DEM is a model of soil and its mechanical response. In this, it does not differ from all the work that has been done in geotechnical engineering to the present and the modeling decisions we discussed in the previous sections. The decision that some researchers sometimes appear to advocate is to abandon solid mechanics as a vehicle to model soils and embrace DEM or, more generally, particulate mechanics for that purpose. We will examine this specific question in our discussion of DEM.

DEM development is a scientific pursuit, with hypotheses made about soil particle interactions, and predictions obtained using these hypotheses coupled with the established laws of mechanics to solve problems. In contrast, pure artificial intelligence is not a model of soil and its mechanical response. It does not explore the connection between variables through the laws of physics. Physical causation is not part of artificial intelligence methods used so far in geotechnical engineering. Instead, artificial intelligence explores correlations. One may attempt to infer causation from correlation, but that is not an immediate AI result. We will explore the implications of this different paradigm for teaching and practicing geotechnical engineering.

Last in this section, we will discuss the coverage in geotechnical engineering courses of how the discipline fits into certain themes related to a planet affected by the consequences of overconsumption: dealing with mine tailings, designing in the context of climate change, and the development of renewable energy infrastructure. This discussion differs from our previous discussions in that we will not address how to model and solve problems, but instead we will discuss the importance of teaching certain applications in geotechnical engineering courses.

5.1 Explicitly accounting for the particulate nature of soil

The Discrete Element Method was proposed roughly 45 years ago, when it was referred to as the "Distinct" Element Method (Cundall & Strack, 1979). Either way, the acronym "DEM" applies. The essence of the method is to model the transmission of forces at the contacts between particles in an assemblage. Loading can be applied in the same way as in any other problem: through activation of gravity and as tractions on the boundaries of the assemblage.

Instead of constitutive relationships relating stress and strain rates at points within a continuum, DEM relates forces and displacements and rotations at particle contacts. Explicit integration of the equation of motion is the norm.

Original DEM models were rather simple, initially cylinders in a two-dimensional assembly (Cundall & Strack, 1979), then gradually evolving to spherical particles and irregular particles made by “gluing” together spherical particles of different sizes (see, e.g., Ferellec & McDowell, 2010), the use of polyhedra of different sizes (Cundall, 1988), the use of “superquadrics” (Williams & Pentland, 1992), and representation of the particles by single elements or meshes of elements (Zhao et al., 2023). Other efforts have included scanning real particle assemblages using X-Ray CT and using the real particle shapes in analysis (see, e.g., Wang et al., 2007). Save for contact points between spheres, contact mechanics has been an ongoing object of research in DEM (Zhao et al., 2023).

One of the main challenges in the application of DEM, certainly in a practical context, has been computing power. The reason this is a challenge is that a large number of particles must be used to simulate even a laboratory soil sample, requiring many calculations of particle interactions at each time step, assuming integration of the equation of motion using an explicit solver. This is compounded if the particles are modeled as complex (or realistic) in shape. Simulating problems at prototype scale with particles of realistic size is generally impractical and likely to remain so for at least some time.

The modeling of real or realistically shaped particles also presents an obstacle of its own: the proper modeling of contact interaction between particles. Whereas contact is simple to model if particles are modeled as spheres, with contact forces with defined point of application and direction, that is far from true if particles have irregular shapes. In the modeling of clay, complications go beyond the modeling of contact forces. In clay, particle interactions involve physical interactions that go beyond just normal stress and shear stress transmission, involving also van der Waals forces, double-layer forces and other long-range forces (Jaradat & Abdelaziz, 2019). Moreover, clay particles can have varied and complex shapes (including plates, membranes, tubes and needles), which are not easily modeled realistically. An additional complication exists when the pore fluid is composed of both liquid and gaseous phases: modeling the interaction of the two phases with particles is not trivial.

Combining the challenges in modeling interparticle forces and particle shapes with the large number of particles in even a small soil volume of clay, which is orders of magnitude greater than for an identical volume of sand, leads to a very challenging computation task if realistic answers are sought. Scaling DEM analysis up to prototype scale appears impractical. Whereas research is in progress to overcome these limitations, it is difficult to see DEM overtaking solid mechanics-based methods—like FEM or MPM (See, e.g., Salgado & Bisht, 2021)—in predictive ability or efficiency in the solution of full-blown boundary-value problems involving clay for some time to come.

So how does particulate soil modeling enter a geotechnical engineering curriculum? Certainly, interest in it is broad, extending beyond just soil mechanics (O’Sullivan, 2011; Zhao et al., 2023), and research in the topic is active, so its teaching in graduate courses on soil mechanics is fully justified. However, given the challenges that exist to its application in practice for likely many years to come, extensive teaching of DEM at the undergraduate level in replacement of continuum mechanics would not be justified. This means that, as a practical matter, geotechnical practice will not likely rely on DEM to any significant extent for some time. The challenges to DEM applications in practice stem from both infrastructure requirements (computer power requirements) and modeling challenges (especially challenging for clays).

To the extent that DEM is taught, emphasis should be placed on the mechanics involved, computational schemes, particle representation, and particle contact/interaction modeling.

5.2 Artificial intelligence and machine learning

There are multiple definitions, not necessarily contradictory, of artificial intelligence. The emphasis of some definitions is on the ability of an AI system to act or think “rationally.” Other definitions tend to focus on acting or thinking “like a human” (Kok et al., 2009). In order to do either—think or act like a human (not necessarily rationally) or think or act rationally (not necessarily as a human)—a system would need to have a number of capabilities, starting with the five basic senses: vision, hearing, touch, smell and taste. We immediately see that image recognition and processing, sound and language processing, and sensors that can measure the values of mechanical, physical and chemical variables are all needed, depending on the application. Then the system must be able to process this information, reason using it, and act or communicate the product of that reasoning. To do all this, a variety of technologies are required (see Figure 9).

It is important to understand that, despite the excitement with it in 2023, AI is not omni-capable. In deciding what to deliver in an education setting, it is important to analyze what AI can and cannot do. It would be highly valuable to educate engineers for tasks that AI cannot do, because that means that they cannot be replaced by AI. But it is also valuable to teach them to be users of AI, and that requires understanding the flipside of the issue: what can AI do?

Geotechnical engineers perform a range of tasks. With slight simplification, these tasks include:

- interact with a client to understand a problem;
- read drawings;
- design site investigation or monitoring plans;
- perform site investigation or install instrumentation;
- interpret test or measurement results;

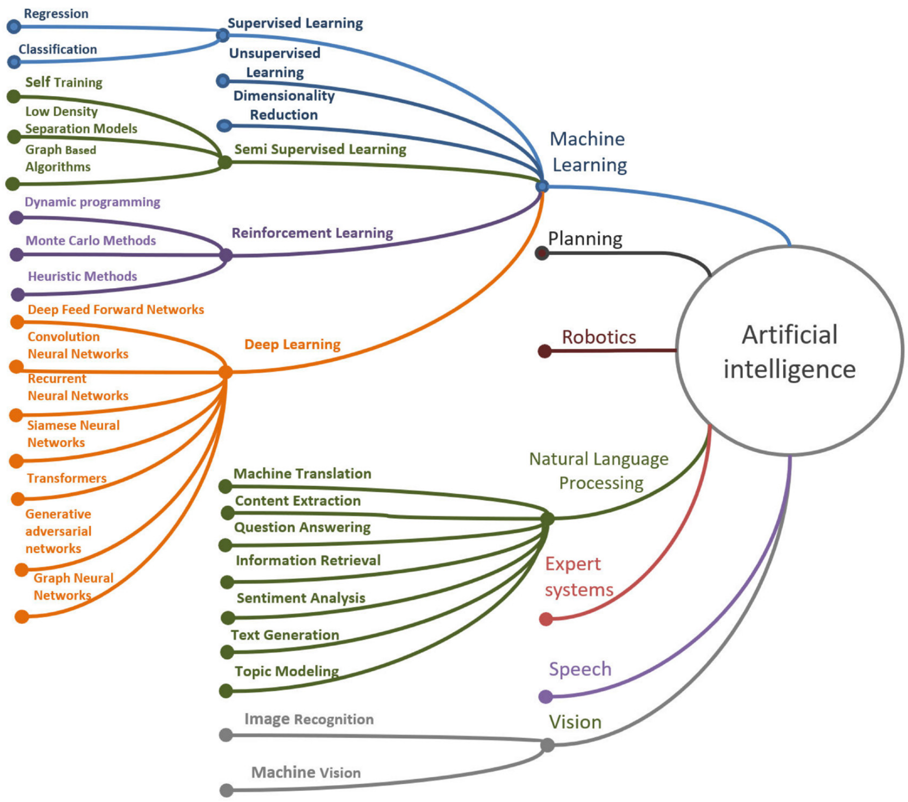


Figure 9. Artificial Intelligence and its various enabling technologies (Mukhamediev et al., 2022).

- perform calculations;
- perform design;
- reduce the design to plans and drawings and a report;
- explain the basis for a design to a client
- interact with other parties, including structural engineers.

A system that can generate new text, images, or sounds when prompted is sometimes called generative AI (Baidoo-Anu & Owusu Ansah, 2023). Such systems will have a significant impact on education and on professional practice, but there are pitfalls. Shoemaker et al. (2023) asked ChatGPT, a generative AI system in which interest spiked in 2023, to solve questions from a professional licensure exam and to perform typical tasks that a geotechnical engineer involved in design activities would perform. It was not clear how the questions were selected, except that none involved figures or charts; ChatGPT answered 67% of the answers correctly. The performance of the design tasks also contained errors. Nonetheless, it is clear from this simple exercise that AI can, even if imperfectly, do certain tasks. As technology improves, it is likely to make fewer errors. This shows that AI will have a role to play in future geotechnical engineering practice.

It is clear that the tasks in the list provided earlier are not uniformly well suited to be done by AI, and that much work remains if we were to rely exclusively on AI to do the work of a geotechnical engineer. Nearly complete replacement of a person would require most of the technologies shown in Figure 9. Image recognition, for example, can be used to calculate deformations or displacements or read and interpret design drawings. Sensors of many types can be used in instrumentation that can be directly connected to an AI-based data acquisition system. Interpretation of various types of information and performance of design tasks would rely on the branch of AI called "Machine Learning."

Machine learning ("ML") is, as the term makes explicit, "learning." We learn to do certain things, like walking, by trial and error. When we learn how to walk, outcomes may range from moving forward or back, fast or slowly, or falling in various ways. We gradually correlate our gait, that is, how we move our feet—such as how high to raise them to overcome an obstacle or slight unevenness of the ground—when attempting to go from one location to another to these outcomes, and learn how to walk naturally and safely. ML is also essentially the finding of correlations between input and output (or outcomes), both described using variables.

The learning that geotechnical engineers do, particularly in a research setting, has an element that is not inherently part of AI: the development of understanding of causal relationships. Science, as discussed earlier, has, as its focus, the establishment of predictive models. These models not only allow us to make successful predictions, but also to understand why the predictions are successful. For example, if a body is deformable, we expect that application of loads to it will lead to deflections and deformation (a hypothesis). We can continuously refine the hypothesis, and perform experiments to confirm the hypothesis, which then becomes a model. For example, we can see that, depending on certain properties of the body, the displacements and deformation that result from applying a given loading to it will be different. We can then establish exactly what these properties are, and then use mathematics to frame this knowledge. Causation is an inherent process of reasoning involved in the scientific method. We know that stress changes cause strain changes. They are not merely correlated if the deformation resulted from increasing loading: we then know that the reason for the observed deformation is the stress change. Temperature changes also cause deformation, because materials tend to change volume upon temperature changes; if this is constrained, stress results instead. Again, in this way of thinking, temperature is not only correlated, but causally linked to deformation. Further inquiry would lead us to understand, at a microscopic level, why that happens. The scientific process forces us to think in this manner: it invites us to understand the reasons for observed outcomes. In the physical sciences, causation is associated with physical processes that research helps us understand. The ML paradigm is different. No hypothesis is made. Observations are fed to the ML system, and it would learn how variables correlate, but the search for causation is neither required nor inherent to it. As often repeated, correlation is not causation (Wright, 1921). This is not to say that causation may not be inferred once correlation is established; it may, but not without more.

ML is not new. The spike in interest in ML in the 2020s can be attributed to the much greater availability of data that has been collected on everything, including people, as the Internet, the World Wide Web, and cell phones have become ever more pervasive. This availability of data has enabled AI to be an effective tool in connection with many areas of human activity. Naturally, the greater storage and computational infrastructure capabilities have also been enabling factors. A question about the application of ML in geotechnical engineering that must be asked is whether there is enough data for ML predictive ability to match that of methods developed based on the rigor of the scientific method. Given how costly data generation is in geotechnical engineering, the answer will frequently be no. But even if there is enough data, challenges remain regarding curating the data and “cleaning” it for training purposes, given that the data would likely be noisy and possibly contaminated by extraneous factors. It is obvious that the availability of large volumes of data on the World Wide Web has not been sufficient to avoid certain AI pitfalls, like “hallucinations” (Ji et al., 2023). Hallucinations are misperception by the AI system, such as generating (often eloquent or convincing) writing that is untrue, or misidentifying objects. The fact that AI does not get the answers in a licensure exam 100% correctly, as discussed earlier, illustrates that it “guesses,” much as a student might do if he did not know the answer to a question. It will try. It will provide an answer to a prompt, but that answer may be completely wrong.

One possible approach to overcome the limited availability of data in geotechnical engineering would be to use the results of simulations performed using continuum mechanics-based or other numerical methods to train the ML engine, much as has been done before to develop relatively simple regressions for design applications. Another possibility is to develop physics-aware deep learning algorithms, fully integrating scientific knowledge (such as the knowledge that a process is driven by a specific differential equation) into the deep learning scheme. Efforts to do this have recently started, but apparently not yet in geotechnical engineering.

Artificial intelligence is a tool with which geotechnical engineers should be familiar, both as users and developers. I expect that writing effective AI prompts (Kumar, 2024) will become an attractive skill, much as search keyword selection has become. Customizing engines for geotechnical engineering applications will also be important. Teaching the essence of AI and ML to geotechnical engineering students, even at the undergraduate level, is desirable. But stressing the limitations of AI and ML, and what must be used instead, is just as important. The most important such limitation is one intricately connected to education and learning: the fact that physical process understanding—the answers to “why” and “how” questions in particular—does not easily follow from AI. In contrast, understanding causal relationships is an integral part of the application of the scientific method to the solutions of engineering problems. In a discipline like geotechnical engineering, the limited volume of data will likely require strategies that bring information learned from the physics of the problem into the ML analysis. But, in some problems in which AI could be most useful, the science itself may yet be entangled, with variables required for the description of the problem not all identified, let alone relationships between them.

5.3 Other timely topics

There are certain themes that are related to geotechnical practice aimed at addressing some of the pressing challenges that our planet currently faces. The talk of voyages to Mars notwithstanding, the Earth remains, and likely will continue to be, the only inhabitable environment that is available to humans. But our planet faces major challenges: 8 billion people consuming limited resources at a high rate and a resulting pollution so significant that it is changing the planet’s climate. Geotechnical engineering is intricately connected to these challenges. I will point to three illustrations of this that deserve to appear in the teaching curriculum: (1) the role of geotechnical engineering in mining and the disposal of mine tailings, (2) the design and installation of offshore foundations and infrastructure, and (3) the mitigation of certain consequences of climate change. There is active research, therefore active decision making, happening in connection with these themes.

Geotechnical engineering plays a major role in mining. Mining activities predominantly involve excavating and drilling into rock and soil. The one aspect of mining that presents the most challenge is however the disposal of mine tailings. This is usually done using tailings dams, and the failure rates of these structures are so high that, in many jurisdictions, the law holds defendants strict liable for damages when there is a dam failure (Salgado, 2022a). Such high failure rates suggest that the profession must approach the design and construction of these structures differently or, alternatively, look for other approaches to disposal of the tailings. Teaching about this topic is important because it raises awareness of the connection between mining and the increasing demand for resources; it also highlights an area of geotechnical engineering that would benefit from performance at a higher level of care.

Offshore geotechnical engineering was originally mostly related to oil and gas exploration and production but has now become an essential component of the envisioned transition from fossil fuels to renewable or clean energy. The same challenges remain. Designing in shallow, intermediate, and deep waters requires different strategies. Whereas the monopile has been the most often used solution for shallow to intermediate-depth waters (see, e.g., Doherty & Gavin, 2012; Hu et al., 2022), future developments will rely on heavier turbines, often installed in deeper waters (Doherty et al., 2011). This development will likely rely on versions of strategies traditionally used for oil production platforms (see Randolph & Gourvenec, 2017), such as floating wind turbines anchored to the seafloor using piles, suction caissons or plate anchors. All viable design strategies for the foundations or anchors of wind turbines should be covered in geotechnical engineering curricula.

As a last example of a timely topic, climate change has led to extremes in temperature and precipitation. In some areas, wildfires have grown in number, size, and intensity. One of the many consequences of wildfires is to change the state of superficial soil (Costa et al., 2023), with important implications for stability of slopes or structures built on it. In others, intense precipitation has led to flooding that has not been seen in many decades and creates risks of coastal erosion, river margin erosion, slope and levee failures, and other similar problems. Additionally, permafrost in some regions of the world is now melting (see, e.g., Jardine, 2020), undermining design strategies relying on what had been viewed as a perennially frozen material that had always been effectively used in these areas.

Introducing these topics to undergraduate classes helps them see the relevance and timeliness of geotechnical engineering, and providing coverage of the same topics in greater depth in graduate courses helps prepare the workforce that will be required in a changing environment.

6. Conclusions

The pioneers of soil mechanics faced some difficult choices. Faced with difficult challenges and limited knowledge, they made some decisions on how to model soil and analyze the boundary-value problems of soil mechanics that have had a significant impact on how the discipline and its teaching evolved.

The three choices that were made that are highlighted in the paper are the use of Terzaghi's "ideal sand" and "ideal clay" models, the use of an associated flow rule with these models, and the neglect of shear strain localization in the solution of boundary-value problems. These choices led to some confusion regarding how soil responds to load, left engineers at a loss as to how to estimate shear strength parameters, and produced solutions to core problems in soil mechanics—such as the bearing capacity problem, the axial loading of a pile or the response of pile groups—that are not as accurate as desirable.

The discipline has overcome these initial modeling choices, and there are now better models and better theories for modeling both soil—the material—and the various engineering problems of interest. These better approaches should be included in textbooks and shared with the community. With the right way of presenting these newer theories, it is possible to teach them to undergraduate, as well as graduate students.

It is interesting to speculate about how decisions that are being made now—particularly regarding how much effort to invest in Artificial Intelligence and Discrete Element Method research—will have on the practice of geotechnical engineering. It seems that AI will have a definite role to play, but it has important limitations that may have to be addressed by making AI engines think not only "like a human," but like a "human with a science background" and one without pathologies or ethical challenges to avoid so-called "hallucinations" and answers that are imperfect "guesses." Research on the Discrete Element Method has led to impressive results, enabling the modeling of soil in accordance with its nature (that of a collection of interacting particles), but limitations remain to its widespread use in practice. These include computational cost and the modeling of clay particles and their interaction.

Finally, overconsumption on our planet has led to many undesirable consequences. Mine tailings, the mining industry version of industrial waste, has been a source of life loss, monetary damages, and environmental damage through frequent tailings dam failures. Climate change has led to a number of challenges—such as changes to the soil caused by wildfires, the melting of permafrost, the susceptibility of structures to floods—that fall clearly within the geotechnical field of knowledge. And the need to transition to clean energy has led to increasing investments in offshore wind energy development, in which offshore geotechnical engineering plays a key role. These are all topics that deserve priority coverage in geotechnical engineering courses.

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Declaration of interest

I have no conflicts of interest or financial interest to report.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols and abbreviations

c	Cohesive intercept in the Mohr Coulomb yield criterion
p'	Mean effective stress
q	Mises stress
q_{bL}	Limit unit shaft resistance
q_0	Overburden stress
q_{sL}	Limit unit bearing capacity
t_s	Shear band thickness
AI	Artificial Intelligence
A_ψ	Parameter in dilatancy correlation
B	Foundation width
DEM	Discrete Element Method
D_p	Plastic dissipation rate
F	Yield function
FEM	Finite Element Method
G	Plastic potential function
I_D	Relative density as a number
I_R	Dilatancy index
$J(\phi,\psi)$	Parameter in bearing capacity equation for soil following non-associated flow rule
K	Coefficient of lateral earth pressure
N_q, N_γ	Bearing capacity factors
ML	Machine Learning
MPM	Material Point Method
Q	Parameter in dilatancy correlation
R	Parameter in dilatancy correlation
SNAC	Finite element analysis software
X-Ray CT	X-Ray Computed Tomography
ε	Strain
ε_a	Axial strain
$\dot{\varepsilon}_{ij}^{\,p}$	Plastic strain rate tensor
$\dot{\varepsilon}_v$	Volumetric strain rate
ϕ	Friction angle
γ	Unit weight
$\dot{\gamma}_{\max}$	Maximum shear strain rate
$\dot{\lambda}$	Plastic multiplier
σ	Stress
σ_1	Major principal stress
σ_3	Minor principal stress
$\sigma_{a,max}$	Peak axial stress
σ_{ij}	Stress tensor
ψ	Dilatancy angle

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Use of ICT to implement an active learning strategy in soil mechanics courses at undergraduate level

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Article

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Guided exercises

Abstract

Nowadays engineers are constantly dealing with more complex problems, uncertainty, incomplete data, and demands of customers, governments, environmentalists, and public. This requires technical skills as well as skills in human relations. So, during their academic background it is necessary to incorporate more skills, social and technological, into their base knowledge. This can be accomplished introducing Information and Communication Technologies (ICT) in Higher Education (HE). Several studies show that the use of ICT in teaching promotes participation, engagement, collaboration, and student interaction, making them more active participants and responsible for their learning. In addition to these advantages, ICT allow to give equal importance to learning processes and to the contents, as the activities offered by ICT allow to the students develop communication skills, teamwork, finding and evaluating information, access, and manipulation of large amounts of data, work with other technologies, update and refine existing skills and knowledge. It was in this context that Guided Exercises emerged. A Guided Exercise permits students to relate models and help them to solve a complex exercise step by step. This strategy was used in two consecutive courses of an undergraduate degree in Civil Engineering, Soil Mechanics I and Soil Mechanics II at the University of Aveiro, Portugal. The results show that students considered the strategy useful for the understanding of the concepts covered in the course. Analysing the students' academic performance, it can be concluded that those who used this methodology had a better approval ratio. This paper presents data to support these statements.

1. Introduction

This paper reports our experience in implementing a strategy called "Guided Exercises" in two courses of the Civil Engineering undergraduate study programme at the University of Aveiro, Portugal. The main objective of this strategy is to ensure that students solve exercises autonomously, in a more organised manner, and that the quality of their autonomous study can be continuously monitored throughout the semester.

Students' autonomous work is stimulated through the proposal to solve exercises on the guided form. These were implemented through Moodle quizzes, where automatic evaluation and feedback on the answers allow students to understand where and why they failed. We can see this process as a cycle where students do autonomous work (with guidance), which allows them to assess their knowledge, check what they did wrong, and then they can repeat the process in other exercises, week after week. Some preliminary studies (Macedo et al., 2020; Oliveira et al., 2018) have already been done and they showed that students considered that the "Guided Exercises" strategy was important for student learning. The main objective of this paper is to demonstrate that there is a direct relationship between students' use of the Guided Exercises strategy and their approval ratio at the end-of-semester exam. The influence of this strategy in the performance obtained was also analysed.

This paper is organized as follows. In this introductory section we contextualize: i) the advantages of Information and Communication Technology (ICT) as a tool for promoting autonomous work in Higher Education (HE); ii) the topic of Blended Learning is addressed; iii) the most relevant features of the Moodle, a Learning Management System (LMS), which has served as a platform for the implementation of Guided Exercises; iv) the Guided Exercises strategy is presented. Section 2 reports our case study, namely describing the course in question and its teaching and evaluation methodology. Section 3 evaluates the methodology identifying the research methodology. Section 4 elaborates on the presentation, analysis, and discussion of the results of our study. Finally, Section 5 presents some conclusions and paves the way for future work.

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1.1 ICT in Higher Education: a brief approach

Information and Communication Technologies (ICT) are playing an important role in our more demanding, dynamic, and technological society (UNESCO, 2002). The awareness of the enormous potential of ICT-based tools for the construction of knowledge, for autonomous and joint study indicates a new culture emerging: the digital culture. The creativity, competitiveness and innovation are characteristics inherent to ICT, which show the development based on information and knowledge.

In education, there is an ever-increasing need to combine a better, faster and effective qualification of professionals for the labour market with the eagerness to attract and motivate students (Tinio, 2003). As far as Higher Education Institutions (HEIs) are concerned, there is an additional challenge to encourage students to develop their individual skills more autonomously and to stimulate their continuous and permanent training.

Scoz & Ito (2013) argue that the various aspects related to the modernization of Higher Education (HE) involve the development of nationwide assessment systems as well as the use of ICT for improving teaching and learning.

The use of ICT is causing significant changes in the teaching and learning process, as it has several advantages over traditional teaching methods. As early as 1996, Smith (1996) stated that ICT facilitates the immediate exchange of information, the adaptation of information to different learning styles, and encourages autonomous study. The integration of ICT aids constructivist learning in which students interact with other students, teachers, information sources, and technology (Gredler, 2000). ICT also gives tools that facilitate access to people, content, strategies, activities, guidance, and opportunities to apply new strategies that make learning a personal process. Technology allows students to choose how, when, and where to participate in the learning process and to gather a variety of learning resources, including people, places, and materials to which they would otherwise never have access (New Media Consortium, 2007).

Nowadays, students' interests are different, and so are their habits. The use of computers, internet and social media has changed the way students interact with the world. There are several studies that have been carried out with the objective of characterizing the habits of Internet/ICT use by HE students. One of those studies, conducted in Portugal by Rosalina Babo et al. (2012), showed that most students access the Internet several times a day, that they are connected on average 1-3 hours a day. In the same study it was shown that the students who spend more time online are those who are enrolled in "technology" related courses. Furthermore, the main reasons for students to use the Internet were identified as (Rosalina Babo et al., 2010): i) to research work/study; ii) to access documents in their LMS (e.g., Moodle).

In this scenario, ICTs are used widely in several dimensions of HE, whether face-to-face or distance learning environments, such as the Moodle platform - "Modular Object-Oriented Dynamic Learning Environment" (Moodle, 2023).

Teachers play a crucial role in the integration of ICT. In 1998, Sarmento et al. (1998), said that "The widespread use of ICT by younger teachers is also a sign of confidence". Evidently, with this new way of managing education, particularly in HE, teachers are faced with a new paradigm, since teaching today is not simply knowledge transmission (Angadi, 2014). Teachers soon began to interact in the construction of knowledge and became researchers on how to use new technologies in teaching (Zhao & Cziko, 2001). According to the literature, because of organizational, curricular, extracurricular and policy changes in HE teachers are required to continuously acquire new skills. They need to be able to adapt content objectively and clearly, to make it attractive and enjoyable. Nevertheless, many teachers still do not take advantage of the potential of ICT to promote higher quality teaching/learning (Barolli et al., 2012; Cubukcuoglu, 2013).

1.2 Student's autonomous study

The amount of autonomous study by students in HE began to be clarified more objectively and more quantitatively with the introduction of the European Credit Transfer and Accumulation System (ECTS) in 1989 under the Erasmus program, and later with the request of the Bologna Ministers in the Bucharest Communiqué in 2012 (Bucharest Communiqué, 2012). This was a call by the Ministers to institutions to further bind study credits to students' learning outcomes and workload and to integrate the achievement of learning outcomes in assessment procedures. In accordance with the ECTS Users' Guide (Bucharest Communiqué, 2012), workload is an estimate of the time a student normally needs to complete all learning activities (e.g., lectures, seminars, practical work, individual and group research, report writing, projects...), and individual study required to attain the defined learning outcomes.

Today, there is a better estimate on the amount of time a student should allocate to autonomous work. However, the quality of autonomous work is difficult to quantify and guarantee (Holmes, 2018). It is important to note that the student is now the centre of the educational process, where they are expected to play an active and critical learning role. This is important, because we want students after their graduation to be prepared to enter the labour market, where such autonomy is requested. On the other hand, there is the danger of the student feeling abandoned. In fact, the tendency is to simplify all this by decreasing the number of classes and "force" (the idea would be more "motivate") the student to achieve the outcomes proposed through autonomous work.

Many students who attend HE become disoriented or even lost during their academic path (Neri de Souza, 2006). One of the reasons for this scenario has to do with their schooling because the demand for autonomous work in primary/secondary education is often very low and when they enter HE the students are faced with a new reality where autonomous work is preponderant (Neri de Souza, 2006). Note that in HE the number of hours allocated to autonomous work is higher and consequently the number of contact hours with the teacher is lower than in high school.

Autonomous study implies the mobilization of many student skills, such as: i) knowing the objectives they need to achieve; ii) knowing and recognizing what has been taught; iii) defining/planning tasks and work priorities; iv) knowing how to use information resources, selecting bibliography, and making summaries, knowing how to work in groups, etc. Since freshmen do not yet possess these autonomous work skills, it is essential to find ways of monitoring their evolution, i.e., the skills students acquire during their study.

In this context, it is very important that teachers make different kinds of materials and support tools available to students, be willing to answer their questions, and assess their skills and knowledge regularly along the way (especially those acquired through autonomous work).

But how can autonomous work in HE be defined? According to Bonham (1992, p. 192), "[…] independent study is a process by which a student acquires knowledge on their own and develops the ability to question and critically evaluate". Knight (1996) further completes this definition by stating that "[…] independence is not the absence of guidance but the outcome of a learning process that enables students to choose the guidance they need to achieve their goals". Finally, Thomas (2014) states that "[…] in general, autonomous study is done outside of contact hours but contributes to specific learning outcomes. This learning is carried out by students, alone or with other students, without direct participation from teachers".

Nevertheless, it is extremely important for teachers to support and guide students throughout the semester. It is also important to assess students' competencies at different moments (and in different areas) so that students can receive timely and relevant feedback on their study methodology and effort (Young, 2002).

1.3 Blended learning

Learning can take place in different modalities. A distinction is often made between face-to-face classroom learning and virtual learning, as well as asynchronous and synchronous learning (Chaeruman et al., 2018). As information and communication technologies (ICT) have become more sophisticated, popular, and widely used, the need for their integration into the various teaching modalities has increased. In recent years there has been a significant increase in the use of these types of technologies blended with traditional classroom teaching. In higher education, the blended approach is highly desired because of its flexibility and individualization, which allows teachers to propose, in each situation, the most advantageous training solutions for their students, to give them the opportunity to adapt the learning process to their own needs and specific stages of life (Barnett, 2014; Lencastre & Coutinho, 2015; Müller & Mildenberger, 2021). It is increasingly evident that blended learning can overcome several limitations related to online learning and face-to-face teaching (Alammary et al., 2014). Some examples are hardware capabilities, computer skills, lack of interpersonal interaction, delayed feedback (online learning) and need to travel to some location, low flexibility to create individual learning paths, and higher costs (face-to-face teaching) (Gherheș et al., 2021).

Originally, the term blended learning was used as the link between the traditional classroom and distance learning supported by a computer. More recently, due to the increasing spread of the Internet and the ease of use of LMSs, blended learning represents a diversity and variety of combinations (Lencastre & Coutinho, 2015).

Allen et al. (2007) employs the online proportion of a learning environment as a differentiation criterion for the four modalities: traditional, web-facilitated, blended/hybrid and online learning (Table 1).

According to Allen et al. (2007), the classification of a course into: traditional; web-facilitated; blended/hybrid; and online learning, depends on the percentage of the course that is delivered online. Thus, according to the authors a course to be considered a blended learning approach must have between 30% and 79% of the course content delivered online. With this classification, the term Web-facilitated is introduced for face-to-face courses that have up to 29% online content (see Table 1).

Table 1. Course classifications according to Allen et al. (2007).

Proportion of Content Delivered Online	Type of Course	Typical Description
0%	Traditional	Course without the use of online technology – content is delivered orally or in writing
1 to 29%	Web Facilitated	Course which uses web-based technology to facilitate what is essentially a face-to-face course. Uses a Learning Management System (LMS) or web pages to post the syllabus and/or assignments
30 to 79%	Blended/Hybrid	Course that blends online and face-to-face delivery. Substantial proportion of the content is delivered online. Typically uses online discussions, but also has some face-to-face meetings
80+%	Online	A course where most or all the content is delivered online. Typically have no face-to-face meetings

It is clear that the use of ICT is an essential condition for the implementation of teaching modalities that have an online component. In recent years there has been a marked growth in technological solutions (LMSs, video conferencing platforms, audience response systems, among others) that make it easier for teachers to implement strategies with an online component, a situation that has been enhanced by the COVID-19 pandemic.

1.4 Learning Management Systems (LMS) - Moodle

Engineering education faces new challenges since students are different and teaching methodologies have not adapted or evolved in accordance, or at least not at an adequate pace. Today's students are dependent on the Internet, and HEIs must take advantage of this fact to promote teaching and learning. The teacher's role has changed (or it should change), and other types of learning environments have emerged, trying to make the most of the potential that ICT has to offer as facilitators of teaching/learning. In this context, most HEIs have been providing LMS platforms for more than a decade.

LMS platforms are web-based software applications that support learning content, allow interaction of and with students, have assessment tools, and allow producing learning progress reports (Kasim & Khalid, 2016). The most popular open-source LMS platforms are Moodle, Sakai, and Atutor. Blackboard, SuccessFactors, and SumTotal are examples of non-open-source LMS platforms and are more commercial. The LMS platform we will look at in more detail will be Moodle, since it is the most widely used platform in HE and it is the one used in the institution under study in this chapter.

Moodle (Modular Object-Oriented Dynamic Learning Environment) was originally developed by Martin Dougiamas and was first made available online in 2002 (Grant et al., 2018). It is used in 242 countries by over 411 million users, featuring more than 47 million courses and 158,300 sites (Stats Moodle, 2024). In Portugal, there are 2,316 registered sites (Stats Moodle, 2024). Moodle allows for the creation of web-based courses and content and is designed to provide educators, administrators, and students with a single robust, secure, and integrated system for creating personalized learning environments and experiences. It is worth noting that Moodle is open source, which is quite appealing to HEI with ICT courses and programming skills.

From the perspective of the teacher, Moodle is user-friendly (at a basic level) and offers an enormous amount of functionality (see Figure 1). Essentially, interaction

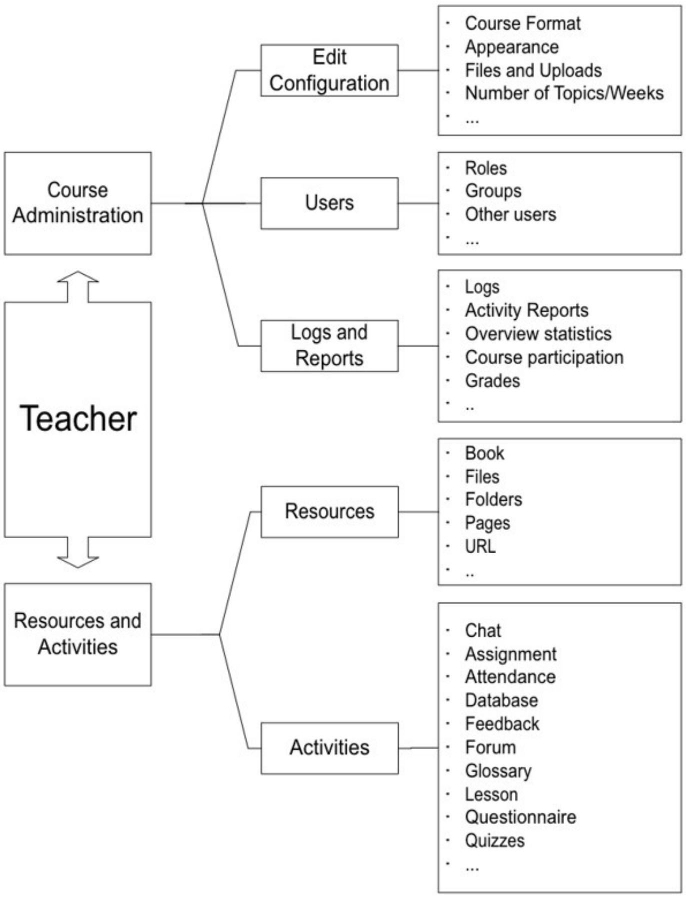

Figure 1. Moodle features in teacher perspective.

with Moodle can be divided into two main blocks: Course Management and Resources and Activities (Büchner, 2016; Henrick & Holland, 2015; Nash & Moore, 2014).

In the Course Administration section, teachers can perform all activities related to the formal part of the course. This includes defining course Format, Appearance, Files and Uploads where teachers can define if they allow uploads and the maximum file size, number of topics or weeks, enrolling students/teachers, assigning roles, creating workgroups, defining assessment criteria, reviewing student grades, and generating various types of reports.

Resources and Activities are the key functionality for interaction between teachers and students, as well as direct interaction among students. In Resources, teachers can provide all supporting content such as slides, exercises, books, lab guides, and sample exams. Activities can include chat rooms, forums, quizzes, lessons, among others.

Moodle has several interesting features, namely (Lustek et al., 2019; Meikleham & Hugo, 2020; Kasim & Khalid, 2016; Olmos et al., 2015):

- Makes it easy to look up content, as it is available online, can be accessed anywhere/anytime, which potentially increases student motivation (especially for working students);
- Allows for automatic evaluation and grading of students, through tests/quizzes, giving them immediate feedback;
- Allows the teacher to monitor students' activity more easily (for example, it is possible to check the records of when and how many times a student has logged in, what he/she has consulted, which activities/resources he/she has been in, how long he/she has been in each activity/resource);
- Allows easy administration of assignment/report submission, submission deadlines control and version control (for example, you can check deadlines, date and time of file submission...).

Studies indicate that the interactivity provided by tasks/assignments in Moodle has led to more active students, with greater motivation and willingness to learn (González et al., 2013). Furthermore, the integration of online components into traditional classes has been shown to substantially improve communication between students and teachers, increase access to Internet resources, and increase student satisfaction (Chung & Ackerman, 2015).

1.5. Guided exercises

One of the problems that science and engineering teachers face is the difficulty that their students have in solving exercises. To develop students' problem-solving skills, a strategy called "Guided Exercises" was implemented through a collaboration process with a researcher in didactics from the Research Centre on Didactics and Technology in the Education of Trainers (CIDTFF) at the University of Aveiro. It was found that during the studies conducted in the scope of this collaboration, students exhibited a behaviour similar to what is described in the literature (e.g., Heller et al., 1992; Heller & Hollabaugh, 1992; Saul, 1998), where they only focused on finding the formula to solve the exercise without seeking to understand the concepts and/or models related to the physical situation of the exercise. According to Saul (1998), students may be able to solve traditional exercises or typical end-of-chapter exercises in textbooks, but this does not indicate that they have understood the underlying physical situation or that they can make connections between physical concepts and real-life situations. To address this problem, Heller et al. (1992) and Heller & Hollabaugh (1992) started by studying the mechanisms used by students to solve end-of-chapter exercises. When students work together in groups to solve these exercises, the discussions that take place within the group often revolve around questions like "Which formula should we use?" rather than "Which physical concepts and principles should be applied to solve the problem?" In that study, it was estimated that about two-thirds of students use the approach of "Which formula should I use?" when solving end-of-chapter exercises. Therefore, it was concluded that typical exercises from textbooks do not promote high-level cognitive discussions among students.

In response to the identified problems, a strategy called "Guided Exercises" was conceptualized. This is an active learning strategy that aims to promote the application of knowledge and reasoning in exercise solving by combining conceptual questions with calculations. A Guided Exercise can be created, for example, based on a typical end-of-chapter exercise. In this type of exercise, students are usually only asked to perform calculations. To perform these calculations, students need to mobilize and relate models and reasoning. Therefore, a Guided Exercise breaks down the typical exercise into several questions that students must answer in a logical sequence. Thus, before performing each calculation, students must answer a question about the concept/phenomenon associated with that calculation. This methodology is in line with a study conducted by Hegde & Meera (2012). In their work, the authors argue that the first step in problem-solving is to identify the applicable physical principle to the situation. The same authors found a weak association between students' conceptual structure and physical principles, which acts as a major obstacle in problem-solving. Most of the time, the physics terms in the exercise statement trigger the search for an equation, and if there is an inability to do so, it can hinder the complete resolution of the exercise. The goal of this type of exercise is for students to not only apply formulas but also associate those formulas with the underlying concepts. By applying this strategy, students can understand the models and reasoning required to solve these "typical exercises" and later apply this knowledge to new situations.

This strategy, Guided Exercises, promotes the learning of complex content and requires active student participation in their own learning process, starting with an in-depth analysis and providing increased cognitive flexibility through the sequence of various questions. This participation demands reflection, knowledge maturation, and cognitive flexibility (Spiro & Jehng, 1990). With this strategy, the aim is for students to understand, reflect upon, and apply the covered content.

The feedback provided by Guided Exercises can be of different types. We can classify the feedback into three types: I and II. Type I feedback is given when students choose a response option and simply find out if it is correct or incorrect. Type II feedback provides students with indications of where they went wrong and how they can improve if they choose the wrong option, without revealing the solution. If they choose the correct option, they receive an encouraging message.

2. Case study

The pedagogical practice described in this paper was implemented in two courses of the 3rd year of the actual bachelor's in Civil Engineering of the University of Aveiro: Soil Mechanics I and II. In each academic year, these courses are taught consecutively in the 1st and 2nd semester to a group of students that is practically the same. The courses, Soil Mechanics I and II, have been the object of transformative pedagogical practices since the school year 2007/2008. These practices, the authors' reflections, and the results of the evaluation of their implementation have been shared in several national and international forums, like conferences, workshops and scientific papers. In a first transformation, a project-based learning model was implemented (using a cooperative, and collaborative models), described in detail by Pinho-Lopes et al. (2011) and Pinho-Lopes & Macedo (2016). Since 2015/2016 the strategy named "Guided Exercises" was implemented (Macedo et al., 2020; Oliveira et al., 2018). This is the strategy object of study in this paper. In 2019/2020 immediate feedback sessions were introduced (similarly to Pinho Lopes & Powrie, 2020). In consequence of the COVID-19 pandemic context, in 2020/2021 flipped learning was implemented in these courses using a hybrid model (Pinho-Lopes & Macedo, 2022).

The SMI course is an introductory course where the fundamental concepts and basic proprieties of Soil Mechanics are presented. Considering that the behaviour of Civil Engineering constructions is significantly affected by the mechanical and hydraulic properties of the soils where they are implanted, their study is essential for subsequent application in the design of Civil Engineering structures. The SMI program is grouped into four distinct chapters: (1) Physical properties and soil identification; sedimentary and residual soils; (2) Stress state in soils; capillarity; (3) Water in soils; seepage and (4) Compression and consolidation of clay soils.

In the second semester, SMI contents are complemented in SMII. In this course, the fundamental concepts and basic properties of soils are now used as the basis for the application of concepts, theories and methods commonly used in civil engineering for the conception and design (using the Eurocodes) of several types of geotechnical structures. For that it is fundamental to understand how the structures and/or their components are somehow conditioned by the mechanical behaviour of the soil masses where they are implanted. For this reason, the course starts with the study of soil shear strength and stress-strain relationships. The content also covers the field tests generally used to characterize the mechanical behaviour of soils. The contents are grouped in the following four chapters: (1) introduction to soil shear strength; shear strength and stress-strain relationships in sands and clays; (2) lateral earth pressures; earth retaining structures; (3) stability of slopes and embankments and (4) in situ sampling and testing.

Both courses have presential classes. In relation to the weekly contact hours, both have four hours of classes (in two different days) and one hour of tutorial class. In SMI one lesson is theoretical–practical and the other is practical. In SMII both lessons are theoretical–practical. Each course has 6 ECTS units, which correspond a total of 162 hours work, assuming that each ECTS represents 27 hours work (value adopted by the University of Aveiro). Such workload includes class time, individual study time, preparation of reports, elaboration of projects, bibliographical research, and revision for exams.

As stated, in the beginning of 2007/2008 academic year the two courses on Soil Mechanics (SMI and SMII) were fully redesigned to include project-based learning (PjBL). Triggered by Bologna Process and its requirements, teachers decided that was the right moment to adjust their courses to adopt student-centred learning models, complementing the traditional teacher-centred model. The implementation of this strategy is described in detail by Pinho-Lopes et al. (2011) and Pinho-Lopes & Macedo (2016).

After the first editions of the PjBL implementation, it became clear that there were some limitations. The most relevant one was that students worked more cooperatively than collaboratively. Thus, it was found that within each team, students tended to divide tasks and only focused on their specific task, not communicating with their peers. This led to a compartmentalization of knowledge that was evident in the exam results. Therefore, many times each student developed the relevant knowledge and skills in the part of the project they were working on and knew little about the other subjects (Gredler, 2000). To address this limitation, a complementary strategy was used - Guided Exercises - which was implement for the first time in 2015/16 in SMII.

The aim of Guided Exercises was to improve the teaching-learning process while keeping the students in the centre of the procedure (Oliveira et al., 2018). Supported by ICT, namely the LMS available in the UA (Moodle), one or two Guided Exercises per chapter of the syllabus were prepared and made available to students. The use of

Moodle allows to give immediate feedback to students in two different ways. The first is through the grade, simply formative, obtained by the students when they finish each exercise. The second, through short comments, previously prepared by the teachers, to the answers given by the students to certain questions. These comments can be suggestions for reading certain chapters of the support manual, indication of which is the correct answer, or simply messages of encouragement. The Guided Exercises were available in two moments. Firstly, at the end of each chapter and for a period of 15 days. During that time students had unlimited attempts to the Guided Exercise. Later, during the exam period, all Guided Exercises were available again to help students with revision. Students' participation was voluntary and did not have any influence on their final grade.

Since the second semester of 2015/2016 the strategy Guided Exercises is available to students. However, due the COVID-19 pandemic was necessary to prepare different teaching approaches to deal with the lockdown periods. Thus, in the second semester of 2019/2020, it was necessary to use emergency remote teaching to continue teaching activities. The teachers and students had to learn quickly how to use new technologies, such as video conferencing platforms like Zoom and MS Teams, to maintain the synchronous moments of teaching. The consequent additional workload led to a concentration of students' attention on the tasks that actually counted for their assessment. For this reason, there was a considerable decrease in the use of Guided Exercises, since these were not considered for assessment, serving only as formative purposes.

In the academic year 2020/2021 a blended learning model was implemented. The lessons learned during the previous semester, and the constraints impose by the UA due the pandemic, motivated the teachers to implement a new strategy fully supported by UA's Moodle, the flipped classroom. Traditional classes have given place to online ones implemented with the following structure. First, a video lesson (< 15 minutes) where each content is expose. Then, a short exercise or conceptual question with immediate feedback and finally a short summary with the main ideas. These online classes should be seen prior to the synchronous moments, which were used to conduct discussions with students and resolution of exercises promoting deeper learning. More details can be found in Pinho-Lopes & Macedo (2022). With some adjustments, due to return to face-to-face model, this strategy was also used in 2021/2022. Again, during these two academic years a reduction in the use of Guided Exercises was observed.

3. Methodology

The implementation of the strategy Guided Exercises in SMI and SMII courses was assessed using two different approaches. The first one was the preparation of a questionnaire, distributed to the students in the end of each semester, to collect the students' perceptions about the strategy and to identify if there was a need to adjust it. The second one was the analyses of the students' academic performance through the study of the existence of a correlation between the use of Guided Exercises and obtaining a passing grade on the final exam, carried out by all students individually. The aim is to examinate if Guided Exercises promotes learning in students. This second approach is the study object of this paper.

In the second semester of 2015/2016, after the first experience of implementation of the Guided Exercises, a questionnaire was prepared. The questionnaire was composed by 17 closed questions using a Linkert Scale (1 totally disagree to 5 – totally agree) and 3 open questions. The first was aimed to understand why students used Guided Exercises. The other two intended to identify at least one positive and one negative aspect on Guided Exercises. The intention was to obtain information to support the incorporation of some adjustments in the strategy to meet the expectations of the students.

The study we intend to do in this paper is to understand whether the use of Guided Exercises promotes learning in students and whether this can be measured and correlated with the grades obtained on a final exam.

To do this it was necessary to establish criteria that would allow to divide the students into two groups: those who used the "Guided Exercises" strategy and those who did not use the "Guided Exercises" strategy.

There were two criteria used:

- They did more than 75% of the Guided Exercises made available;
- The grade obtained in these Guided Exercises was greater than or equal to 10 (on a scale up to 20).

The usage rate of the Guided Exercises by the students was obtained at the end of each semester by consulting the Moodle utilization history.

To verify the existence of a correlation between the use of Guided Exercises and the obtaining a passing grade on the final exam, several statistical tests were used. For this purpose, was used a computer software, IBM SPSS Statistics software, version 26. The first statistical test used was the chi-square test of independence. This test allows to find out if two variables are related. In this case it is intended to understand whether solving Guided Exercises is related to passing the final exam. A complementary test to the chi-square test was performed, which was Cramér's V test. This test allows us to measure the strength of association between two nominal variables giving a value between 0 and 1 (the classification is: i) > 0.5 - high association; between 0.3 and 0.5 - moderate association; iii) between 0.1 and 0.3 low association and finally iv) between 0 and 0.1 - little if any association).

These two tests can be complementary since the chi-square test is a test of statistical significance while Cramer's V test is a test of substantive significance. Put in other words, with the chi-square test one answers the question "Is there a relationship between using the Guided Exercises and a student passing the final exam?" while with Cramer's V-test one answers the question "How strong is this relationship?"

4. Results and discussion

The surveys conducted with students between 2015/2016 and 2018/2019 on their perceptions on Guided Exercises allowed to identify a set of evidence on the added value of its use. Thus, in that period Guided Exercises were available to 89 students assessed on the courses. In total, 64 students (near 75% of the assessed students) answered the questionnaire made available at the end of each academic year. The results obtained allow to highlight several aspects (Macedo et al., 2020):

- Guided Exercises were important, to understand the contents covered in class, to their learning process and were a different way of studying;
- Guided Exercises helped students to understand the steps that must be taken to solve an exercise, helped them to understand the reasoning behind that problem and the majority tried to solve the exercises without guessing the corrected answer by trying several times and checking if the answer is corrected;
- Students considered that Guided Exercises were better understood than traditional, the feedback given helped them to understand their difficulties and oriented them to solve other exercises.

From the open questions, the results showed that students used Guided Exercises for study (59%), revise contents (42%) and guide them through an exercise (16%). Regarding the positive and negative aspects, as positive aspects they pointed that Guided Exercises helped them to better understand what was asked in the exercise (38%), to study during the semester (25%) and to organize their answers (22%). As negative aspects students said that they would like to have more Guided Exercises (33%), Guided Exercises should be shorter (28%) and Guided Exercises should be always available (27%). The results of these surveys are described in detail by Macedo et al. (2020).

Regarding the statistical analyses between the use of Guided Exercises and the students' academic performance, the results are presented below.

The sample with all students (academic year 2015/16 to 2021/22 of the two courses: Soil Mechanics 1 and 2) has 199 students. The criterion for using exam grades as the element for comparing the two groups of students is because exams are the element of assessment carried out under similar conditions.

The results can be summarised in the following Table 2.

From the analysis of these results, it can be stated that the number of students who did not do at least 75% of the Guided Exercises made available was 135 (67.8%). Of these 135, 56 (41.5%) were approved in the exam.

On the other hand, 64 students (32.2% of the total number of students) did more than 75% of the Guided Exercises, and of these, 38 (59.4%) were approved in the exam.

To perform a deeper analysis to the academic performance between the two groups of students, their grades in the final exam were compared by analysing the relative frequency of the grades obtained by each group of students (Figure 2).

Analysing Figure 2, it is not only in terms of approval rate that there are differences between the two groups of students. As it can be seen, the group of students that did Guided Exercises obtained higher grades. For example, the percentage of students who obtained grades between 10 and 12 (on a scale of up to 20) was almost two thirds higher (30% vs 18%) for students who did Guided Exercises.

The same conclusion can be drawn by looking at the normal distribution of the grades of the students in the two groups (Figure 3). There is a clear deviation to the right of the normal curve for students who did 75% of the Guided Exercises.

Thus, it may be concluded that Guided Exercises seem to have a positive effect for the approval in the final exam. The chi-square test was used to check whether these results are statistically consistent. The value obtained was 5.578 with a significance level of p=0.023 (<0.05), which

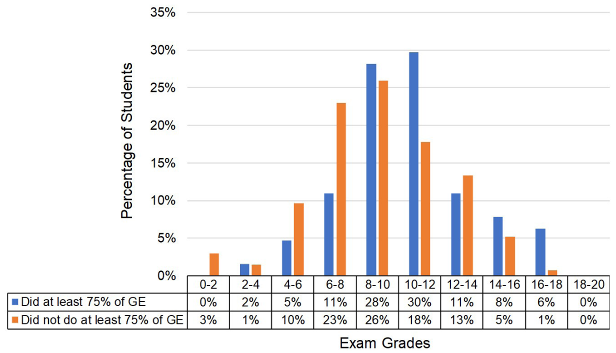

Figure 2. Grades distribution between the two groups of students analysed (all students).

Table 2. Results of approval rate in the final exam vs the use of Guided Exercises (GE) for students from academic year 2015/16 to 2021/22.

	Approved		Failed		Total
	Number of cases	%	Number of cases	%	Number of cases
Total	94	47.2	105	52.8	199
Did not do at least 75% of GE	56	41.5	79	58.5	135
Did at least 75% of GE	38	59.4	26	40.6	64

shows that the number of students who passed the exam is related to the Guided Exercises. For these data, Cramer's Statistic is 0.167 that represents a low association between doing Guided Exercises and be approved in the final exam. This low association may be related with the introduction of new distance learning methodologies. As previously mentioned, from the second semester of the academic year 2019/20 and due to the Covid pandemic, new distance learning strategies have been introduced. Thus, students were eventually encouraged to use other strategies and Guided Exercises naturally ended up being less used. Therefore, we chose to present another study with a smaller sample (with 89 students) from the course units of Soil Mechanics I and II from the academic years between 2015/16 and 2018/19. This sample is prior to the Covid pandemic and therefore the students' focus was more on the only online strategy available which was the Guided Exercises.

The results are summarised in the Table 3. In terms of the exam grades a similar analysis to the one realised for all academic years was carried out (Figure 4 and Figure 5). The first major difference between these results and the results obtained when considering all students (199) is that now the percentage of students who did and did not do the Guided Exercises is almost equal (46 students - 51.7%) did not do the Guided Exercises and 43 students did the Guided Exercises (48.3%).

The second major difference is in the impact that the Guided Exercises had on approval in the final exam. Of the students who did not do Guided Exercises only 26.1% passed. This compares with 48.8% (almost double) of the students who did Guided Exercises and passed the final exam. Again, these results have statistical validation. The result obtained for the chi-square test was 4.930 with a significance level of p=0.03 (<0.05) which shows that the number of students that were approved in the exam is related to the use of the Guided Exercises strategy. When Cramer´s V test is applied, a value of 0.325 is obtained, indicating a moderate association between doing Guided Exercises and be approved in the final exam.

Similar to the previous analysis conducted for all students, a deeper analysis of the academic performance between the two groups of students was performed for those who attended the courses in the period between the academic years 2015/16 and 2018/19. Their grades in the final exam were compared by analysing the relative frequency of the grades obtained by each group of students (Figure 4) and their normal distributions (Figure 5).

Regarding academic performance, the trends observed for all students are the same as those seen above when considering the sample of students who attended the courses

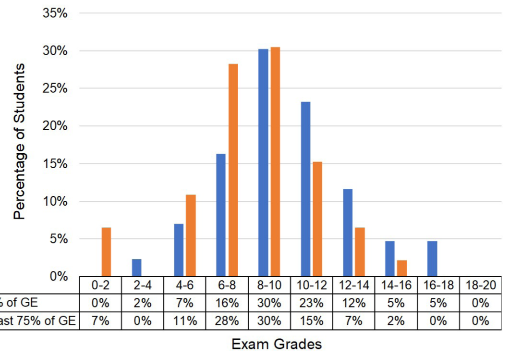

Figure 4. Grades distribution between the two groups of students analysed (2015/16-2018/19).

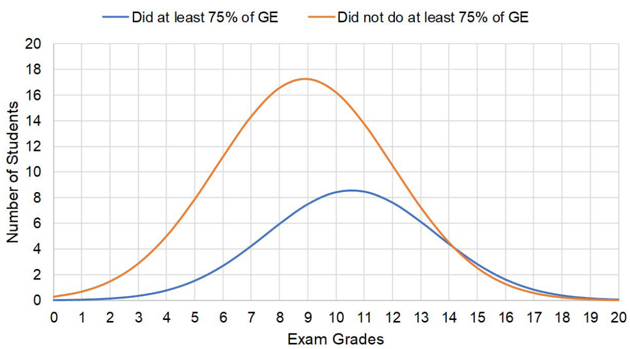

Figure 3. Normal distributions of the exam grades between the two groups of students (all students).

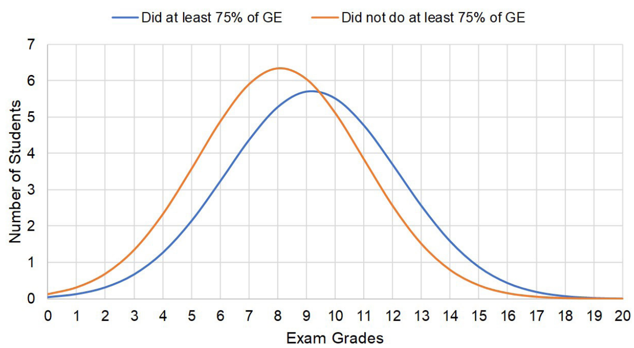

Figure 5. Normal distributions of the exam grades between the two groups of students (2015/16-2018/19).

Table 3. Results of approval rate in the final exam vs the use of Guided Exercises for students from academic year 2015/16 to 2018/19.

	Approved		Failed		Total
	Number of cases	%	Number of cases	%	Number of cases
Total	33	37.1	56	62.9	89
Did not do at least 75% of EG	12	26.1	34	73.9	46
Did at least 75% of EG	21	48.8	22	51.2	43

between the academic years 2015/16 and 2018/19. It is clear that students who did at least 75% of the guided exercises obtained better academic results than those who did not.

All the previous analyses revealed that the use of the learning strategy Guided Exercises have a positive influence both in the approval rate and students' performance in terms of the obtained grades in the final exam.

This active learning strategy can easily be applied, with the necessary adaptations, to other courses in the areas of engineering and exact sciences, e.g. (Urbano et al., 2014). For the success of the strategies some principles should be followed. As reported by students (Oliveira et al., 2018) the length of the exercises should not be too long, the number of exercises available should be enough to cover all the syllabus, be available throughout the semester on the LMS platform and if possible be used in the classroom. Another important aspect is the immediate feedback provided. More important that knowing what questions students got wrong, specific feedback should be provided on each question to guide them to the content they need to revisit. The results obtained from the use of this strategy over the years have revealed that the level of engagement is essential to its success. The use of other strategies and the fact that it is not compulsory in terms of assessment has resulted in a decline in its use in recent years. However, the variety of strategies and resources allow students to have a more flexible and personalised learning environment for which Guided Exercises contribute.

5. Conclusions

In this paper was presented and discussed an experience in implementing an active learning strategy called "Guided Exercises". The strategy is implemented in two consecutive courses on Soil Mechanics (Soil Mechanics I and II) of the Civil Engineering undergraduate study programme at the University of Aveiro, since 2015/2016.

The main motivation for developing and using this strategy in these courses was the necessity to find a solution to one of the problems identified during the implementation of the PjBL. It was found that students tended to compartmentalize content (Pinho-Lopes & Macedo, 2016), and it became necessary to find a teaching-learning strategy that could minimize this issue. With Guided Exercises students could test their understanding of the contents in a more organized and systematic way. Supported by ICT, the Guided Exercises can be used to mobilize knowledge to solve complex problems.

The strategy was assessed using two different approaches, a questionnaire, and an analysis of the relation between the use of Guided Exercises and approval ratio at the final exam. From the first one, it can be concluded that students considered the strategy useful to understand contents and the necessary steps that must be taken to solve a complex problem. They also considered it important for their learning process and a different way of studying.

The results obtained by analysing the grades at the final exam and the use of Guided Exercises strategy by students revealed that there is statistical evidence showing that using Guided Exercises influences the approval ratio. When analysed the period on which the strategy was used in a more systemic way (between 2015/2016 and 2018/2019) the approval ratio of students that used Guided Exercises was almost the double than the students that did not used it. This conclusion is supported by the results of the statistical tests performed, demonstrated by the fail rate which is smaller among the students who did at least 75% of Guided Exercises (40.6% against 58.5% when all students are considered and 51.2% versus 73.9% when are considered only the students that attended the courses in the period 2015/16 to 2018/19) and corroborated by the statistical tests performed which revealed significant statistical differences.

The level of engagement also plays an important role in the success of this active learning strategy. During the period in which students used the guided exercises more (2015/16 to 2018/2019), their influence on the results was greater, as evidenced by the results of Cramer's V test. The obtained value was 0.325, compared to the value of 0.167 obtained for all students.

Since COVID-19 pandemic the use of Guided Exercises had a significant reducing in its use by students, due the introduction of other online strategies. The diversity of strategies and resources provides students with a flexible and personalised learning environment, to which Guided Exercises significantly contribute. The next main challenge is to find a better equilibrium between the different active learning strategies available. One way to achieve this equilibrium is to incorporate all the strategies in more integrated way, for example using a gamification approach.

Future civil engineers face many challenges, and the field of geotechnical engineering education plays a relevant role in their preparation. Challenges such as technological advancements, interdisciplinary approaches, sustainability, innovation, lifelong learning, globalization, and cultural diversity require students to develop a set of both hard and soft skills to address them. In this context, students will increasingly have to use digital tools, be challenged to develop soft skills, and adapt to learning environments tailored to an increasingly diverse student profile where personalization plays a crucial role. As showed in this paper, the Guided Exercises strategy can help promote the use of digital tools and contribute to personalised learning.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Joaquim Macedo: conceptualization, methodology, investigation, data curation, visualization, writing – original draft, validation, writing – review & editing. Paulo C. Oliveira: conceptualization, methodology, investigation, data curation, visualization, writing – original draft, validation, writing – review & editing.

Data availability

The datasets generated analysed during the current study are available from the corresponding author upon request.

List of symbols and abbreviations

p	Probability value, p-value
CIDTFF	Research Centre on Didactics and Technology in the Education of Trainers
ECTS	European Credit Transfer and Accumulation System
GE	Guided Exercises
HE	Higher Education
HEIs	Higher Education Institutions
ICT	Information and Communication Technologies
LMS	Learning Management System
PjBL	Project-based learning
SMI	Soil Mechanics I
SMII	Soil Mechanics II

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Co-creation as a driver of geo-environmental learning approach to adapt cities to climate changes

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Article

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Climate change mitigation

Abstract

Climate change is humanity's 21st century biggest challenge. Due to the higher rates of soil sealing, its effects and consequences are expected to be more severe in cities. To mitigate climate change effects or adapt cities to them, several approaches can be adopted, namely by adopting nature-based solutions, such as blue and green infrastructures. During the course of Study and Behaviour of Soils, of the undergraduate degree in Sustainable City Management, taught at the Institute of Engineering of the Polytechnic Institute of Coimbra (ISEC-IPC), students are faced with the need to present solutions to solve an urban problem by implementing a green solution. Students are involved in a co-creation process to carry out this academic activity. This project-based learning methodology is seen as an active learning process, and its three stages are fully described in this paper. Students' perceptions, academic results and assiduity are compared and contrasted to enhance the benefits of such an approach in geotechnical education. Results show that not only are students more willing to participate in class, reducing absenteeism, but students' final project results increased when compared with a more traditional pedagogical approach. Also, based on the survey, it is possible to conclude that the co-creation approach allows the development of transversal skills and competencies, and such a learning process should be implemented more often during the undergraduate degree.

1. Introduction

Since the founding of the first university in Europe, teaching approaches have been mainly based on lecturing (Brockliss, 1996). The traditional lecture-based classes or courses, usually defined as passive learning, are centred on the teacher, who decides what matters to be learnt (Michael, 2006) and does not allow the development of students' thinking. (Fidalgo-Blanco et al., 2017). Current practice and state-of-the-art suggest that applying new methodologies, based on "ask more, instead of telling" methods, leads to a growth in students' performance (Henderson et al., 2011). In STEM (science, technology, engineering, and mathematics), undergraduate courses average failure rates in conventional lecture courses are 1.5 times higher than in courses where teachers adopt active learning solutions (Freeman et al., 2014). Freeman et al. (2014) also conclude that there is an increase in percentile, passing from 50th in traditional lecture-based lessons to 68th when active learning methodologies are implemented. Contrary to passive learning methodologies, student-centred learning approaches consider the student's position and will, conditioning the pace of learning and what is learnt (Michael, 2006). Despite the current knowledge of pedagogical methodologies, several factors may explain the resistance to change, namely faculty's past experiences as students (Bovill et al., 2016) or habit toward an existing practice, namely by colleagues (Sheth & Stellner, 1979). Also, the perceived risks associated with applying pioneering learning approaches might be an obstacle to switching educational models (Sheth & Stellner, 1979).

Based on the previous statements, adopting teaching methodologies that lead to better involvement of students in the learning process is essential, focusing on problem-solving rather than memorisation (Michael, 2006). Michael (2006) states this will lead to more long-lasting and meaningful learning. By definition, active learning is a process where students are forced to reflect upon ideas and how to use them in practice (Collins III & O'Brien, 2003). During the active learning methodology, students are invited to self- and peer-evaluate, assessing skills while they collect information and solve problems.

Numerous authors have already described several examples of student-centred learning approaches. Among

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the methodologies Michael & Modell (2003) summarised, one may find problem-based or case-based learning and cooperative/collaborative learning/group work. Co-creation methodologies overlap with active learning (Bovill, 2020), as they enhance the interaction between students and teachers and between students and students. According to Michael (2006) and Freeman et al. (2014), students adopt a more active role, performing different activities for gathering information, solving problems, and reflecting upon the current state of the art. Co-creation also enhances students' satisfaction and performance, bringing competitive advantages to educational institutions (Hofstatter, 2010) as they are more engaged with and in the subject (Araújo et al., 2021).

According to Bovill (2020), several types of co-creation can be identified: i) students co-researching university-wide projects; ii) students collaborating with staff in research and scholarship projects; iii) students representatives working together with staff on committees; iv) students participating in course design review committees, being involved in redefining courses and their curricula; v) students as consultants, assessing teachers and providing teaching feedback; vi) students proposing their final projects of masters' thesis topic. Students already do some of the tasks mentioned above at the Polytechnic Institute of Coimbra (IPC), as in other higher education institutions in Portugal. For example, student representatives in the Pedagogical Commission work with faculty to improve courses and their curricula, and part of the teacher's yearly evaluation depends on the students' perception. However, these activities result more from legal or statutory frameworks than co-creation processes. In addition, co-creation initiatives are not often implemented at individual and classroom scales.

To boost the implementation of co-creation processes both in the classroom and across the various modules of the courses, IPC has been promoting, since 2021, pedagogical training courses entitled "Learning based on co-creation processes". This method agrees with what Michael (2006) states concerning teachers becoming learners to reach the projected outcomes when newer methodologies are implemented. Through this experience, teachers can create an environment that encourages active learning. Today, some promising results are visible in the Sustainable City Management bachelor, whose pilot experience is presented in this study.

As part of the evaluation methodology, in the Soil and Behaviour of Soils course, students are invited to propose geo-environmental solutions (nature-based solutions) to mitigate adverse impacts related to climate change events, described as urban challenges, such as urban rapid flood or urban heat island effect. Their proposals are the result of continuous work throughout the semester. However, class assiduity and academic results have decreased in recent years. Aiming for higher involvement of students and better academic results, since the academic year 2022/2023, cocreation methodology has been implemented as the primary pedagogical approach during the development of students' green infrastructure projects. The present study describes all the details of the implemented pedagogical process, giving particular emphasis to the proposed tasks. With these tasks, students are expected to develop a comprehensive understanding of the chosen urban challenges and implement critical and collaborative thinking tools, hopefully leading students to innovative solutions.

To evaluate the results of this new pedagogical approach, two ways frameworks are used: i) an online survey carried out on the last day of classes to understand students' perception; ii) data comparison of academic results and class assiduity achieved in the 2022/2023 academic year and previous academic years. These preliminary results support the urgent need to switch pedagogical approaches in teaching subjects related to geotechnics.

2. Geotechnics' contribution to the sustainable management of cities

2.1 Sustainable cities

In 2015, a historic agreement reached by almost 200 world leaders formalised the recognition of climate change as a global emergency. The "Paris Agreement" became a milestone not only for recognising sustainable development as the only reasonable solution to tackle the many negative impacts of climate change but also for associating it with several goals to which public and private actors committed.

Most of the Sustainable Development Goals (SDG) focus directly on people-related topics (poverty, hunger, health, education, gender, inequalities) and their activities (work, economy, consumption, and production) or the biosphere (life on land or below water, climate). But one of them directly aims at man-made habitat: the cities. The aim is to "make cities and human settlements inclusive, safe, resilient and sustainable".

Cities are recognised as places where the battle for sustainable development will be won or lost. They became a crucial player in this endeavour due to the importance that they have acquired in recent decades. It is estimated that more than 50% of the world's population now live in cities, and the expectation is that this may increase to 70% by 2050. Cities are, and will continue to be, seen as a place of opportunities: jobs, quality of life, culture, or business. This concentration of people in a limited amount of space (cities account for no more than 3% of the land in the world), which constitutes an urbanisation process, raises numerous challenges; from water scarcity to pollution, from mobility to energy consumption, from food supply to informal settlements, from overburden of infrastructures to increased exposure to risks (natural or man-made) (UN-Habitat, 2022).

To overcome all these challenges (and others), a holistic view of the cities and their several systems is required. But also an understanding of the different strategic options and tactical moves that can contribute to increasing urban sustainability, the efficiency of the systems, and the citizens' well-being. The significant events happening in 2015 (Paris Agreement and SDG), plus the awareness of the importance of cities in the future of the planet and the need for professionals able to have a different view on what happens in cities, were the basis for the creation of the undergraduate degree in Sustainable City Management which is taught at the Institute of Engineering of the Polytechnic Institute of Coimbra (ISEC-IPC) since 2018.

In the defining document of the course, it is stated that: "The one who completes a degree in Sustainable City Management will be ready to respond to the challenges associated with a growing urbanised world. Therefore, the locus of their professional action will be the built environment that constitutes the urban areas and its diverse components, with a special emphasis on their management, operation, and optimisation, from a sustainable perspective." From its inception, the undergraduate degree wanted to provide a strong practical emphasis grounded on a solid theoretical background. The focus was on operating, managing, and improving urban systems and infrastructures, keeping sustainability criteria in mind. Hence, the primary learning outcomes were set as follows:

- "To acquire knowledge related to urban sustainability, as well to the existing risks in an urban environment;
- To develop competencies associated with the management, operation and rehabilitation of urban systems and infrastructures;
- To develop competencies associated with the rehabilitation of the built environment (and the soil where it stands), including repair of structures and other constructive elements, improvement of comfort standards, reinforcement of foundations, and introduction of new materials;
- To develop competencies in project and operations management, communication, collaboration and teamwork."

Due to the transversal approach adopted, the syllabus covered diverse topics that included foundations, construction, urban planning, mobility, waste, project management, infrastructures, risks, or GIS (Geographic Information System), among others. But, besides the degree's content, great importance was given to the teaching-learning methods that needed to encourage a personalised approach and meet each student's interests and learning process.

2.2 The importance of geotechnical knowledge in the day-to-day life of a city

Ecosystems provide a wide range of benefits and services for the well-being of humankind that can be grouped into four categories (Millennium Ecosystem Assessment, 2005). In each category, several functions may be identified, as described below (Millennium Ecosystem Assessment, 2005; Adhikari & Hartemink, 2016):

- Provisioning: food, fresh water, wood and fibre, fuel, raw materials, ornamental resources, medicinal resources;
- Regulating: climate regulation, flood regulation, disease regulation, water purification;
- Cultural: aesthetic, spiritual, educational, recreational, ecotourism;
- Supporting: nutrient cycling, soil formation, primary production, and human infrastructures.

These ecosystem services can be related to almost all the United Nations Sustainable Development Goals for 2015-2030. Indeed, Keesstra et al. (2016) state that only goals 5 (achieve gender equality and empower all women and girls), 10 (reduce inequality within and among countries), 14 (conserve and sustainably use the oceans, seas and marine resources for sustainable development) and 17 (strength the means of implementation and revitalise the global partnership for sustainable development) cannot be related to ecosystem services. According to the European Commission (EC, 2006), soils and rocks contribution to ecosystem services may be divided into seven groups of functions: i) biomass production (including agriculture and forestry); ii) storing, transforming and filtering substances, water and nutrients; iii) biodiversity; iv) physical and cultural environment for humankind and human activities; v) source of raw materials; vi) acting as carbon pool, and vii) geological and archaeological heritage.

Several soil sciences contribute to understanding and enhancing soil and rock functions, namely, agronomy, ecology, hydrology, and climatology (Keesstra et al., 2016). Although Keesstra et al. (2016) do not refer to it, geotechnical engineering should also be considered since the utilisation of soils and rocks requires technical design to ensure safety when citizens take advantage, directly or indirectly, of the infrastructures built on, under or with soils and rocks. Thus, the knowledge of soils and rock properties is fundamental. In urban areas, soil and rock functions are provided by parks and gardens, which contribute to air quality regulation, water regulation, local climate regulation, cultural heritage, recreation and education (Millennium Ecosystem Assessment, 2005). Depending on the city's location, other functions may be added, such as storm and wave protection and erosion control.

The ability of soils and rocks to perform the aforementioned functions depends on their intrinsic or situational characteristics, among which stand out (Adhikari & Hartemink, 2016): particle size distribution, bulk density, hydraulic conductivity and infiltration, soil temperature, soil porosity and air permeability, water content, soil *pH*, particles mineralogy or soil biota. In addition to these parameters, one may add soil and rock strength and deformation parameters. These parameters might be grouped under biological, chemical and physical indicators, as Bünemann et al. (2018) stated.

Humankind evolution and population growth have been increasing pressure on ecosystems, resulting in several soil threats (Bünemann et al., 2018), namely erosion, soil organic matter decline, contamination, sealing, compaction, biodiversity loss, salinisation, landslides and floods. According to the United Nations (2018) and World Bank (2022), 55% of the current population lives in cities, and 70% of the world population is expected to live in cities by 2050. Based on this data and previsions, soil threats and related phenomena will likely increase, thus justifying the inclusion of subjects related to geotechnics in sustainable city management. Additionally, natural hazards, such as those resulting from seismic or volcanic activity, should also be considered when planning and thinking about cities.

Given the above, the education offered in the bachelor's degree in Sustainable Cities Management includes three mandatory subjects: Soils and Rocks, Study and Behaviour of Soils, and Foundations and Land Support; one optional subject, Improvement and Reinforcement of Soils and Foundations as well as some modules integrated into other subjects, such as Landslides in Urban Risks. The syllabuses of these subjects contemplate a wide range of soil and rocks topics, such as:

- geology for engineering: Earth formation, plate tectonics, rocks cycle;
- environmental geotechnics: soil contamination, soil and rocks as construction material, quarries and sandpits, ecosystems, blue and green infrastructures, geosynthetics, ground improvement;
- energy and climate change: geothermal energy, urban floods, coastal erosion, urban heat island, air quality, waste management;
- soil testing: recognition and prospecting, laboratory testing, in situ testing;
- soil mechanics: soil identification and classification, hydraulic conductivity, shear resistance, compressibility and consolidation;
- geotechnical engineering: earth retaining structures, shallow and deep foundations, pathologies and foundations reinforcement;
- geotechnical risks: seismicity, liquefaction, quickclays, quicksands, landslides, piping.

These subjects and all the topics taught intend to provide students skills and competencies that allow them to understand or to know how to carry out studies on soils and rocks, how society can take advantage of these materials using nature-based solutions, how soils and rocks respond to external loads, what technical or environmental solutions are available, what are the risks populations face depending on their geographical position. Some of these topics include studying the physical properties of soils and rocks and technical knowledge. However, there is a clear distinction between the knowledge transmitted to a future engineer, who may be responsible for the design and construction of geotechnical structures, and a manager, who may be responsible for the idealisation, promotion or management of geotechnical solutions to face new future challenges in a world in constant and rapid change.

Among these challenges, climate change and its related phenomena should be highlighted. According to the last Intergovernmental Panel on Climate Change (IPCC), several countries or geographical areas have already demonstrated weather and climate changes. For example, since 1950, hot extremes have been recorded in all states-member of the European Union, leading to an increase in ecological drought in the Mediterranean countries and Western and central Europe (Intergovernmental Panel on Climate Change, 2021). Also, except for Mediterranean countries, the rest of Europe has observed changes in heavy precipitation. The extreme events hugely impact ecosystems and human systems (Intergovernmental Panel on Climate Change, 2022a). Indeed, an increase in adverse impacts on health and well-being has been recorded in Europe, namely on cities, settlements, and infrastructures due to inland flooding.

Based on the five Shared Socio-Economic Pathways (SSP) presented by Intergovernmental Panel on Climate Change (2021), it is expected that, for global warming levels up to 2 ºC, hot extreme temperature events that traditionally happen once every 10 and 50 years now occur up to 5.6 and 13.9 times. It is also expected an increase of heavy 1-day precipitation events, passing from a frequency of once per 10 years to 1.7 times in 10 years. It should be noted that these events will likely be 14% wetter than now (Intergovernmental Panel on Climate Change, 2021). Several climate responses and adaptation options are available to face current and expected extreme events. These solutions are transversal to several scientific domains in which geotechnics can significantly contribute, namely in managing land and ocean ecosystems and urban and infrastructure systems (Intergovernmental Panel on Climate Change, 2022a). Geotechnical knowledge is fundamental when proposing or idealising solutions for (Intergovernmental Panel on Climate Change, 2022a, b):

- coastal defence;
- water use efficiency and water resource management;
- sustainable urban drainage systems;
- implementation of green and blue infrastructures;
- sustainable urban and land planning;
- district heating and cooling networks (geothermal energy);
- waste minimisation and management;
- on-site and nearby production and use of renewables (geothermal energy);
- change in construction methods, materials and circular economy;
- carbon capture and storage;
- disaster risk management, including early warning systems;
- nuclear waste disposal;
- others.

The idealisation of solutions to urban issues, the enhancement of environmental approaches (green corridors), the proposal of mitigations and adaptation solutions to climate change (urban flood, urban heat island, carbon capture and storage), the study current state of the art of recent application fields, the forecast of future geotechnical challenges (space mining, for example), the identification of urban areas likely to be intervened for the implementation of green infrastructures or understanding the reasons for better or worse acceptance of geotechnical solutions (such as geothermal) are some of the assignments and challenges proposed in two of the subjects mentioned above taught in the bachelor's degree in Sustainable City Management. In Soils and Rocks and Study and Behaviour of Soils subjects, the continuous assessment methodology foresees group work to be carried out on these and other topics of geotechnical interest.

3. Co-creation approach in classroom

Kambil et al. (1999) presented, for the first time, the concept of co-creation to express the interactions between companies and consumers, generating added value for all the stakeholders and introducing new dynamics between them. Although many definitions have been proposed since then, all share the same characteristics (García Haro et al., 2014): i) co-creation is a process that involves companies and users; ii) the activities require the collaboration of the stakeholders; iii) co-creation aims to create value for both stakeholders. It is also important to mention that a co-creation process should also be perceived as a stimulus to innovation and the development of new solutions (Orcik et al., 2013). The European Commission (2021) considers that co-creation processes are based on innovative approaches, allowing participants to interact from different backgrounds. Also, policymakers have encouraged co-creation processes (Chryssou, 2020). In a global society in which companies intend to benefit from a faster transfer of knowledge (Polese et al., 2021) and universities seeking opportunities to promote research, improve metrics and involve students in the market, co-creation processes are an asset for all parties involved (Cohen et al., 2002). However, partnerships established in co-creation processes depend on some factors to be successful (Rybnicek & Königsgruber, 2019), namely:

- structural, such as bureaucracy, organisation flexibility and decision-making process;
- of commitment, which is related to how much the involved parties identify themselves with the process and its objectives;
- reliability;
- willingness to change, that is, the ability to adapt to different circumstances being receptive to change;
- communication and regular information sharing.

Finally, the outcomes of co-creation challenges depend on the participants' creativity. Although creativity can be identified at any age, due to the curiosity that characterises younger people, the involvement of higher education institutions, where thousands of young people study, in co-creation activities emerges as a logical consequence for developing future solutions and knowledge transfer. During the process, students will experience three dimensions (Dziewanowska, 2018). Under the co-production dimension, which is related to what students really do in the process, they have to learn how to dialogue, control the process, and access and manage information. The second dimension is the experience, which is related to involvement and intellectual stimulation. The last dimension is the relations created among the students and their interaction with others, and how they share the knowledge.

Implementing active learning methodologies alone, such as co-creation approaches, does not guarantee academic success or student participation. According to Vanishree & Tegginamani (2018), successful project-based learning requires, among other assumptions: i) students' attendance and punctuality; ii) steps of the methodology cannot be skipped; iii) the process should be evaluated regularly; iv) students should be proactive and not wait for facilitator to provide all the needed information and details. Not the least, the triggers of the methodology (urban challenges) must stimulate students' motivation and interest in solving the presented challenges. Of course, as with any other pedagogical approach, the co-creation methodology has disadvantages. Concerning the acquired knowledge, Jones (2006) states that it may be less organised than knowledge resulting from traditional learning. Also, the time required for a full engagement of students may not be compatible with crowded curricula (Jones, 2006), being faculty-intensive and time-consuming (Ribeiro, 2011; Abdelkarim et al., 2018). For institutions, implementing such a methodology requires investment in human and physical resources (Pawson et al., 2006). The faculty's educational philosophy can only be changed by training and a differentiated learning environment; for example, more flexible classrooms that provide a creative atmosphere are needed.

The co-creation methodology implemented in the IPC is based on the Demola model developed by Demola Global. This international organisation facilitates co-creation projects between higher education institutions and public and private entities. The group was established in Finland in 2008 and currently operates in 18 countries worldwide. This program brings together students and teachers as facilitators and, depending on the challenge and objectives, it may include organisations. Ideally, the student team should be transdisciplinary to enhance strategic thinking based on the perception of the new generations and, thus, provide solutions to real challenges/problems posed by organisations, when involved, or by the teacher, as illustrated in Figure 1.

As the present study was conducted at the classroom level, the implemented co-creation model has to be adapted. The student team is comprised of only students who attended the Study and Behaviour of Soils course. During the fall semester of the academic year 2022/2023, 24 students in the second year of the bachelor's degree in Sustainable Cities

Management were invited to participate in a co-creation process as part of the continuous assessment methodology. Among the 18 students who were effectively evaluated (6 of the students gave up), most are male, counting 83.3% against 16,7% of females. All the students are between 19 and 23 years old, most of them being 19 years old (66.7%). The weekly workload of the course is 3.5 hours, and the semester lasts 15 weeks. During the implementation of the co-creation process (8 weeks), the first 1.5 hours of class were dedicated to the co-creation, introducing the weekly task and allowing the groups of students to start working on it. During the remaining class time, the syllabus planned for the class was presented, and expository sessions were interspersed with laboratory and problem-solving moments. The class was divided into three groups of 6 students. Given the conditions of access to this bachelor's degree, different paths in high school could be identified. Thus, it ensured the greatest heterogeneity in the groups to improve the creative process, which took place, as stated before, over eight weeks and followed the double diamond model. This model, which was first proposed by Banathy (1996), comprises two distinct phases: "Discovery" and "Creation" (Figure 2).

The "Discovery" stage of the process, which is the first stage, is intended for students to gather as much information as possible on the challenge topic. In the 2022/2023 academic year, under the motto of the European Commission, the main topic of the challenge was "Green infrastructure project: a network of healthy ecosystems provides alternatives to traditional grey infrastructures". Once the groups have been formed, each group proposed a challenge integrated into the main topic of the process, that should agree with the objectives of the bachelor's degree. Although the outcomes of each challenge are beyond the scope of this study, the proposed challenges were:

- study of solutions for the occurrence of floods in Praça 8 de Maio, in Coimbra;
- integration of green infrastructures in the Norton de Matos neighbourhood (Coimbra) to collect rainwater and return green spaces to residents;
- model of the use of green infrastructure to the reuse of rainwater in typical dwellings.

Group formations and challenges proposal, which took place during the first week of the co-creation process, represent the first task of the methodology. Through the following three

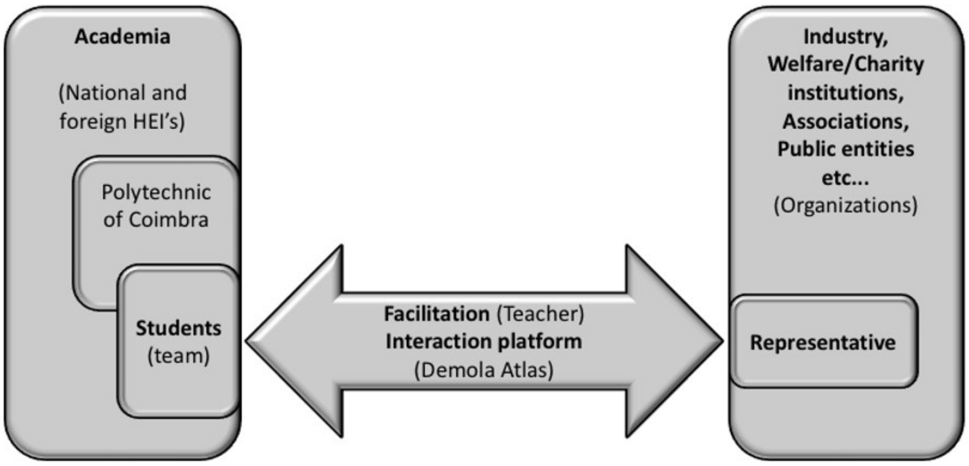


Figure 1. Demola innovation co-creation model.

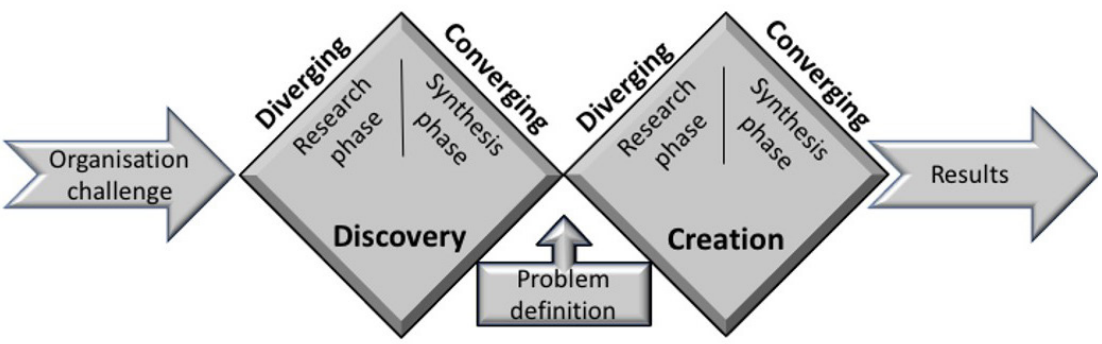


Figure 2. Double diamond model applied to innovation co-creation process (adapted from Banathy, 1996).

weeks, students carry out several tasks, which can be divided into two distinct phases: i) the research phase and ii) the synthesis phase (Figure 2). During weeks 2 and 3, students must list all the stakeholders that directly or indirectly can influence or be influenced by their challenge topic. After this long list, students must identify three to five stakeholders on which the students' research will focus. They will identify potential interviewees whose knowledge of the topic will complete the information acquired from reading and analysing articles and all other relevant sources of information. Despite the time devoted to projects in class, students must continue the work at their own pace. Thus, it is recommended that all the collected information be compiled in collaborative and visual platforms (e.g., virtual boards, shared documents). The use of virtual and blackboards facilitates the tasks of the synthesis phase of the "Discover" stage of the process. In the synthesis phase, during weeks 4 and 5 of the process, students are invited to complete empathy maps where each target stakeholder is characterised based on what it says, does, feels or thinks. When synthesising all the information, students must identify design insights, which are outcomes that stand out from the rest of the information more conjectural. After completing the previous tasks, students may write their midway report. In addition to empathy maps and design insights, the research results, as well as the evidence collected during the interviews, allow students to have a macro understanding of the topic. All this information is summed up in a PESTLE report in six dimensions: political, economic, social, technological, legal, and environmental.

During the "Discovery" stage, the teacher acts as a facilitator, offering assistance and advice while working on the team's motivation and fellowship. The facilitator also: i) presents and proposes several tools for collaborative work; ii) helps to separate relevant sources of information from less reliable ones; iii) moderates and schedules weekly meetings where the entire team should be present, which, usually, takes place during classes. If the challenge involves third parties, the facilitator enhances contact between the representative of the organisation and the students, promoting virtual or physical meetings. This supporting role gains relevance during the second part of the challenge: the "Creation" stage. To not conditionate students' creative process, the facilitating teacher and the organisation's representative (if any) have limited interference during this stage. The facilitator supports the team by promoting interviews with specialists/researchers on the challenge topic and coordinating field trips to research, innovation centres, or other places. These activities, which also provide a creative atmosphere within the team, ensure that the team's vision has not been unsuccessfully explored. The creative atmosphere supplements the atmosphere of trust between the students, allowing the sharing of opinions, thoughts, and skills without fear (European Commission, 2021).

The "Creation" stage can be seen as the creation phase itself, in which, based on the knowledge gathered during the "Discovery" stage of the co-creation process, students carry out speculative work, identifying alternative outcomes to the proposed challenge. The transition from the current situation or state of the art to a probable future is supported by several thinking tools, which rely on identifying "weak signals". Many definitions for weak signals may be found in the literature. In the present work, the authors follow the definition from the compilation proposed by van Veen & Ortt (2021) who refer: "*a perception of strategic phenomena detected in the environment or created during interpretation that are distant to the perceiver's frame of reference*". I.e., weak signals are singularities that take place everywhere and seem unlikely and/or cause bewilderment. Each student is invited to identify at least one weak signal during week six of the co-creation process.

After identifying those weak signals, students can start to define their speculative design by asking two types of questions: What if…?, and How might we…? These questions are part of a creative thinking methodology whose application makes it possible (Lahiri et al., 2021): i) to frame complex problems, ii) to discover needs still unknown, and iii) to propose more appropriate solutions. These questions should be provocative and bold and cannot be limited to factual situations that may or may not happen, such as political, economic, social or any other constraints. The speculative questions and the proposal of future scenarios are the assignments for week 7 of the co-creation methodology. Based on the outcomes of the previous weeks and the speculative questions, students suggest three scenarios, identifying the winds of change and the possible effects of the proposed future vision. The creative stage (Figure 2) ends with the elaboration of a future report (week 8), which compiles all the information contained in the midway report as well as all the speculative work carried out in this second stage, highlighting the future scenarios, which are the primary outcomes of the co-creation process.

After delivering the future report, a third and final stage occurs: the presentation of the team's outcomes. In a classroom context, such as the experiment carried out in the course of Study and Behaviour of Soils of the bachelor's degree in Sustainable City Management, this presentation assumes the characteristics of an academic presentation, with the facilitator teacher encouraging the diversification of instruments to support the presentation, such as models or videos. However, this pitch may also occur for broader audiences, namely final pitches and national or international batches, such as those that the IPC and other Portuguese polytechnics have promoted since 2021. When organisations are involved, the project outcomes are first presented to them. Table 1 summarises the main tasks proposed to all the groups during the co-creation process.

4. Outcomes of co-creation implementation

4.1 Research design

The co-creation pedagogical approach that was applied, and whose description and results are presented in this study, has been implemented in the course of Study and Behaviour of Soils, a subject of the second year, fall semester. The students who participated in this initiative were also asked, in the previous academic year (first year, spring semester), in the course Soils and Rocks, to prepare and present an assignment to be carried out in groups. In this last course, the methodology followed a more traditional approach, in which all information was provided at the beginning of the year. Based on the information provided, students should work autonomously, setting their own pace and goals. Only the final date of the presentation has been defined. Finally, it should be noted that, in both cases, the maximum grade for teamwork was 5 points out of 20.

Once the outcomes of the co-creation projects were presented, students were asked to answer a final survey to evaluate their satisfaction level with the methodology and their perception of the development of various social, personal, and professional skills. Since the students had already attended another subject in the field of geotechnics, questions aimed at a direct comparison of pedagogical methodologies were also prepared.

The questionnaire counted eighteen questions. The first set of questions comprised eight questions about the students' perception of the skills developed during participation. The second set of questions (six questions) referred to applying the co-creation methodology in a classroom context, aiming to evaluate and understand the degree of satisfaction with the process and the impact of such a pedagogical approach on students. A third set with two questions intends to directly compare co-creation methodology with traditional assignments. Finally, a last set of questions has two open-ended questions to collect information about difficulties felt by the students during the co-creation process and improvements that can be made to this pedagogical approach. Except for the two last questions, the questionnaire was applied on a multiple-item scale (from 1 to 7), Likert type. On this scale, 1 represents "completely dissatisfied" or "strongly disagree", while 7 suggests "completely satisfied" or "strongly agree".

4.2 Results and discussion

4.2.1 Soft and scientific skills improvement

Student's perspectives about the competencies developed during the implementation of the co-creation methodology are shown in Figure 3. In an overall analysis, it is easy to conclude that students recognise that their skills improved during the process, namely the so-called 21st Century skills (World Economic Forum, 2016). According to this document, the 21st-Century skills may be divided into three

Table 1. Co-creation methodology tasks timetable.

	Timetable	Tasks
Discovery Stage	Week 1	Selection of working groups and definition of the challenge (theme chosen within the syllabus of the curricular unit)
	Week 2	List of Stakeholders, potential interviewees
	Week 3	Conducting interviews, questionnaires and collecting information / compiling information
	Week 4	Empathy maps / Design insights / PESTLE analysis
Creation Stage	Week 5	Midway report
	Week 6	Signals (3 main takeaways)
	Week 7	Speculative questions. Future Stakeholders - future changes – future scenarios
	Week 8	Final report (Assessment)

Figure 3. Student's perspective on skills and competencies developed during the implementation of co-creation methodology.

groups: i) foundational literacies, ii) competencies, and iii) character qualities. The second group of skills has the most cited competencies, also known as the 4C: critical thinking, creativity, communication and collaboration. Concerning creativity and communication (Figure 3), students have a positive perspective on the contribution of this pedagogical approach to developing these competencies, reaching 83% and 92% of positive opinions for creativity and communication, respectively. Notably, 50% of students answered “agree” or “strongly agree” in both competencies.

Although 75% of the students also have a positive perception of the influence of co-creation methodology on the development of their critical thinking, 17% of students “somewhat disagree”, and 8% have a neutral opinion. Finally, 8% of students consider that their collaboration competency (teamwork in Figure 3) did not improve during the process, which contrasts with the opinion of 84% of their colleagues who answered “agree” or “strongly agree”. One possible reason to justify these less favourable standpoints may be related to the working group itself. As stated in Section 3, the elements of the groups were chosen to guarantee the greatest possible heterogeneity, and this choice was not always in line with the personal affinities of the students, leading to misunderstandings between the elements of the group. This conclusion is supported by the suggestions and difficulties presented by the students in the two last open-ended questions of the survey. The impossibility of choosing group members and the problematic relationship between some members were issues mentioned in 33% of the comments written by students. Another interesting deduction is that, despite the experience acquired in online work during Coronavirus Disease 2019 (COVID-19) lockdowns, the difficulties in gathering the group members and the physical distance between the places of residence were mentioned in 13% of the comments presented.

The character qualities, the third group of skills valued by World Economic Forum (2016), relate to how students deal with changes in their surroundings. Among the listed qualities, one may identify initiative, adaptability and leadership, which were also considered in the student survey. When asked if co-creation methodology helps students to increase their entrepreneurship (Figure 3), which can be understood as initiative, 92% of students have a positive perspective (33% agree and 42% strongly agree). Students’ adaptability to new challenges may be measured through their ability to research and collect data to face unforeseen events or situations. Students’ opinions could not be enlightening, with all the students having a positive perception, 50% of them strongly agreeing with the contribution of this pedagogical approach to increase this quality. The worst results are related to leadership; 25% of students perceived that the quality was not improved during the process. To conclude the analysis of the skills developed throughout this methodology, one may refer to the digital skills, which can be encompassed in ICT literacy (Information and Communication Technology), a core skill of the foundational literacies, according to the World Economic Forum (2016). 83% of students consider participating in the project improved their digital skills.

The results above align with the study conducted by Costa et al. (2021) with 87 students from 19 different countries across all the higher education levels. According to Costa et al. (2021), based on a 4-point scale, creativity, teamwork, leadership, and entrepreneurship reached 3.5, 3.6, 3.4, and 3.4 points, respectively. It should be noted that similar to the results of this study, students’ perception of leadership skills is not as favourable as the other skills. On the other hand, in Costa et al. (2021) study, the students concluded that co-creation methodology enabled them to develop teamwork skills.

4.2.2 Academic performance

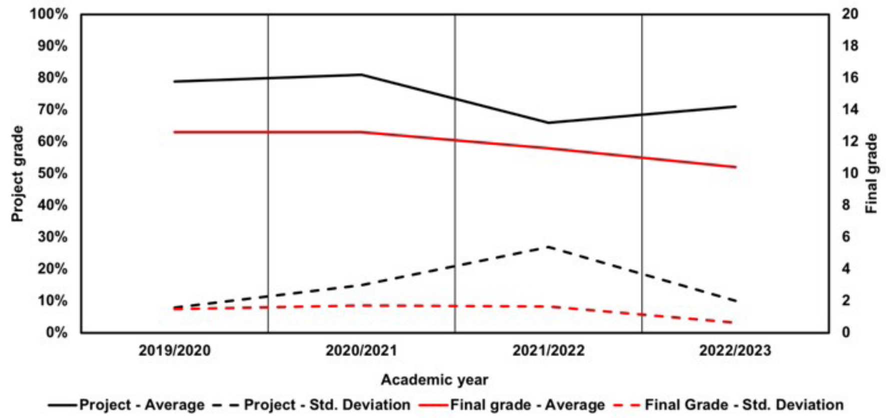
Implementing a co-creation methodology as a pedagogical approach is intended to provide a more favourable knowledge acquisition and transfer environment. Thus, it is also essential to evaluate students’ academic results. For this, in addition to the average data of the academic year 2022/2023, to which the survey results relate, the results are also presented since the opening of the bachelor’s degree in Sustainable City Management. It should be noted that, during the COVID-19 pandemic, although Study and Behaviour of Soils classes were always held face-to-face (since it is a subject from the fall semester), students were affected by the lockdowns that occurred in Portugal in 2020 (March to May) and 2021 (January to March). Starting by analysing students’ performance in the subject assignment/project, it can be seen in Figure 4a that the implementation of the co-creation methodology allowed recovery from the significant decrease of students’ marks (14%) registered between 2020/2021 and 2021/2022. Another interesting result is the decrease in the standard deviation resulting from the group formation process.

Contrary to the improvement of results in continuous evaluation, students’ final grade, which comprises the assignment/project and written examinations, is still decreasing. It should be noted that although the implementation of the co-creation methodology changed, its weight in the final grade remained the same, that is, 25% of the subject’s final grade. The authors currently have no explanation for this observation. However, the social and school effects of decisions taken during the COVID-19 pandemic cannot be disregarded. Interestingly, despite the decrease in the average students’ final performance, the number of students failing the subject decreased from 36% to 25%, as shown in Figure 4b. This improvement may be related to the increase in class attendance recorded in 2022/2023. Comparing this assiduity data with data referring to the subject of Soils and Rocks attended by the same students, there is a 5% increase in class attendance.

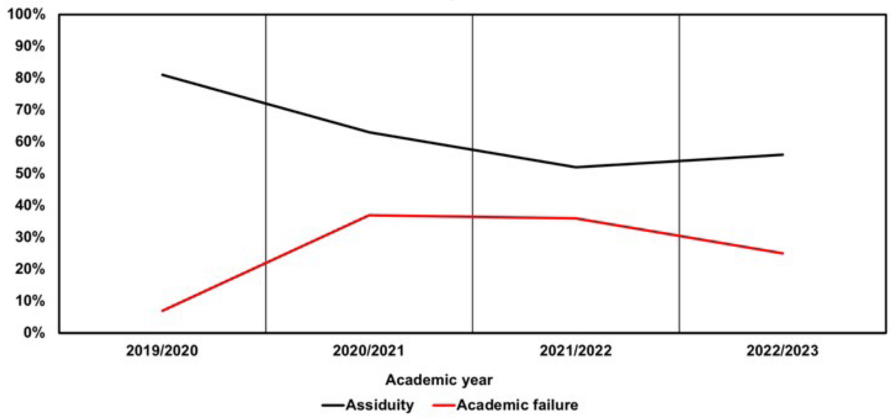
4.2.3 Overall evaluation of the methodology

From a pedagogical point of view, the implementation of co-creation methodology in a classroom context has also been evaluated through a second set of questions, whose results are summarised in Figure 5. As it can be seen, according to the students' perspective, the overall evaluation is positive. In particular, 84% of students are satisfied with participating in the project and the methodology. Also, 92% of the students would like to see this methodology applied to other subjects, of which 75% answered "strongly agree". These results are corroborated by the perception of the students who participated in the study of Costa et al. (2021), in which participation in the project was rated 3.8 out of 4.0, and 93% of students would recommend other colleagues to participate in such an experience.

According to the students, the conduction of classes and lessons is positively affected by implementing this pedagogical approach: 92% of students answered that class productivity and the dynamics of the classes themselves improved (Figure 5). Indeed, Araújo et al. (2021) state that when co-creation methodology is implemented, students tend to be more active in the learning process. However, the students have identified some limitations related to the task timetable (Table 1). A small



a)



b)

Figure 4. Students' academic performance: (a) scientific and technical evaluation; (b) academic data.

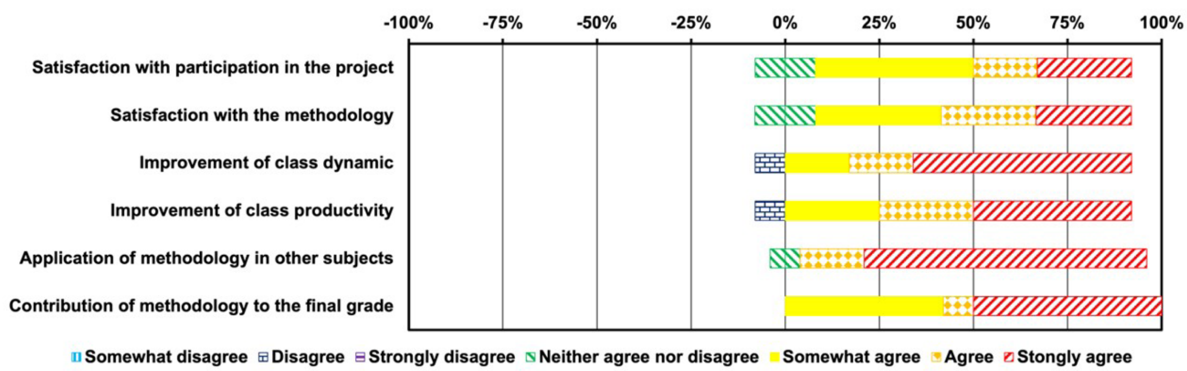


Figure 5. Students' perspective of the benefits of implementing co-creation methodology in the classroom context.

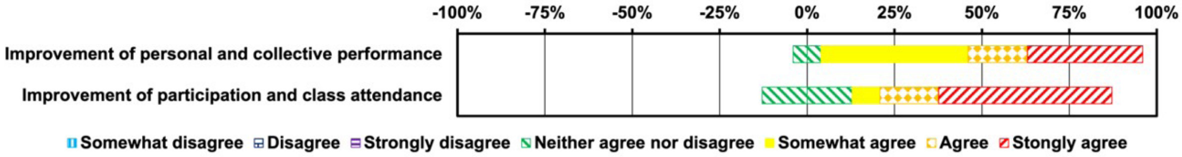


Figure 6. Students' opinion on the implementation of the co-creation methodology, comparing two subjects in the geotechnics field.

percentage of students (6%) point out the need for more delivery times to better organise their research and teamwork. 20% of students also identified the need for diversification of learning tools during the implementation of the process, such as the inclusion of more laboratory tasks, field visits and/or the use of more audio-visual means when presenting and explaining the geotechnical concepts of the course syllabus.

An essential outcome of this set of questions is students´ perception concerning the contribution of this pedagogical approach to their final grade in Study and Behaviour of Soils. All the students positively perceive the benefit of co-creation in the achieved results. Although the average final grade is still decreasing compared to the previous academic years, academic failure decreased by 11%. This perception can be understood by considering the academic results of the students in the subject Soils and Rocks, which the same students attended the previous semester. Indeed, after all the exam calls that ISEC-IPC provides to all its students, 61% of students failed, which is 2.5 times more than the failure rate obtained in Study and Behaviour of Soils. This observation was, in fact, at the origin of the adoption of this new pedagogical approach.

These conclusions are reinforced by the last set of questions, intended to directly compare Soils and Rocks (spring semester of the academic year 2021/2022) and Study and Behaviour of Soils (fall semester of the academic year 2022/2023). As stated in Section 4.1, the continuous evaluation of Soils and Rocks presupposes a group assignment with the abovementioned characteristics. As Figure 6 shows, students consider that their personal and collective performance improved (92%). This result agrees with the engagement outcomes presented by Araújo et al. (2021). When comparing the average final grade of students, there is an increase from 10.1 to 10.4 (out of 20 points). Also, the standard deviation decreases from 2.13 to 0.65. This reduction translates, understandably, to a decrease in higher grades but also an increase in the lower grades of students. The average grade in the proposed group work in Soils and Rocks is 75%, slightly higher than the 71% obtained in Study and Behaviour of Soils. However, once again, the standard deviation decreases from 18% to 10%. This reduction, as well as the one verified in the average final grade, may explain students' perception of their performance, namely if students had reached the lowest grades in Soils and Rocks. According to 26% of the students, implementing the co-creation methodology in a classroom context had a neutral effect on increasing participation and class attendance (Figure 6). This contradicts the data collected on the ISEC-IPC academic management platform, as illustrated in Figure 4b.

5. Conclusions

Humankind's evolution is at the origin of several social, economic and environmental issues in current times, such as climate changes, land use and (mega)city management. Aiming to prepare citizens to face these challenges by idealising, providing or applying solutions, the Institute of Engineering of the Polytechnic Institute of Coimbra (ISEC-IPC) proposed a new bachelor's degree in Sustainable City Management, which has been training and preparing students since 2018. Among the numerous topics covered, students attend mandatory or optional geotechnics courses, learning basic concepts of soil mechanics, environmental geotechnics, ecosystem function of soils, soil improvement, and natural capital, among others.

Aiming to increase students' performance in a particular subject of the undergraduate degree, Study and Behaviour of Soils, and taking into account recent results in another geotechnics-related subject (Soils and Rocks), a new pedagogical approach has been implemented in the academic year 2022/2023: co-creation process. This methodology, which aims to develop and propose innovative solutions to solve current and future geotechnics-related issues of cities, is presented, and some tasks that can be proposed to the students are fully described in this study.

This implementation is an undergoing pedagogical experiment and requires enhancements, such as more extended deadlines and diversification of learning tools. Nevertheless, this case study provides a positive perception of students, aligning with previous studies in different fields. Generally, it is possible to highlight the following findings:

1. 75% of students have agreed, although at different levels, that implementing a co-creation methodology helps improve their soft skills. The most deviant result refers to teamwork, which several students have highlighted in the open-ended questions;
2. When examining students' final results, although the final grade did not improve, the student failure rate decreased by 11%, and the lowest mark increased. Academic data also reveal that class assiduity increases, although students do not have this perception;

3. 92% of students want this methodology to be applied to other subjects. 84% of students concluded it is more advantageous and leads to better personal and collective performance.

The present study corroborates previous research by identifying the benefits of co-creation methodology as a pedagogical process to enhance soft skill acquisition and students' motivation and participation, hopefully leading to better grades. However, geo-environmental education also requires hard skills, such as basic and advanced knowledge of permeability, shear strength and compressibility. The next challenge is to adapt this methodology to captivate the attention of students, who have shorter concentration times, less tolerance for delayed results and a growing digital presence, to continue training and educating the next generations of professionals in geotechnics. To achieve this purpose, the authors suggest to:

- Replicate the double diamond model (Banathy, 1996) for different topics of the course syllabus;
- Introduce a blended learning approach during the methodology's discovery phase. Using e-activities (digital environment) may enhance students' learning process, according to their own pace and learning profile, to acquire the scientific or empirical background needed. The design of these e-activities should contemplate all the principles proposed by Salmon (2002). By implementing these e-activities, more contact hours can be dedicated to practical or laboratory implementation;
- In the creation phase, which should occur only in a physical environment (classrooms), developing problem-oriented learning approaches allows students to apply the recently acquired knowledge. Through collaboration, students can achieve deeper and longer-term retention, as suggested by the learning pyramid model.

Declaration of interest

The authors have no conflicts of interest to declare.

Authors' contributions

Vera Cristina Ribeiro: conceptualization, validation, writing - original draft preparation, writing - reviewing and editing. Sara Isabel Azevedo Proença: data curation, funding acquisition, project administration, writing - reviewing and editing., visualisation. Luis Manuel Araújo Santos: resources, formal analysis, writing - original draft preparation, writing - reviewing and editing. João Armando Pereira Gonçalves: writing - original draft preparation, writing - reviewing and editing.

Data availability

The datasets presented and analysed throughout the study are available upon request to the corresponding.

List of symbols and abbreviations

4C 21st century skills	critical thinking, creativity, communication and colaboration
pH	potential of hydrogen
COVID-19	Coronavirus disease 2019
GIS	Geographic Information System
ISEC-IPC	Institute of Engineering of the Polytechnic Institute of Coimbra
IPC	Polytechnic Institute of Coimbra
IPCC	Intergovernmental Panel on Climate Change
SDG	Sustainable Development Goals
STEM	Science, Technology, Engineering and Mathematics

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TECHNICAL NOTE

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The difficult task of teaching shear strength of soils

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Technical Note

Keywords
Geotechnical education
Shear strength
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Abstract

Shear strength is a classical topic in Soil Mechanics and generally there is little concern about the inconsistencies behind the theories used to predict its value. In fact the debate on this issue is rather limited as the geotechnical community considers this a well-established concept. This note intends to highlight the difficulties that arise when teaching that concept in an undergraduate Soil Mechanics course. Those difficulties are related to the drained/undrained behavior of soils, but also to the fact that cohesion is a tricky parameter, with a misleading physical meaning, depending not only on the properties of the contacts between particles, but also on external conditions (i.e., saturation or unsaturation). All these aspects are not analyzed in detail in many textbooks, but they should be considered in a modern Soil Mechanics course.

1. Introduction

Soil Mechanics is a typical subject in most of the Civil Engineering degrees everywhere. Also, most of the Mining degrees and some Architecture Engineering degrees include some Soil Mechanics topics in the curriculum. In general, students in the Civil Engineering Schools attend a lot of courses on Mechanics and Structural Engineering, following the traditional organization from the oldest Civil Engineering Faculty in the world: the "École Nationale des Ponts et Chaussées", founded in Paris in 1747. A few specific courses on Soil Mechanics were implemented later, during the 20th century, in the Civil Engineering Schools. However, nowadays, typically, there are fewer courses on Soil Mechanics and Geotechnical Engineering than courses on Concrete or Steel technology.

It is obvious that Soil Mechanics uses many concepts from other disciplines as Continuum Mechanics or just Mechanics, but the material involved, soil, is particularly different from other materials used in construction, and this is quite difficult for students when comparing soil properties with concrete or steel. Some of the differences are:

- Soils are natural materials. There is not any quality control on their mechanical properties (as in a man-made material), so diversity and heterogeneity are inherent features;
- Soils have been in nature for many years (thousands…), undergoing mechanical changes (and even chemical changes). They may have been loaded and unloaded and they have initial stresses before being loaded further due to construction;
- Soils are not elastic materials, that is, they do not behave in a reversible manner. Loading and unloading processes must be carefully analyzed working in increments of stresses and strains;
- Soils do not have constant mechanical properties in general. The same soil has mechanical properties depending on confinement, that is, depending on depth;
- Pore water pressure has much influence on soil properties as soil is a porous medium. Students find difficult to realize that for a particular soil at a particular depth, strength is not constant, but depends on pore water pressure as well, a quantity that is essentially variable;
- Soil strength depends on strains also, and the same clay may behave as a ductile or as a brittle material, depending on the past loading and unloading history.

Considering all these aspects, shear strength is a mechanical concept that is particularly difficult to teach properly to the students (Pantazidou, 2015). However, there is not much debate on that and the teaching resources available, in general, do not focus on those difficulties, which arise from the fact that the procedure used to estimate shear strength and related concepts are not very precise. In several provocative papers, Schofield (1998a, b), suggested that Coulomb theory included an error. Surprisingly, the comments on this among the Geotechnical community are scarce. Schofield referred to the physical interpretation of the cohesion and friction terms in the Mohr-Coulomb strength criterion, a point that is discussed below.

2. The Mohr-Coulomb strength criterion

The classical Mohr-Coulomb criterion, accepted today as the fundamental law for soil shear strength in saturated conditions, is the result of the evolution of the initial idea

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from Coulomb, back in 18th century. Coulomb considered the thrust on gravity retaining walls working with forces (the concept of stress was not defined yet), and solved the limit equilibrium problem of a failure wedge determining the true position of the sliding surface using calculus concepts for maxima and minima. His paper from 1773 was recently reprinted in the Revue Française de Géotechnique (Coulomb, 2023) and has been analyzed by several authors as Heyman (1972), Schofield (1998a, b), Salençon (2022) and Lacasse (2023), among others.

Coulomb assumed that the soil strength had several components: adhesion, cohesion and friction, but the definition of each component was not very precise (translation to English by Salençon (2022):

- "Friction and cohesion are not active forces such as gravity that always fully exerts its effect, but only coercive forces; those two forces are assessed through their limits of resistance";
- "The resistance due to friction is proportional to the pressure exerted";
- "Cohesion is measured by the resistance that solid bodies oppose to the direct disunity of their parts";
- "Adhesion forces are equally resistant whether they are directed parallel or perpendicular to the fracture plane".

Coulomb did some experiments with rock and he used the word "adhesion" when referring to experiments in tension, and "cohesion" for shear failure conditions. However, he measured similar values for both concepts. He also realized that remoulded soils should have zero cohesion or adhesion. Coulomb continued for several years his experiments on friction (Kerisel, 1973).

About 50 years later, Cauchy developed the concept of stress and eventually Mohr, about 1882, defined the graphical construction that allows obtaining the stress state at a point, acting on any plane: the Mohr circle.

Later, in 20th century, Terzaghi proposed the current version of the Mohr-Coulomb criterion. He kept the same structure of the formula: a constant term called cohesion and a term that depends linearly on the normal stress due to friction. However, he introduced the effective stress in the computation of the normal component. That is, the limit shear stress (strength) acting on a plane can be computed as:

$$\tau = c' + \left(\sigma - p_w\right)\tan\varphi' \tag{1}$$

where τ is the maximum shear stress (strength), σ is the normal stress (perpendicular to the sliding plane), p_w is the pore water pressure, c' is the cohesion and φ' the internal friction angle.

The term $\tan\varphi'$ represents a friction coefficient. Note that c' and φ' should be measured in the laboratory under drained conditions and this is why traditionally the superscript (') is used for c and φ. The effective stress, σ', is defined as $\sigma'=\sigma - p_w$. Classical Soil Mechanics sign convention is used here, that is compressions for stresses and water pressure are positive (Terzaghi, 1925, 1936, 1943).

Terzaghi tried to define more precisely the physical meaning of cohesion and friction angle. On the one hand, the tangent of friction angle is equivalent to a friction coefficient, as already defined by Coulomb and others. The use of that angle was adopted because it follows from the slope of the geometric line tangent to the Mohr circle. Also, the friction angle was related to the angle of a slope of dry granular soil at limit equilibrium (angle of repose). On the other hand, cohesion is a bond between particles (Terzaghi, 1943). Within this context the words "cohesive soil" or "cohesionless soil" were used as a simple soil classification. Cohesive was synonymous of clay and cohesionless of sand, a classification still used today in daily practice and as a nomenclature in codes and standards. Nowadays we know that these words are not precise as it is examined below.

3. The approach from Taylor (1948)

Taylor, in 1948 published a book entitled "Fundamentals of Soil Mechanics" which is a good reference to analyze the knowledge on this topic at that time. Some of the concepts already presented in Terzaghi's book from 1943 are shown in a different manner. Cohesion is one of those concepts.

Taylor indicates that the basic mechanism responsible for shear strength is friction, and it needs an external pressure or stress to be active. But some materials "have strength which cannot be attributed to any visible source of pressure… This condition often may be described as a result of a pressure which was exerted on the material at some time in the past, the effects of which have in some way been retained". Taylor refers to overconsolidated clays and to experiments showing cohesion that he relates to the capillary pressure induced when extracting the sample from the field (that is, unloading the sample and generating water tension). He proposed to call that strength "apparent cohesion". Some clays, however, maintain some "internal pressure" and have some type of bonding, exhibiting a "true cohesion", as for instance most sedimentary rocks.

When dealing with sands, Taylor considers the results of direct shear tests on dense and loose samples. Dense sands dilate and have a peak strength and a final strength (usually defined today as constant volume strength). Loose sands have just a final or constant volume strength (Figure 1). Taylor assigns the extra strength of dense sands to the effect of interlocking, whereas friction is responsible for that constant volume strength. Each shear strength, either peak or constant volume, would correspond to a different value of the friction angle.

Taylor (1948) concluded that the experiments allow to define an envelope of the soil shear strength (Figure 2). For overconsolidated clays, tested at low stresses, a peak strength is observed, and an envelope is clearly defined on

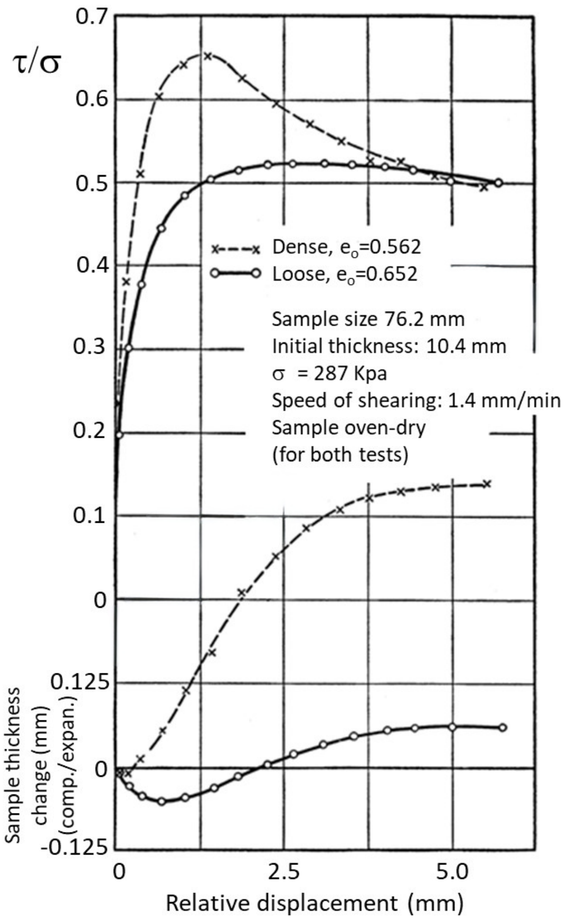

Figure 1. Direct shear experiments on Ottawa sand (modified after Taylor, 1948).

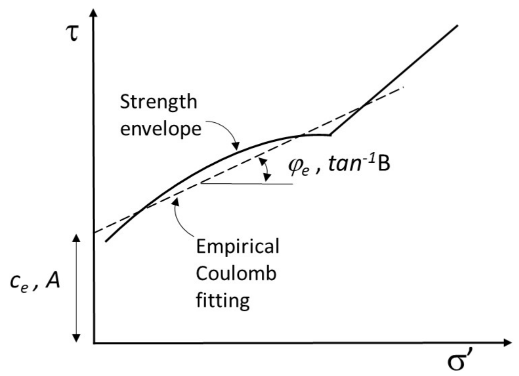

Figure 2. Interpretation of Coulomb's empirical law (modified after Taylor, 1948).

the left hand side of Figure 2; whereas the same clay, when tested at higher stresses (on the right hand side of Figure 2), shows a strength directly proportional to the effective stress. Coulomb's law is just a linear fitting of that envelope:

$$\tau = A + \sigma' B \tag{2}$$

where τ is the shear strength, σ ' is the effective stress and A, B are fitting parameters.

The words cohesion and friction angle are used traditionally for the coefficients of that line, but they are essentially fitting parameters of an empirical law. Taylor proposes to use the words "effective cohesion, c_e" and "effective friction angle, φ_e",

$$c_e = A \; ; \; tan\varphi_e = B \tag{3}$$

but warns about their values in this way: "[…] [they] are not constant soil properties but are empirical coefficients which may vary over wide ranges for a given soil under the various possible conditions of precompression, drainage, and other variables" (Taylor, 1948).

This rational is different from the approach typically observed in textbooks. Cohesion and friction angle are not conceptual soil parameters, but fitting coefficients that may have a wide range. Shear strength depends on so many factors and mechanisms, that it is more convenient to present those "parameters" not as fundamental concepts, but as empirical coefficients.

Schofield has published several papers highlighting the weakness of considering cohesion and friction as fundamental soil parameters corresponding to physical properties (Schofield, 1998a, b, 2001). Cohesion and Friction do exist as mechanisms providing strength, but they are not always active or they depend on external factors. Interlocking as defined by Taylor (1948) is another mechanism that may be active as well and should be taken into account (Schofield, 2001).

4. Residual shear strength

There is another strength that should be considered in clayey soils: the residual strength. That strength is due to the friction between clay particles when they become oriented after large strains. Although the idea of a residual low friction in the context of catastrophic landslides is quite old, the initial works measuring that strength by means of a ring shear apparatus are attributed to Hvorslev (1936). The experiments showed clearly that clay strength is a strain-dependent concept and there is not a unique strength for soils. This is indeed a challenge, as it is difficult to predict strength without considering the strains, that is, with an appropriate soil constitutive model. A classical approach in Mechanics is based on predicting limit forces or stresses when considering ultimate states, and estimating displacements under serviceability conditions, using elasticity for the sake of simplicity. That is, traditionally, ultimate states are predicted without considering strains; however, this approach oversimplifies soil behavior.

If the Mohr-Coulomb criterion is used to predict strength, then it is required to define different sets of cohesions and friction angles, for peak strength, for constant volume strength and for residual strength.

5. Undrained shear strength

Another strength can be defined for clayey soils when there is not drainage upon loading. It is the undrained shear strength. Under undrained conditions, there is an increment, positive or negative, of pore water pressure due to the external load (part of the load is "taken" by water). This increment is difficult to predict in general and thus, it is difficult to compute effective stresses and to evaluate the soil shear strength according to the Mohr-Coulomb Formula 1. As a consequence of this, it is almost inevitable to use total stresses, and therefore we have to change the Mohr-Coulomb criterion because it is defined in terms of effective stresses.

If total stresses are used and there are not water content changes (undrained conditions), the strength of clays can be predicted as:

$$\tau = c_u \tag{4}$$

where τ is the maximum shear stress (strength) and c_u is the undrained shear strength.

This is in fact a Tresca type strength criterion. Comparing Expression 4 with Equation 1 suggests that in undrained conditions it is like having a cohesion equal to c_u and a zero friction angle. Obviously, this is just a mathematical interpretation, but not a physical one.

The idea of using this type of strength criterion is attributed to Fellenius in 1922 (reported by Skempton, 1948). Fellenius computed the stability of clay slopes using limit equilibrium conditions assuming pure cohesion and $\varphi = 0$. Different authors, including Terzaghi, confirmed that assumption experimentally later. Skempton (1948) presented a revision on this and some application to real cases, and explicitly he warned on the use of $\varphi = 0$:

- This strength criterion only applies when there is not water content change in the saturated soil during loading (that is undrained conditions);
- The true friction angle is not zero. The behavior is controlled by the true cohesion, the true friction angle and the effective stresses;
- This $\varphi = 0$ cannot be used if soil is unsaturated.

It becomes evident that using $\varphi = 0$ is just a mathematical trick, and Skempton (1948) is aware of that when concluding: "It may be possible to evolve an analysis which overcomes the difficulties expressed … Meanwhile, provided its limitations are appreciated, the $\varphi = 0$ analysis is a method of great value in civil engineering design".

When teaching Soil Mechanics, one of the fundamental concepts is the idea of effective stress, a concept that is usually presented at the beginning of a course. The mechanical behavior of a saturated soil depends on the effective stress changes, and therefore, a "correct" analysis even in undrained conditions should be carried out in terms of effective stresses always. However, at this point we have to recognize that the effective stress is very difficult to compute in undrained conditions, due to the unpredictable pore water pressure change. Some expressions have been historically proposed to predict the pore water pressure increment in undrained conditions (e.g. Skempton (1954) formula, Henkel (1960) formula) but they are not very good in general as water pressure increments are nonlinear and depend on many factors.

As a compromise solution, only for this case, it is possible to use total stresses if the strength criterion is changed: using (4) instead of (1). The difficulty of predicting pore water pressure is avoided, but now we have to estimate c_u, which has proven to be simpler. In fact, the geotechnical community realized soon that c_u is half of the unconfined compression strength of the clay (Skempton, 1948). In fact, c_u is equivalent to the deviatoric stress (using Lambe's variables) at failure: $q_{Lambe} = (\sigma_1 - \sigma_3)/2$. There are also many empirical expressions relating c_u with other soil properties: plasticity index, confinement and loading history (normally consolidated or overconsolidated).

Figure 3 shows a typical stress plane with the effective stress paths of four conventional triaxial tests from a low plasticity clay (Gens, 1982), at different confining stresses, with and without drainage. The undrained shear strength, c_u, is half the Cambridge deviatoric stress at failure: $q_{Camb} = \sigma_1 - \sigma_3$. Note that all experiments (drained and undrained) finish on a final strength line if effective stresses are used. In this case, that line passes through the origin (zero cohesion) and with

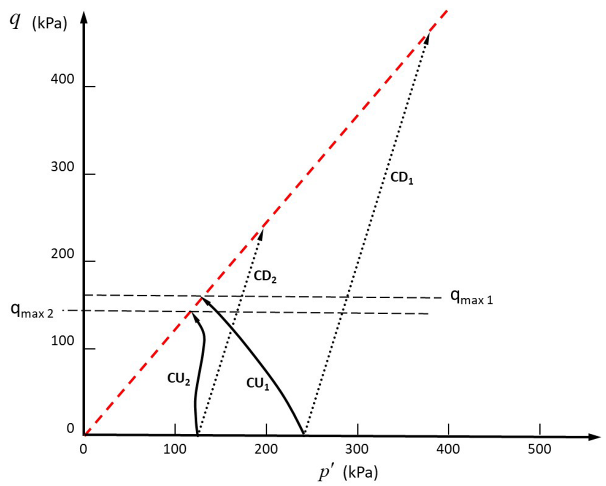

Figure 3. Effective stress paths of four triaxial tests from the same clay: undrained tests (CU_1 and CU_2) and drained tests (CD_1 and CD_2). Sample 1 is normally consolidated and sample 2 oversonsolidated. Cambridge variables: $q = \sigma'_1 - \sigma'_3$, $p' = (\sigma'_1 + 2\sigma'_3)/3$, where σ'_1 and σ'_3 are the major and minor principal effective stresses. $q_{max\ 1}$ and $q_{max\ 2}$ are the undrained strengths obtained for samples 1 and 2, using Cambridge variables, that is, $c_u = q_{max}/2$. (modified after Gens, 1982).

a slope related to its friction angle. Soil fails in undrained conditions when the effective stress paths reaches that final strength line. However, we know this effective stress in the laboratory as we can measure pore water pressure, but it is not the case in the field, and we need to work with total stresses and with the undrained shear strength. Note that two samples of the same clay do not have the same undrained shear strength, that is, for the same clay, c_u depends on the confining stress before the loading path of the triaxial test. For a layer of a normally consolidated clay, c_u depends linearly on depth, as confinement increases linearly with depth, being theoretically nil at ground surface.

Designing geotechnical constructions with a value of c_u increasing linearly with depth is cumbersome and most of the books and exercises consider a constant value for a layer. In addition to that, close to the ground surface the undrained shear strength is not zero in practice, mainly due to unsaturation. Considering constant undrained shear strength is a matter of convenience and generates confusion to students.

Definitely, the concept of c_u is a sort of escape route in undrained conditions. The idea that it is a compromise because we don't know how to compute effective stresses in undrained loading, should be clearly exposed to students.

Modern numerical methods as finite elements are able to solve the coupled hydro-mechanical problem representing the solid-fluid interaction in the soil, so a prediction of the pore water pressure can be attempted in undrained problems nowadays. Nevertheless, that prediction is very sensitive to the constitutive model considered. As an example, the collapse of Nicoll Highway in Singapore in 2004, was mainly due to an overestimation of the undrained shear strength computed using a finite element code and an elastic Mohr-Coulomb model for the soil working in effective stresses (Puzrin et al., 2010). That model has been very popular in the past, but behaviour of the clay was not elastic before failure and that model does not predict any water pressure increment in pure shear, resulting in a large unrealistic undrained shear strength. Therefore, the use of a total stress analysis, although not very consistent with Soil Mechanics fundamental principles, is still very convenient in practice. As indicated by Skempton (1948), "meanwhile the $\varphi = 0$ analysis is a method of great value in civil engineering design".

6. The contribution of Critical State Soil Mechanics

In 1968 the book by Schofield & Wroth (1968) established a starting point for a new development in the understanding of soil behaviour. The general theory of plasticity and in particular, the Cam-clay model, were able to reproduce the results from triaxial tests on both normally consolidated and overconsolidated clays. Before that, it was quite common to distinguish these types of soils as different materials. On the one hand, normally consolidated clays are ductile and they experience volume reduction when shearing under drained conditions. On the other hand, overconsolidated clays are brittle, they show a peak and a constant volume strength, and they dilate (increase volume) when shearing in drained conditions. Traditionally each type of clay was a different chapter when teaching Soil Mechanics. With the Cam-clay model, the same clay, with the same parameters, can behave ductile or brittle, depending on the loading history. Cam-clay model was able to simulate both behaviors with a unique set of parameters. Conceptually this is very important and it is also useful for teaching purposes. The model is a bit more complex than using elasticity or just Mohr-Coulomb, but it is a consistent framework to reproduce soil behaviour and facilitates the understanding. Figure 4 presents a sketch of the yield surface of the modified Cam-clay model showing the stress-strain behaviour of two samples, one normally consolidated and another one overconsolidated following a drained triaxial test. The strength envelope predicted with the modified Cam-clay model is consistent with the considerations of the soil shear strength indicated in previous sections.

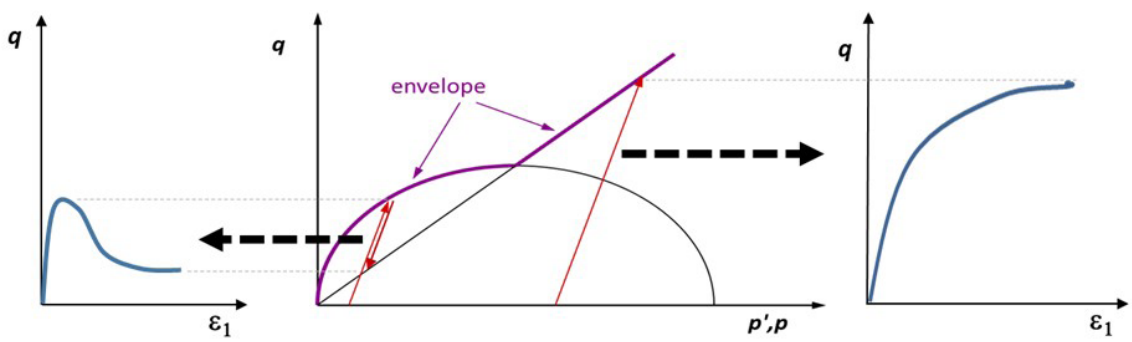

Figure 4. Sketch of the yield surface of the modified Cam-clay model and two drained triaxial tests, showing the deviatoric stress (q) - strain (ε_1) curve predicted for a normally consolidated clay (right) and overconsolidated clay (left).

7. The Unsaturated Soil Mechanics approach

A modern version of a Soil Mechanics course should include at least a brief description of the effects of unsaturation on the mechanical behaviour. The books by Terzaghi (1943) and Taylor (1948) include already a chapter on capillarity. Obviously there has been much scientific development since then.

Although there have been proposals to define generalized effective stress for unsaturated soils (Jaksa, 2020), it is accepted that two variables are required to characterize unsaturated soils, i.e., net stress (total stress minus air pressure) and suction (air pressure minus water pressure). Fredlund et al. (1978) extended the Mohr-Coulomb shear strength criterion for unsaturated conditions, in which a "cohesion term" dependent on suction was considered:

$$\tau = c' + s\tan\varphi^b + \left(\sigma - p_a\right)\tan\varphi' \tag{5}$$

where s is suction, p_a is air pressure and φ^b is a soil parameter.

This is consistent with observations in nature: a clean dry or immersed sand is cohesionless ($c' = 0$), but under partial saturation shows cohesion due to the term [$s \tan \varphi^b$] in (5). This is the key factor when constructing sand castles in the beach! However, this cohesion is just apparent, as it can be lost if sand is wetted.

Clays in general have zero cohesion, as there is not any bond between particles. However, when taken from the field, they develop suction, event at saturations above 99% and therefore an apparent cohesion is generated. Assigning the adjective "cohesive" to clays is misleading because it is not a "true" cohesion. The adjectives "cohesive" and "cohesionless" should not be used in textbooks and codes. "Fine" and "granular" or "coarse" soil should be used instead (Burland, 2012).

The Cam-clay model can also be generalized to account for the unsaturation (Alonso et al., 1990). Here the theoretical background is more complex. Suction is included as an additional variable and the yield surface (that is the elastic region) increases with suction. Figure 5 shows a simple sketch of the extended yield surface of the so-called Barcelona Basic model. The strength envelope is expanded as suction increases. The details of the model may not be appropriate for undergraduate courses, but it is a good framework for a Master course.

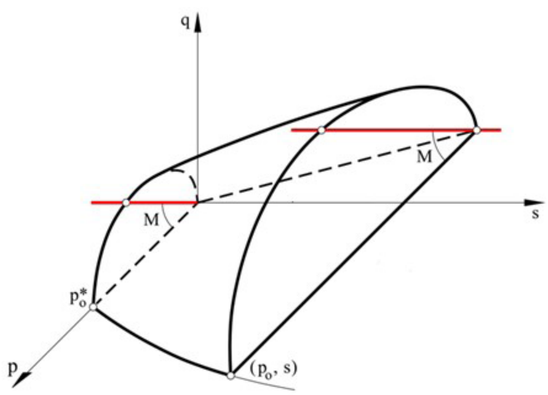

Figure 5. Yield surface of the Barcelona Basic Model in the mean net stress (p) – deviatoric stress (q) – suction (s) space. M is the slope of critical state line (modified from Alonso et al., 1990).

8. Discussion and conclusions

Soil shear strength is not a simple concept, despite what most textbooks apparently present. In undergraduate courses there is a tendency to oversimplify this concept, presenting Mohr-Coulomb as the basic theory, but with many options that are a bit "magical". This is because cohesion and friction angle are assumed as conceptual parameters with physical meaning, but they change for the same clay depending on whether the strength is the peak strength or the constant volume strength or the residual strength or the undrained shear strength. Both, cohesion and friction, correspond to physical mechanisms that may contribute to shear strength, but they may be "active" or not for a particular soil under particular conditions (i.e., a cohesionless sandy soil exhibits some cohesion when unsaturated). Another mechanism that may contribute to strength is interlocking, as indicated by Taylor (1948). All these mechanisms correspond to well defined physical phenomena, but their contribution to shear strength depends on several factors, some of them external to the soil (as unsaturation, or loading history).

In an undergraduate Soil Mechanics course it would seem more convenient to consider a strength envelope and some fitting parameters useful for computations, but without a specific physical meaning. However, a physical meaning is better understood when the Cam-clay model is used to explain soil behaviour. Perhaps only in a Master's course there is time to present all the faces of the same concept: true cohesion, apparent cohesion, etc., but otherwise cohesion and friction angle are so variable that they are very difficult to transmit as fundamental soil parameters, mainly because strength depends on strain. The classical classification between cohesive and cohesionless soils is not appropriate, despite being used in most textbooks and standards. It is more convenient to use the words: "fine soils" and "granular soils". All of them can exhibit cohesion depending on external factors, so cohesion is a property that can be acquired or lost. Likewise, friction angle is a coefficient that could be even zero or may have several values depending on whether we have peak, constant volume or residual conditions. This idea should be conveyed in undergraduate courses and to do that properly, a conceptual framework as Critical State Soil Mechanics should be introduced. This is always a matter of debate, as undergraduate courses have many constrains. However, a modern view of Soil Mechanics should present an introduction to the Cam-clay model, to use its capacity to teach soil shear strength in a proper manner. Referring to general terms in the context of the Civil Engineering syllabus, the phenomenological aspects of the Plasticity theory should be understood at undergraduate level. It is not appropriate to present concepts without a supporting theoretical framework that is nowadays available, so we are committed to adapt those theories to the undergraduate level. Overall, this is why teaching soil shear strength is indeed a difficult task.

Declaration of interest

The author has not any conflict of interest to declare.

Data availability

No dataset was generated or evaluated in the course of the current study; therefore, data sharing is not applicable.

List of symbols and abbreviations

c'	cohesion
c_u	undrained shear strength
M	slope of critical state line
p	mean stress / net mean stress
p'	mean effective stress
p_a	pore air pressure
p_w	pore water pressure
q	deviatoric stress
s	suction
ε	strain
σ	normal total stress
σ'	normal effective stress
τ	shear stress / shear strength
φ'	angle of internal friction
φ^b	angle of friction for suction changes

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CASE STUDY

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Helping students classify and frame capstone geotechnical design courses

Charles John MacRobert[1#]

Case Study

Keywords
Teaching design
Complex problems
Framing
Classification

Abstract

Students often express an anxiety about how knowledge is classified (i.e., differentiated) and framed (i.e., prioritized, and sequenced) in capstone design problems. This anxiety is by design as capstone design courses are meant to test students' ability to solve complex problems that are weakly classified and framed. Nevertheless, educators can play a role in scaffolding student progress, so students advance past a conceptual understanding of problems to applying technical acumen learnt in prior years. This paper presents three geotechnical design projects set by the author, along with three interventions used to scaffold student progress. Projects included the design of an industrial waste facility for dry filtered residue, design of remedial works for a clay river embankment subject to undercutting, and design of a remining method for mine slimes contained behind a sand embankment. Interventions included requiring students to prepare, present and critique presentations based on weekly stage gates, collaboratively brainstorming, and ranking high level implications of a design, and collaboratively brainstorming specific implications of a design. When implementing such interventions care must be taken to ensure they remain student driven, or the learning benefits of a capstone design course may be lost.

1. Introduction

Engineering education strives to provide students with a skill set with which they can advise clients on the best way to tackle their problems. In civil engineering, problems faced are often the design of an engineering artefact, such as a dam, building, bridge, or road. Often these artefacts are bespoke, as they are non-prototypical, and this introduces significant uncertainties in the design process (Bulleit et al., 2015). These uncertainties can be summarized as ignorance, uncertainty and complexity (Elms, 1999). Ignorance pertains to a lack of designer knowledge, uncertainty relates to information the designer needs but does not have, and complexity captures the reality that it is difficult to predict the actual behavior of an artefact.

Engineering science has made significant strides to address complexity in predicting artefact behavior. Consequently, engineering education has increasingly focused on teaching engineering science to address ignorance (Bulleit et al., 2015). Nevertheless, particularly in geotechnical engineering, complexity remains and information available to implement elegant scientific methods is often limited. Capstone design courses are therefore advocated in engineering programs (Harris et al., 1994). These allow students to apply scientific methods they have learnt and to grapple with uncertainties inherent to the design process. Geotechnical design courses allow students to appreciate how theory is applied to practice, especially the shortcomings of theory, how to develop a good geotechnical model through coming to grips with obtaining soil parameters from field and laboratory tests (Atkinson, 2008; Poulos, 1998). Nevertheless, it must be kept in mind that design is not a skill that can be taught in its entirety in the classroom and there remains an obligation on employers to contribute to the continual education of their employees (Atkinson, 2008).

Two difficulties in presenting design courses are the choice of project and the pedagogical approach. Projects set ideally need to meet all the attributes of a complex problems as set out in the Washington Accord (IEA, 2015):

- Depth of knowledge required: Cannot be resolved without in-depth engineering knowledge (…) allows a fundamentals-based, first principles analytical approach;
- Range of conflicting requirements: Involve wide-ranging or conflicting technical, engineering, and other issues;

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- Depth of analysis required: Have no obvious solution and require abstract thinking and originality in analysis to formulate suitable models;
- Familiarity of issues: Involve infrequently encountered issues;
- Extent of applicable codes: Outside problems encompassed by standards and codes of practice for professional engineering;
- Extent of stakeholder involvement and needs: Involve diverse groups of stakeholders with widely varying needs;
- Interdependence: High level problems including many component parts or sub-problems.

Phang et al. (2018) show how difficult it is to set problems that meet all these criteria. However, complexity and uncertainty involved in geotechnical problems (Cardoso, 2015) often means they can meet the complex problem attributes listed above. Very few geotechnical engineering problems have been codified, and codes and standards that are available largely dictate the level of safety that should be achieved rather than the design steps to be followed. Nevertheless, careful consideration is required to meet the above attributes taking into account what students know or can figure out from resources available to them. If problems are too complex, student solutions can remain conceptual and not test students' ability to apply technical acumen.

Closely connected to the choice of design project is the pedagogical approach taken. Wolmarans (2013) recommends the following two fundamental analytical concepts of Bernstein (2000) as a useful framework for the pedagogical approach in design courses: classification (i.e., the extent to which one type of knowledge is separated from others) and framing (i.e., deciding what knowledge to apply and when). Design courses earlier on in a degree program need to have strong classification (i.e., limited to one domain of knowledge) and lecturers need to provide strong framing (i.e., projects are sequenced so that specific pieces of knowledge are applied stepwise). However, as students build a more diverse knowledge design courses should tackle problems with weak classification (i.e., in multiple domains) and weak framing (i.e., students should become responsible for deciding what knowledge to apply and when). This case study presents various interventions developed to scaffold student progress as they undertook weakly classified and framed capstone projects.

2. Capstone design course at Stellenbosch University in South Africa

Students at Stellenbosch University complete a capstone design course in the last semester of the final year of their 4-year Bachelor of Civil Engineering degree. Students are divided into cohorts and undertake design in either structural, pavement, geotechnical, hydraulic, or coastal engineering. Design projects need to be based on real world projects and therefore instructors are either full-time staff members with industry experience or ad hoc appointees from industry. Although centered in single domains, projects must still be weakly classified and require interacting with other knowledge domains for completion. As projects need to involve various stakeholders, instructors (or guest lecturers) take on various roles during the course. For instance, instructors take on the role of client, setting deliverables for students to achieve. Roles extend to parties providing information for students to consider in the design (e.g., environmental specialists, site investigation practitioners, regulators, surveyors, and contractors). Finally, instructors need to be teachers, scaffolding student progress as problems are unfamiliar and do not have closed form solutions commonly encountered in earlier engineering science courses.

The design course is divided into two stages; a five-week conceptual design stage followed by an eight-week detailed design stage. In the conceptual stage, students work in groups to come up with various solutions to the problem. Solutions require ranking conflicting requirements to propose a preferred option. Typically, the amount of information provided at this stage is limited and students are expected to apply depth of analysis that extends past learnt engineering science. Students are then required to propose what additional information they would require when developing the solution further. Table 1 details the various conceptual design problems set by the author for geotechnical designs. The final deliverable at the end of the conceptual design stage is a group report. Groups also complete a buddy ranking exercise to proportion the group mark to individuals.

For the detailed design stage, students work individually to develop the design by applying engineering science. At this stage the scope is reduced, and students are provided with additional information. The reduction in scope is usually presented as a decision by the client to highlight that stakeholders that are not the design engineer can influence the direction of a project. However, this reduction still provides room for students to come up with different variations. The depth of analysis shifts from abstract concepts to applying technical acumen. Interaction between different components or phenomena must be considered in carrying out calculations to ensure proposed solutions are safe. Table 2 outlines the various detail design problems set by the author for geotechnical designs.

3. Conceptual design stage

3.1 Interventions

During the year in which the "Design of an industrial waste facility for dry filtered residue" was undertaken, two targeted interventions were trialed during the conceptual design stage to inform future practices. The first was an intuitive design exercise on the first day of class and the second was a series of weekly group presentations.

On the first day of class, following a brief presentation (23 slides) introducing the class to industrial waste, the conceptual design brief was distributed to the class along with a paper-based intuitive design exercise. This three A4-page paper-based intuitive design exercise outlined six (6) tasks, see Table 3, and provided space for notes and sketches to be made in response. No time limit was set for the exercise, but students took on average 1-hour to finish. Responses were assessed to determine whether students had a well-formed idea of the solution prior to the commencement of the conceptual design stage, and whether this improved in the final conceptual design report. Students were also asked to rate (1 to 10) their confidence in completing the conceptual design and state reasons for their confidence (or lack thereof).

To gauge and shape progress during the conceptual design stage, the second intervention required students to prepare weekly slide presentations based on stage gates (i.e., defined decision points where project progress was evaluated according to specified criteria). This helped students to sequence their work, but still required them to classify and decide what knowledge was important. During class sessions, two to three randomly selected groups presented their slides and fielded questions from the rest of the class. This was anticipated to be largely student driven to prevent the lecturer 'giving away' or framing the solution. Presentations also exposed students to real world industry practices wherein engineers need to provide regular updates to clients on design progress.

Table 1. Details of various conceptual design problems set.

Project:	Design of an industrial waste facility for dry filtered residue.	Design of remedial works for a clay river embankment subject to undercutting.	Design of a remining method for mine slimes contained behind a sand embankment.
Deliverables: (Not stated categorically but as a narrative in the brief)	1. Site selection 2. Deposition 3. methodology 4. Airspace model 5. Lining system 6. Information required to advance design	1. Geotechnical model 2. Slope stability analysis 3. Various remedial measures 4. Trade-off between remedial measures 5. Site investigation proposal	1. Geotechnical model 2. Cross section 3. Various remining methods 4. Trade-off between remining methods 5. Site investigation proposal
Information provided:	1. 1-page brief 2. Map of area 3. Photographs and notes from site visit 4. Grading curves 5. Atterberg limits 6. Moisture density relationships (Standard Proctor and Modified Proctor)	1. 1-page brief 2. Topographical map of area 3. One borehole log 4. Atterberg limits with depth 5. Natural water contents with depth 6. Post failure survey	1. 1-page brief 2. Grading curves for sand and slimes 3. Atterberg limits for sand and slimes 4. Moisture density relationships for sand (Standard Proctor) 5. Survey with cross-sections

Table 2. Summary of different detail design problems set by the author.

Project:	Design of an industrial waste facility for dry filtered residue.	Design of remedial works for a clay river embankment subject to undercutting.	Design of a remining method for mine slimes contained behind a sand embankment.
Deliverables: (Not stated categorically but as a narrative in the brief)	1. Updated geotechnical model 2. Depositional methodology 3. Design of liner system 4. Stability analysis 5. Capital and operational costs 6. Drawings	1. Updated geotechnical model 2. Update of slope stability analysis 3. Design of gravity retaining structure 4. Consideration of construction methodology 5. Cost estimate	1. Updated geotechnical model 2. Two-option trade-off 3. Design of chosen option considering: a. Seepage b. modelling c. Stability modelling
Information provided:	1. 1-page brief 2. Client decision on site 3. Letter report on site investigation 4. Letter report on field compaction and Guelph permeameter testing 5. Direct shear box testing on residue 6. Large shear box tests results for different liner interfaces 7. Sections of legislation 8. Airspace model and cross-sections 9. Rates list	1. 1-page brief 2. Client decision favouring gravity retaining structure 3. Layout of site investigation 4. 2 borehole logs 5. 2 unconsolidated undrained triaxial test result sets 6. 4 consolidated drained triaxial tests 7. 4 cone penetration tests 8. Rates list	1. 1-page brief 2. Client decision favouring two solutions 3. 1 borehole log through sand embankment 4. 3 cone penetration tests within the slimes 5. 3 direct shear box tests on sand 6. Constant head permeability test on sand 7. Falling head permeability on slimes

Table 3. Intuitive design exercise.

Task	Description
1	By listing positive and negative aspects for Site A and Site B, decide which site is best suited for the waste facility.
2	Calculate the airspace (i.e., volume) required for the waste facility over the facility life, then propose and illustrate a stable mound (dimensioned) sketch.
3	Suggest suitable equipment to handle the material and build up the waste facility. Estimate how many truck trips will be required each day.
4	Suggest a number of methods to prevent ground water contamination and discuss how each would impact the safety and cost of the waste facility.
5	What factors are most likely to influence the design?
6	What additional information do you require to complete the design?

Table 4. Conceptual design evaluation form.

Questions and statements	Response type
Was the conceptual design 'given away'?	
During class the lecturer did not give away the conceptual design.	Likert
The lecturer easily gave away the conceptual design solution during class.	Likert
Was the conceptual design challenging?	
The conceptual design was very challenging.	Likert
As a student I found the conceptual design very easy to carry out.	Likert
Were the conceptual design submission requirements clear?	
The conceptual design submission requirements were confusing.	Likert
I did not know what to produce for the conceptual design submission.	Likert
The lecturer made it clear what was required for the conceptual design.	Likert
I understood what was required for the conceptual design submission.	Likert
Opinions of students	
Which one (1) aspect was most helpful about the course?	Open
Which one (1) aspect was most annoying about the course?	Open

Following the submission of the conceptual design report, students were asked to complete a feedback form to evaluate the interventions (see Table 4). This consisted of eight statements that students evaluated using a Likert scale (Strongly agree, Agree, Neutral, Disagree and Strongly disagree). These statements were set to evaluate whether the lecturer 'gave away' the solution, how difficult students found the project and whether submission requirements were clear. Two open-ended questions asked students to list helpful and annoying aspects of the course.

3.1.1 Confidence in completing design after intuitive design exercise

On average, students stated a confidence level of 5/10 to complete the design successfully, although this ranged from 1/10 to 10/10. Stated confidence levels had no correlation to performance at any stage of the design project. When reviewing reasons for stated confidence it became apparent that most responses could be divided into two groups, students either raised reservations regarding their knowledge of the subject or deficiencies in provided information.

Sixteen (16) of the twenty-five (25) students (i.e., 64%) highlighted an uncertainty of the subject as a reason for their lack of confidence[1]. Three (3) students (i.e., 12%) suggested that their lack of confidence was due to a lack of information. Four (4) students (i.e., 16%) highlighted both uncertainty and insufficient information as obstacles to completing the design project. Students that highlighted uncertainty of the subject also stated that this could be overcome by revising previous work, engaging with the lecturer and fellow students, or searching through library and internet resources. These results highlight the importance of lecturers scaffolding students through a design project as they are weakly classified and framed. Lecturers need to think carefully about how to remind students of material covered in previous courses and make sure that it can be applied in capstone design courses.

[1] The total class size was 30. Five students were absent on the day of the survey.

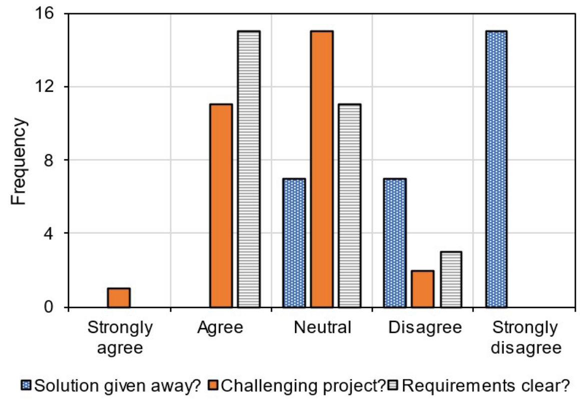

Figure 1. Histogram summarizing student feedback.

3.1.2 Performance in intuitive design exercise relative to final conceptual design marks

On average students scored 55% for the intuitive design exercise. This average improved to 74% for the final conceptual design submission. However, there was no correlation between student marks for the two activities (Pearson correlation coefficient, $r = 0.04$). The increase in marks suggests that the students' understanding of the design improved because of the tasks undertaken during the conceptual design stage. This intuitive design exercise was not used in subsequent years.

3.1.3 Post conceptual design student feedback

Figure 1 plots the aggregated Likert responses per feedback question (see Table 4). Twenty-nine (29) students completed the evaluation. This shows that most students felt that the lecturer did not 'give away' the solution, which means they felt they had to discover it themselves. Most students were neutral on whether the project was challenging, although a larger group felt it was difficult compared to those who did not. Most students felt that requirements were clear, however, a large group were neutral on this aspect.

Twenty-five (25) of the students (i.e., 86%) found the weekly progress presentations to be the most helpful aspect of the conceptual design. Verbatim quotes below highlight reasons why students found these sessions helpful:

- "Weekly presentations helped to observe other group's ideas and to critic [sic] each other. Keeps one up to date with each section of conceptual design";
- "The interactive class presentations. Students learned to speak in front of the class and interact with other student[s]";
- "The fact that we were a task for each week, it minimize[ed] the confusion that could have happened if we were given all the task in a goal";
- "Lecturer sessions and feedback from the class, the sessions assisted in clarifying most concepts that were initially unclear and validated most mistakes".

These quotes highlight how the presentations enabled students to sequence their work and figure out what knowledge was important. The positive response to this intervention, and the comments received helped to validate progress presentations as a means to gauge and shape progress at the conceptual design stage. This intervention was therefore implemented in subsequent years.

Categorizing responses to annoying aspects was challenging. However, a common theme was a lack of or an uncertainty about how to apply knowledge they had learnt to solving the problem and information overload. For instance, common phrases included, "amount of information", "number of unknowns", "vaguely", "deciding which assumptions needed to be made", "lack of information", "atmosphere of uncertainty", "not much information known", "need more guidance", "vagueness of some the topics", "no clear instruction on what is right/wrong" and "not enough background". Some students also struggled with understanding the distinction between concept and detail design. Poor group dynamics was also raised by a few students. This feedback again highlighted the need to help students frame and classify the project so they can see how content they have already learnt can be applied.

4. Detail design stage

4.1 Intervention

During the year in which the "Design of a remining method for mine slimes contained behind a sand embankment" was undertaken, two targeted interventions were undertaken during the detail design stage to inform future practices. These interventions were collaborative learning exercises designed to help students develop guiding documents to tackle the detail design stage. Remining the slimes required flooding the slimes compartment so that a barge could be used to recover the slimes. This water would result in a phreatic surface developing within the sand embankment (also referred to as a wall). The detailed design stage required students to evaluate geotechnical implications of either remining slimes up to the sand embankment or leaving at least 4 m of slimes against the sand embankment. Students had to then design measures to prevent the sand embankment from failing.

The first intervention was a planning session during which students brainstormed geotechnical implications to consider in the design. This session was hosted online using a video conference platform (Microsoft Teams). At the start of the session a link to a shared file (Microsoft Word) was distributed to all students. Students were then separated into ten (10) random online breakout groups (3 to 4 students as the class size was 35). In these groups, students populated the shared document with bullet points on geotechnical implications of design options, parameters required to assess these concerns, and the analysis that would need to be performed. A time limit of 45 minutes was set for this exercise, during which the lecturer visited – virtually – each breakout group to assess progress. The shared document was left available for 24 hours and then taken down. These statements were then copied into an online survey and ranked by students using the following criteria a week later:

- Irrelevant to the problem: Score = 1
- Minor point and poorly developed: Score = 2
- Minor point and well developed: Score = 3
- Major point but poorly developed: Score = 4
- Major point and well developed: Score = 5

This ranking was undertaken to sperate statements based on relevance. The ranked statements were then distributed to students as a Planning Document.

The second session (held a week after the ranking exercise, by which time students had become more familiar with information provided) used the same digital crowdsourcing approach but focused on parameters, analysis, and sources of knowledge. In similar breakout groups students populated two shared tables, one for the embankment material and the other for slimes material, with the following:

- Parameter/Information
- What test is used to determine the parameter/information?
- Where in the textbook[2] can you find relevant information?
- How do the values vary?
- What is the significance of this variation?
- Why do you need this parameter/information?

These questions were designed to help students classify knowledge needed and to frame the way knowledge would be applied. Students had 45 minutes to complete the exercise. They were not allowed to delete anything already added but could highlight and comment on points they were unsure about. The lecturer was also able to monitor progress and insert comments. At the end of the session the document was saved in portable document format (i.e., PDF) and distributed to the class. This was termed the Geotechnical Model Guiding Document.

[2] Knappet & Craig (2012).

To evaluate the utility of the collaborative learning exercises students completed an online survey. Table 5 details the questions asked, responses students could select to answer the questions, and the proportion of students selecting each response. Twenty-seven (27) students completed the evaluation.

4.2 Evaluation

4.2.1 Collaborative learning documents produced

Table 6 reproduces the top two ranked statements and the bottom ranked statement for each of the planning questions posed to the class. A total of 118 statements were proposed by the students. The student driven ranking exercise was efficient at separating relevant and irrelevant statements and no intervention by the lecturer was necessary. Table 7 reproduces two rows with responses regarding the geotechnical model for the sand embankment and slimes material respectively. For the embankment material five (5) rows were developed covering: permeability, phreatic surface, drained strength parameters, unit weights and relative density. For slimes material ten (10) rows were developed covering: cone tip resistance, permeability, effective stresses, undrained shear strength, phreatic surface, stability criteria, overconsolidation ratio, cone calibration factor (N_{kt}), pore pressure parameter (B_q) and drained strengths.

Table 5. Evaluation of collaborative learning exercises.

Questions	Potential responses	Frequency
How would you rate you understanding of the project before the collaborative learning exercises?	I had no idea what to do.	7 (26%)
	I had a vague idea of what to do.	13 (48%)
	I had a good idea of what to do.	5 (19%)
	I knew what to do.	2 (7%)
	I knew exactly what to do.	0
How effective were the collaborative learning exercises in guiding you?	The exercises were vital in guiding me.	4 (15%)
	The exercises helped to fill in blanks.	15 (56%)
	The exercises helped clarify concerns.	3 (11%)
	The exercises showed me a few extra things I needed to consider.	5 (19%)
	The exercises were a waste of time.	0
How often did you use collaborative exercises documents when working on the project?	I did not download them.	0
	I downloaded them but did not use them.	0
	I used them a few times.	12 (44%)
	I used them often.	12 (44%)
	I used them every time I worked on the project.	3 (11%)

Table 6. Examples of ranked planning document statements (statements are verbatim and retain imprecise terminology used by students).

Score	Statement
	What are the geotechnical implications of the two proposed re-mining options? Option 1: Re-mining slimes right up to the embankment.
4.5	Phreatic surface might be raised due to addition of water required for freeboard.
4.2	Saturation of the wall material due to the increased phreatic surface.
⋮	⋮
1.5	Larger water usage area.
	What are the geotechnical implications of the two proposed re-mining options? Option 2: Keeping a minimum of 4 m slimes against the embankment.
4.7	From the falling head permeability test, the times between readings is higher than those from the constant permeability test. This shows that the slimes are less permeable than the sandy material making up the embankment. Hence during construction when the dam is full of water, there is a lower risk of seepage occurring through the embankment wall when compared to option 1.
4.1	The slimes will reduce the infiltration and slow drainage through the wall as they are fine and have a lower permeability.
⋮	⋮
2.2	Barge floating equipment may experience space/movement restrictions as there is less room to operate within the basin.
	What parameters will you need for your geotechnical model? Embankment material
4.6	The drained parameters (internal friction angle) from the 3 shear box tests, and 1 SPT test on the embankment material. The SPT results can be interpreted by Ch 7.2 in the textbook.
4.5	The permeability of the wall, k, determined from the constant head (CH) permeability test on the embankment material.
⋮	⋮
2.0	Single borehole.
	What parameters will you need for your geotechnical model? Slimes material
4.5	The permeability of the slimes, k, determined from the falling head (FH) test on the slimes material.
4.3	The undrained strength parameter, cu, obtained from the 3 CPT tests on the slimes material. This can be interpreted by Ch. 7.5, 8th edition, which discusses the CPT analysis.
⋮	⋮
2.3	Elasto-plastic soil behaviour.
	What geotechnical analysis will you need to carry out?
4.6	Slope stability analysis & determination of safety factor - Section 12.3 in textbook; During operation safety checks for a *SF* of 1.3, post-operation safety checks for a *SF* of 1.5 (long-term stability).
4.3	Seepage: use flow nets through embankment dams (Section 2.9 in textbook, 8th edition) and filter design (Section 2.10, 8th edition) and transfer conditions (Section 2.8 in textbook, 8th edition).
⋮	⋮
2.0	Tunnelling works.

Table 7. Examples of geotechnical model statements (statements are verbatim and retain imprecise terminology used by students).

Item	Embankment material	Slimes material
Parameter/Information	Drained strength parameters (shear strength *s*, and internal friction angle)	*k*
What tests is used to determine the parameter/information?	Direct shear box test (select most appropriate result from the 3 DSB tests, namely the test with the most representative density)	Falling head permeability test
	SPT test- find density which is most representative to use for DSB test	
Where in the textbook can you find relevant information?	Ch 5.4 (8th edition)	Chapter 2.2, 2.8 and 2.9 (8th edition)
	Ch 5.5 (8th edition) - example 5.1	
	Ch 7.2 (8th ed) - SPT	
How do the values vary?	Phi angle and c' value increases slightly with depth, as normal and peak stress increases.	3.7E-7 < *k* < 6E-7
	From the three different DSB tests performed on the soil, it is clear that soil with a lower dry density that is less compacted, will have a lower peak shear strength and a greater internal friction angle. Test 1 indicates a loose silty sand, which is cohesionless and has an internal friction angle of 0.	on average *k* = 4.7E-7
What is the significance of this variation?	Lower part of wall has a higher shear strength than top part of the wall, as saturation increases downwards in the wall.	Variation is little in the data thus not that significant.
		Values fall in the range of low permeability.
Why do you need this parameter/information?	To determine a critical shear strength failure to design for, you would need to know where in the wall this value would occur. It is best to design for the worst-case scenario, which is represented in the first sample in the borehole logs at 6 m from the crest of the wall.	The permeability, *k*, will be needed to construct flow nets through the embankment (Ch 2.9) and determine transfer conditions (Ch 2.8).
	To use drained strength parameters for slope stability analysis.	

While some statements contained errors and imprecise terminology it was generally not necessary to intervene as students had identified correct textbook sections to consult. An example of an intervention was where particle specific gravity (*SG*) was discussed. The following details the written exchange between lecturer and student:

- Student: [*SG*] Determines stability of slope and whether it will fail;
- Lecturer: I am not sure *SG* will determine if the slope fails;
- Student: Would *SG* not be used in the determination of slope stability? – Isn't the weight of the soil in the 'failure zone' required?;
- Lecturer: I guess in that sense.

4.2.2 Perceived usefulness of collaborative learning documents

Table 5 shows that prior to the collaborative learning exercises a large group of students had a very poor understanding (no idea to vague idea) of what to do for the detail design. Most students ranked the documents as useful guides (vital to fill in gaps), and more than half used them regularly (often to every time) when working on the design. This feedback confirmed the utility of the collaborative exercises. These exercises were performed when in-person interactions were not permitted due to COVID restrictions. Nevertheless, in an in-person setting students can still be divided into groups and can populate a shared document on laptops in a classroom or computers in a laboratory. Due to rotation of teaching duties the author has not had a chance to run the exercises with an in-person class.

5. Conclusions

Design is introduced at various stages during an undergraduate program in engineering. Initially, design is introduced with strong classification (i.e., limited domain of knowledge) and with strong framing (i.e., sequenced steps). Later in the program, typically in a capstone design course, the design is presented with weak classification (i.e., requiring knowledge from different domains) and with weak framing (i.e., students are responsible for determining what knowledge is relevant and when to apply it). Projects set must also meet the attributes of a complex problem if programs are aligned with the Washington Accord.

Surveys undertaken amongst students showed anxiety about the uncertainty that results from undertaking projects with weak classification and framing. This paper presented three interventions introduced to help students classify and frame the work required to solve design problems (with minimal lecture intervention):

- Preparing and presenting weekly presentation for critique by the rest of the class: Presentations were prepared according to stage gates (i.e., providing some assistance in sequencing work) but students were still required to classify and prioritize knowledge. Student driven critique was in most cases sufficient to frame what work was required;
- Poorly structured collaborative brainstorming activity followed by ranking: Students in small groups populated a shared document with statements in response to high level questions regarding implications of a proposed design. These statements helped students classify what knowledge was required,

but a student driven ranking exercise was required to frame these (i.e., decide what was important);
- Structured collaborative brainstorming activity: Students in small groups populated a shared document with statements in response to specific questions regarding the geotechnical model (an important sub-component) for the proposed designs. These questions spoke to the how (i.e., framing of analysis) of the problem and not the what (i.e., the solution). Students remained responsible for coming up with unique solutions of their own.

As students evaluated these interventions as useful to their studies, other educators may wish to implement these in their own courses. However, care must be taken so that educators do not intervene to the extent that students are no longer learning to stand on their own feet. Too much intervention can turn a weakly classified and framed project into a strongly classified and framed project. This then defeats the point of a capstone design project.

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Without encouragement from Professor Kátia Vanessa Bicalho (Federal University of Espírito Santo) this paper would have remained on a dusty shelf.

Declaration of interest

The author has no conflicts of interest to declare.

Data availability

Design projects outlined in this paper are available from the corresponding author upon request. Raw student feedback is not available for confidentiality reasons.

List of symbols and abbreviations

c'	Effective cohesion
k	Hydraulic conductivity
PDF	Portable digital format
r	Pearson correlation coefficient
B_q	Pore pressure coefficient
N_{kt}	Cone calibration factor
CH	Constant head
CPT	Cone penetration test
DSB	Direct shear box
FH	Falling head
SF	Factor of Safety
SG	Particle specific gravity
SPT	Standard penetration test

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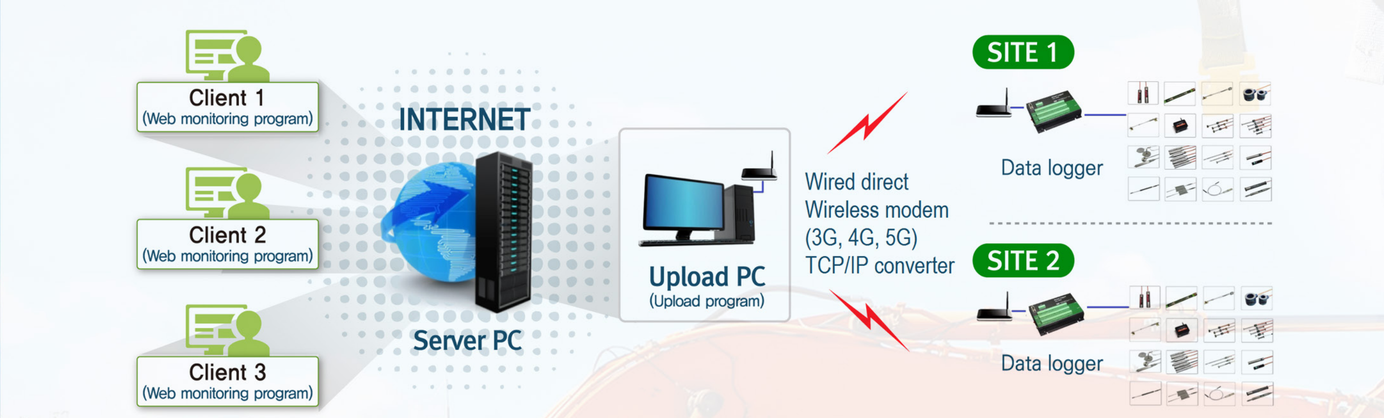


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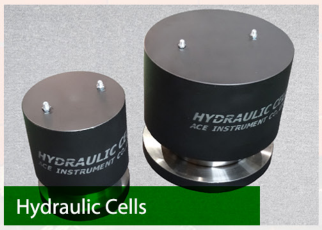

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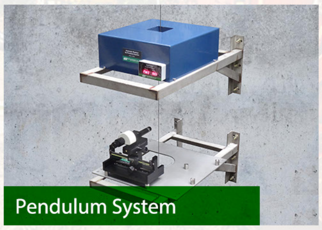
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A list of symbols and definitions used in the text must be included before the References section. Any mathematical constant, variable or unknown quantity should appear in italics.

6.1 Citations

References to other published sources must be made in the text by the last name(s) of the author(s), followed by the year of publication. Examples:

- Narrative citation: […] while Silva & Pereira (1987) observed that resistance depended on soil density
- Parenthetical citation: It was observed that resistance depended on soil density (Silva & Pereira, 1987).

In the case of three or more authors, the reduced format must be used, e.g.: Silva et al. (1982) or (Silva et al., 1982). Do not italicize "et al."

Two or more citations belonging to the same author(s) and published in the same year are to be distinguished with small letters, e.g.: (Silva, 1975a, b, c.).

Standards must be cited in the text by the initials of the entity and the year of publication, e.g.: ABNT (1996), ASTM (2003).

6.2 References

A customized style for the Mendeley software is available and may be downloaded from this link.

Full references must be listed alphabetically at the end of the text by the first author's last name. Several references belonging to the same author must be cited chronologically.

Some formatting examples are presented here:

Journal Article

Bishop, A.W., & Blight, G.E. (1963). Some aspects of effective stress in saturated and partly saturated soils. *Géotechnique*, 13(2), 177-197. https://doi.org/10.1680/geot.1963.13.3.177

Castellanza, R., & Nova, R. (2004). Oedometric tests on artificially weathered carbonatic soft rocks. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(7), 728-739. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:7(728)

Fletcher, G. (1965). Standard penetration test: its uses and abuses. Journal of the Soil Mechanics Foundation Division, 91, 67-75.

Indraratna, B., Kumara, C., Zhu S-P., Sloan, S. (2015). Mathematical modeling and experimental verification of fluid flow through deformable rough rock joints. *International Journal of Geomechanics*, 15(4): 04014065-1-04014065-11. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000413

Garnier, J., Gaudin, C., Springman, S.M., Culligan, P.J., Goodings, D., Konig, D., ... & Thorel, L. (2007). Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling. *International Journal of Physical Modelling in Geotechnics*, 7(3), 01-23. https://doi.org/10.1680/ijpmg.2007.070301

Bicalho, K.V., Gramelich, J.C., & Santos, C.L.C. (2014). Comparação entre os valores de limite de liquidez obtidos pelo método de Casagrande e cone para solos argilosos brasileiros. *Comunicações Geológicas*, 101(3), 1097-1099 (in Portuguese).

Book

Lambe, T.W., & Whitman, R.V. (1979). *Soil Mechanics, SI version*. John Wiley & Sons.

Das, B.M. (2012). *Fundamentos de Engenharia Geotécnica*. Cengage Learning (in Portuguese).

Head, K.H. (2006). *Manual of Soil Laboratory Testing - Volume 1*: Soil Classification and Compaction Tests. Whittles Publishing.

Bhering, S.B., Santos, H.G., Manzatto, C.V., Bognola, I., Fasolo, P.J., Carvalho, A.P., ... & Curcio, G.R. (2007). *Mapa de solos do estado do Paraná*. Embrapa (in Portuguese).

Book Section

Yerro, A., & Rohe, A. (2019). Fundamentals of the Material Point Method. In *The Material Point Method for Geotechnical Engineering* (pp. 23-55). CRC Press. https://doi.org/10.1201/9780429028090

Sharma, H.D., Dukes, M.T., & Olsen, D.M. (1990). Field measurements of dynamic moduli and Poisson´s ratios of refuse and underlying soils at a landfill site. In *Geotechnics of Waste Fills - Theory and Practice* (pp. 57-70). ASTM International. https://doi.org/10.1520/STP1070-EB

Cavalcante, A.L.B., Borges, L.P.F., & Camapum de Carvalho, J. (2015). Tomografias computadorizadas e análises numéricas aplicadas à caracterização da estrutura porosa de solos não saturados. In *Solos Não Saturados no Contexto Geotécnico* (pp. 531-553). ABMS (in Portuguese).

Proceedings

Jamiolkowski, M.; Ladd, C.C.; Germaine, J.T., & Lancellotta, R. (1985). New developments in field and laboratory testing of soils. *Proc. 11th International Conference on Soil Mechanics and Foundation Engineering,* San Francisco, August 1985. Vol. 1, Balkema, 57-153.

Massey, J.B., Irfan, T.Y. & Cipullo, A. (1989). The characterization of granitic saprolitic soils. *Proc. 12th International Conference on Soil Mechanics and Foundation Engineering*, Rio de Janeiro. Vol. 6, Publications Committee of XII ICSMFE, 533-542.

Indraratna, B., Oliveira D.A.F., & Jayanathan, M. (2008b). Revised shear strength model for infilled rock joints considering overconsolidation effect. *Proc. 1st Southern Hemisphere International Rock Mechanics Symposium*, Perth. ACG, 16-19.

Barreto, T.M., Repsold, L.L., & Casagrande, M.D.T. (2018). Melhoramento de solos arenosos com polímeros. *Proc. 19º Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica*, Salvador. Vol. 2, ABMS, CBMR, ISRM & SPG, 1-11 (in Portuguese).

Thesis

Lee, K.L. (1965). *Triaxial compressive strength of saturated sands under seismic loading conditions* [Unpublished doctoral dissertation]. University of California at Berkeley.

Chow, F.C. (1997). *Investigations into the behaviour of displacement pile for offshore foundations* [Doctoral thesis, Imperial College London]. Imperial College London's repository. https://spiral.imperial.ac.uk/handle/10044/1/7894

Araki, M.S. (1997). *Aspectos relativos às propriedades dos solos porosos colapsíveis do Distrito Federal* [Unpublished master's dissertation]. University of Brasília (in Portuguese).

Sotomayor, J.M.G. (2018). *Evaluation of drained and non-drained mechanical behavior of iron and gold mine tailings reinforced with polypropylene fibers* [Doctoral thesis, Pontifical Catholic University of Rio de Janeiro]. Pontifical Catholic University of Rio de Janeiro's repository (in Portuguese). https://doi.org/10.17771/PUCRio.acad.36102*

* *official title in English should be used when available in the document.*

Report

ASTM D7928-17. (2017). Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. *ASTM International, West Conshohocken, PA.* https://doi.org/10.1520/D7928-17

ABNT NBR 10005. (2004). Procedure for obtention leaching extract of solid wastes. *ABNT - Associação Brasileira de Normas Técnicas*, Rio de Janeiro, RJ (in Portuguese).

DNIT. (2010). Pavimentação - Base de solo-cimento - Especificação de serviço DNIT 143. *DNIT -Departamento Nacional de Infraestrutura de Transportes*, Rio de Janeiro, RJ (in Portuguese).

USACE (1970). Engineering and Design: Stability of Earth and Rock-Fill Dams, Engineering Manual 1110-2-1902. Corps of Engineers, Washington, D.C.

Web Page

Soils and Rocks. (2020). *Guide for Authors*. Soils and Rocks. Retrieved in September 16, 2020, from http://www.soilsandrocks.com/

6.3 Artworks and illustrations

Each figure should be submitted as a high-resolution image, according to the following mandatory requirements:

- Figures must be created as a TIFF file format using LZW compression with minimum resolution of 500 dpi.
- Size the figures according to their final intended size. Single-column figures should have a width of up to 82 mm. Double-column figures should have a maximum width of 170 mm.
- Use Times New Roman for figure lettering. Use lettering sized 8-10 pt. for the final figure size.
- Lines should have 0.5 pt. minimum width in drawings.
- Titles or captions should not be included inside the figure itself.

Figures must be embedded in the text near the position where they are first cited. Cite figures in the manuscript in consecutive numerical order. Denote figure parts by lowercase letters (a, b, c, etc.). Please include a reference citation at the end of the figure caption for previously published material. Authorization from the copyright holder must be provided upon submission for any reproduced material.

Figure captions must be placed below the figure and start with the term "Figure" followed by the figure number and a period. Example:

Figure 1. Shear strength envelope.

Do not abbreviate "Figure" when making cross-references to figures.

All figures are published in color for the electronic version of the journal; however, the print version uses grayscale. Please format figures so that they are adequate even when printed in grayscale.

Accessibility: Please make sure that all figures have descriptive captions (text-to-speech software or a text-to-Braille hardware could be used by blind users). Prefer using patterns (e.g., different symbols for dispersion plot) rather than (or in addition to) colors for conveying information (then the visual elements can be distinguished by colorblind users). Any figure lettering should have a contrast ratio of at least 4.5:1

Improving the color accessibility for the printed version and for colorblind readers: Authors are encouraged to use color figures because they will be published in their original form in the online version. However, authors must consider the need to make their color figures accessible for reviewers and readers that are colorblind. As a general rule of thumb, authors should avoid using red and green simultaneously. Red should be replaced by magenta, vermillion, or orange. Green should be replaced by an off-green color, such as blue-green. Authors should prioritize the use of black, gray, and varying tones of blue and yellow.

These rules of thumb serve as general orientations, but authors must consider that there are multiple types of color blindness, affecting the perception of different colors. Ideally, authors should make use of the following resources: 1) for more information on how to prepare color figures, visit https://jfly.uni-koeln.de/; 2) a freeware software available at http://www.vischeck.com/ is offered by Vischeck, to show how your figures would be perceived by the colorblind.

6.4 Tables

Tables should be presented as a MS Word table with data inserted consistently in separate cells. Place tables in the text near the position where they are first cited. Tables should be numbered consecutively using Arabic numerals and have a caption consisting of the table number and a brief title. Tables should always be cited in the text. Any previously published material should be identified by giving the original source as a reference at the end of the table caption. Additional comments can be placed as footnotes, indicated by superscript lower-case letters.

When applicable, the units should come right below the corresponding column heading. Horizontal lines should be used at the top and bottom of the table and to separate the headings row. Vertical lines should not be used.

Table captions must be placed above the table and start with the term "Table" followed by the table number and a period. Example:

Table 1. Soil properties.

Do not abbreviate "Table" when making cross-references to tables. Sample:

Table 1. Soil properties

Parameter	Symbol	Value
Specific gravity of the sand particles	G_s	2.64
Maximum dry density (Mg/m^3)	$\rho_{d(max)}$	1.554
Minimum dry density (Mg/m^3)	$\rho_{d(min)}$	1.186
Average grain-size (mm)	d_{50}	0.17
Coefficient of uniformity	C_u	1.97

6.5 Mathematical equations

Equations must be submitted as editable text, created using MathType or the built-in equation editor in MS Word. All variables must be presented in italics.

Equations must appear isolated in a single line of the text. Numbers identifying equations must be flushed with the right margin. International System (SI) units must be used. The definitions of the symbols used in the equations must appear in the List of Symbols.

Do not abbreviate "Equation" when making cross-references to an equation.