Enhancing geotechnical site investigation and project-based education through virtual reality: the GeoSim experience

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ABSTRACT: This paper presents GeoSim, a virtual reality (VR) tool designed to enhance geotechnical site investigation and project-based education. GeoSim offers an immersive experience, allowing engineering students to be immersed into a real-world site investigation project for a building construction. They can optionally access short but engaging multimedia educational materials as reminders of the general approach and usual testing methods. By addressing the limitations of traditional teaching methods, GeoSim provides a cost-effective and logistically feasible alternative. Allowing students to iteratively change their initial choices and progressively improve their ground model, is a key feature for developing their decision-making skills. GeoSim integration in the project-based learning activities is expected to significantly enhance students' understanding and application of site investigation process, making it a valuable resource for geotechnical engineering education.

Keywords: Virtual reality, Site investigation, Project-based, In situ tests, Laboratory tests

1 Introduction

Geotechnical site investigation is crucial for ensuring the safety and durability of built structures. Traditional teaching methods, which focus on theoretical aspects, must be complemented by project-based activities to develop and assess engineering students' skills. These activities help students make informed choices about selecting laboratory and in situ testing methods, and designing and positioning coring and testing on construction sites. Training geotechnical engineering students in site investigation practices is essential for balancing risk assessment and mitigation with project cost reduction. However, the equipment and maintenance required for geotechnical in situ testing often exceed the available funding of educational institutions. Consequently, teaching teams resort to simplified equipment for practical work, which remains costly and complicated to organize, and depends on weather conditions and site accessibility. Partner companies sometimes organize on-site demonstrations, but these are also complex to arrange and depend on teaching schedules, company workloads, and site accessibility.

Recent advancements in Virtual Reality (VR) technology and availability of adapted hardware solutions offer a promising solution for engineering education. Oje et al. (2003) provided a comprehensive review on VR-assisted engineering education covering a wide variety of applications and discussing benefits and shortcomings. They reported that most applications focused on aesthetic and attractiveness of VR technology, and suggest that future developments should consider learning efficiency through empirically tested learning theories.

GeoSim, an artificial environment simulating a real-world construction site for an industrial building, is developed to address these challenges specifically in geotechnical investigation design. GeoSim can be used with a standard VR headset or on a PC, tablet, or smartphone. It is intended to provide geotechnical engineering students with an immersive experience into the design and processing of a site investigation project.

2 Current practice in Geotechnical Engineering courses

The geotechnical engineering curriculum at Université de Lorraine - ENSG combines theoretical courses with practical learning units as summarized in Table 1. One of these practical units focuses on experimental soil mechanics, allowing students to practice current soil identification and testing methods. Whenever possible, visits to construction sites and demonstrations of in situ geotechnical tests are organized with the support of partner companies. In the learning units dedicated to geotechnical design and stability analysis (including foundations, tunnels, retaining structures, and slope stability), project-based learning activities complement the theoretical courses. During these activities, students are provided with soil properties data and tasked with designing projects. Professors are often asked to explain how the data was obtained and how site investigations are conducted, relying on theoretical considerations and selected case studies to address these questions.

Table 1. Learning units of the geotechnical engineering specialization curriculum at Université de Lorraine - ENSG

Semester	Theory courses	Practice and Design-Oriented courses
1	Soil mechanics (40h) Rock mechanics (24h)	Experimental soil mechanics (24h) Shallow and deep foundations (24h) Slope stability and retaining structures (24h) Tunnels and underground structures (24h) Environmental geotechnics (24h) Geology/Geotechnical field work (2 weeks)
2	Advanced soil & rock Mechanics (24h)	Foundations and retaining structures (24h) Tunnels and underground structures (24h) Soil dynamics, vibration and earthquake analysis (24h) Energy Geotechnics (24h) Natural hazards management (24h) Linear infrastructures (24h) Geotechnical structures design (24h) Geophysics applied to civil engineering (24h) Construction site management (24h)

Developing students' skills for site investigation, requires repeated experiences covering the variety of site and project configurations. Engaging the students in the whole process of defining and interpreting the reconnaissance operations, and going a step further to designing the project. Repeated practice iterative feedback/improvement sequences, is undeniably the best way to measure the consequences of the choices the engineers can make when selecting testing methods and positioning boreholes. Putting such activities is highly resource-consuming and doesn't generally align with faculty and equipment availability. Developing VR-based tools is an interesting solution matching site investigation learning outcomes with logistical and financial support in universities.

3 Virtual Reality in Education

Oje et al. (2023) reviewed the educational uses of VR technologies distinguishing non-immersive and immersive technologies. They pointed out that in the engineering education, students frequently face the difficulty of understanding abstract concepts and visualising complicated 3D configurations, and non-immersive VR technologies are very helpful to clarify these concepts and configurations while immersive VR adds a higher degree of interaction for a more-realistic experience.

Immersive technologies offer interesting opportunities in the civil and geotechnical engineering education context. 360-cameras are able to capture a view covering an entire sphere by assembling the views taken by two half-sphere lenses (forward and backward). Software tools allow then to reconstruct the 3D-view of the captured scene. The end-user can be immersed into the reconstructed environment using a VR-headset or simply on a screen of a personal computer, a tablet or a smartphone. 3D-displacements and rotations are possible and allow the user to evolve in the VR-environment. Additional multimedia materials (photos, videos, text and sounds) can be also added to enrich the user experience and offer interaction possibilities. The use of a VR headset is a way more immersive experience than a computer/tablet/smartphone flat screen that necessitates actions from the user to interact with the environment. Simple VR goggles can however be used for a low-cost enhanced immersive experience.

Jaksa (2020) reported that these technologies are used at the University of Adelaide (Australia), for offering virtual visits to various civil engineering construction activities to the students providing them with a wide variety of learning experiences. In particular, an educational project reconstructed three distant multi-storey building and introduced for the convenience of the users a 'teleport' function in the simulation, avoiding long and uninteresting walking sequences when moving from one building to another. Fernandez et al. (2023) developed a virtual experience of a drilling work where the user is asked to perform drilling and extracting the soil coring following instructions given by a virtual supervisor with a focus on safety and risk prevention. The simulator was built in a videogame development environment, from 3D models of the geotechnical drilling machine and a realistic construction site environment, and scenarios of inventoried interaction possibilities. Afsharipour and Maghoul (2023) explored application of VR and Augmented Reality (AR) to enhance teaching geotechnical concepts. They developed 3D modelling and animation models for soil phase diagram, Consolidated Undrained (CU) and Consolidated Drained (CD) triaxial tests, direct shear test, hydrometer tests and Mohr-Coulomb failure criterion. It is worth noticing that VR and AR technologies are having expanding application in corporate training. In The geotechnical field, this use includes training in safety and risk mitigation on construction sites, and training on the use of sophisticated machinery such as TBM (Tunnel Boring Machine). However, little feedback from geotechnical companies on the specific added-value is available in the scientific literature. Martins et al. (2021) made a literature review on VR/AR use in corporate training report that the technology is clearly maturing but depending on the digital skill level of the target audience. They recommend incorporating artificial intelligence to enhance coaching of trainees to proactively optimize tasks accomplishment.

The most challenging aspect of using VR technologies in education in general and in geotechnical engineering in particular, is aligning the VR experience with the learning outcomes (Ghazali et al., 2024). This aspect is decisive in the student's perception of the VR activity experience. A well-designed realistic scenario allowing for iterative improvement is central for skills' development assessment. Additionally, the health issues have to be considered when designing VR experiences (Ghazali et al., 2024). The most serious issue is the cybersickness induced by the contradictory perceptions by the central nervous system detecting movement and the vestibular system not detecting it. Precautionary recommendations include shortening the VR sessions and adapting their duration to the specifications of the head-mounted devices eventually used.

4 The GeoSim project

4.1. Construction site and project presentation

The selected construction site is located in the "La ferme de La Bouzule" experimental domain owned by the Engineering School of Agronomy and Food Science (ENSAIA), of the Université de Lorraine. It is situated 12 km North-East of Nancy (Figure 1). The projected construction is an administrative/industrial annex three-storey building covering a 20mx15m surface. The structure of the building comprises two lateral load-bearing walls and 11 columns (Figure 2). Table 2 summarises the design load takedowns of the building. The student's ultimate task is to design the foundations of all structural elements of the building based on the geotechnical site investigation program they will have to define.

Based on the desk study, the soil was expected to comprise a surface layer of clayey silt of 3 to 6 m thickness upon a thick clay substratum. The water table depth was expected to be reached between 2 and 3 m depth. A real investigation program was conducted to provide reference experimental data for GeoSim. This program included: (i) one pressuremeter test with maximum depth of 6 m; (ii) dynamic penetrometer test to a 6 m depth; (iii) soil cuttings and cores collection for laboratory tests; (iv) complete set of laboratory tests. The two boreholes were driven in two distant positions on the surface covered by the project. Some additional tests were available from previous boreholes made in the vicinity of the site. The relatively simple geology in the site, allowed to accurately define a ground model up to 15 m depth confirming the presence of a 4m-thick clayey silt layer and a clay substratum down to 15+ m. the water table depth was around 2.5 m.

Figure 1. Construction site location with the projected building location (blue square)

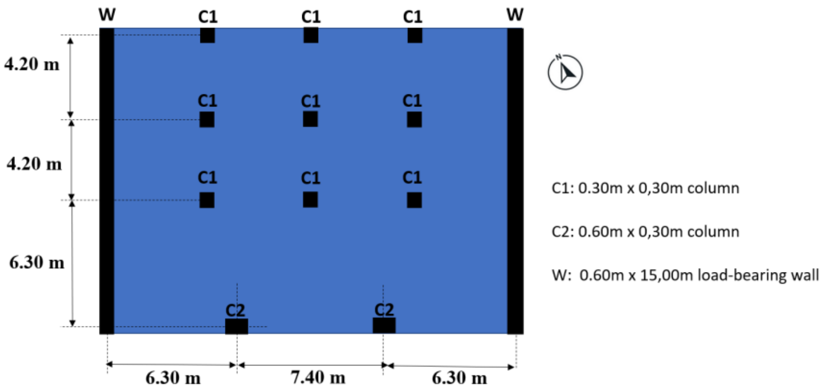

Figure 2. Drawing of the structural elements of the projected building: C1 and C2 stand for sqaure and rectangular columns respectively, and W represents the load-bearing walls

Table 2. Load takedowns of structural elements of the projected building

Structural element	Permanent vertical load	Variable vertical load
W load-bearing wall	120 kN/m	80 kN/m
C1 column	230 kN	94 kN
C2 column	360 kN	108 kN

4.2. Video and photo shooting

Multiple video and photo shooting sessions were necessary to assemble the needed resources for GeoSim Development. In particular, a one-day session was organized with the support from Géotec® Group, a leading consultancy in geotechnical engineering who deployed two drilling machines, testing equipment with one senior engineer and two technical staff members. One 360-camera (Insta360® Pro2) was used for capturing the 3D views of the site and the drilling machinery. Figure 3 shows some photos from the shooting sessions.

Figure 3. Photos from the shooting sessions (top : in situ test and bottom : laboratory tests)

4.3. Additional educational resources

One five-minute video is dedicated to presenting the general process of geotechnical site investigations combining sequences illustrating the desk study, site visit and machinery setting. Seven two-minute videos are focused on laboratory testing (soil identification tests, oedometer, shear box and triaxial) and in situ test (dynamic penetrometer, cone penetration and pressuremeter). Lecture notes, links to websites and other course materials are also made available. For capturing 2D video sequences, the Panasonic® GH5s camera was used. Photo and video editing were made using Adobe® Photoshop and Premiere, while Unity® software was used for creating the VR environment. The last was selected in particular for its advanced functionalities permitting to introduce interactivity to the 360°-scene with clickable buttons and elements and incrusting images and videos.

4.4. Scenario implementation

GeoSim is designed as a learning platform featuring four modules as shown in Figure 4. The primary objective is to provide the user with a standard pathway simulating the different phases of a real-world site geotechnical investigation for an administrative/industrial three-storey building construction project. The secondary objective is to deliver as an option to users, a complementary training on the general methodology for setting up a geotechnical site investigation, including multimedia documents combining slide presentations, text documents, videos and interviews, to introduce/remind the general approach of setting boreholes and the most frequently used testing methods. Figure 5 shows the Moodle LMS (Learing Management System) space dedicated to the material library. The user can navigate forth and back to these learning materials from any module.

5 GeoSim in practice

GeoSim's standard pathway starts in a virtual meeting room, with a welcome message and a presentation of the project specifications given by a virtual representative of the project owner (Figure 6). Architectural drawings and load takedowns for the projected building along with the local geological/topographic maps, precise location and aerial photo of the site are provided. At this stage, the user is asked to carry on a desk study, including searching for any available additional data which could be useful for the project. The overall geological configuration should be estimated and used to preconfigure the relevant investigations.

Afterwards, the user is 'teleported' to the virtual site for a site visit. They can visit the site and note any useful particularity, check the access of the testing machinery, make GPS position measurements to calculate distances and level differences, and stake borehole locations. For each stake, They are asked to define the maximum depth of investigation, and to choose the testing methods including in situ tests (pressuremeter, dynamic penetrometer, cone penetration tests) and/or laboratory tests (geotechnical identification: grain-size distribution, water content and bulk density, Atterberg limits, methylene blue test, compaction curve, CBR; oedometer test; shear box or triaxial shear strength parameters). In order to raise the student awareness of the financial aspects of the investigation, the platform shows the estimated cost of the selected tests.

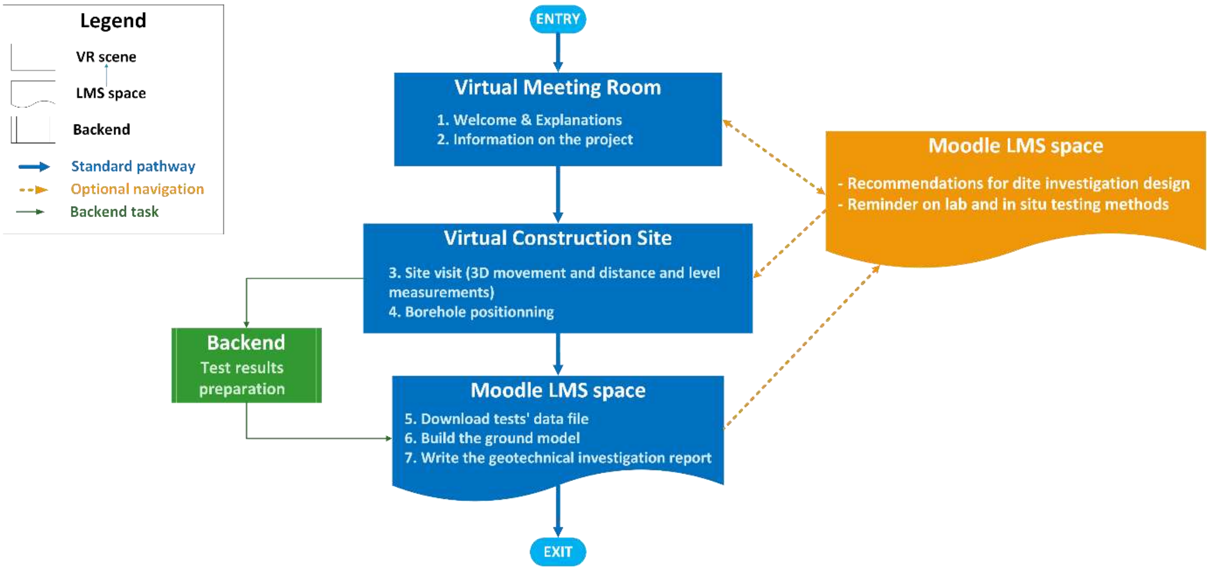

Figure 4. Workflow of the GeoSim project storyboard

Figure 5. Optional educational resources frontend in the Moodle LMS space (right: sitting of the boreholes and left: pressuremeter test presentation)

Based on the available results from real in situ and laboratory tests, the professors generate in the backend, the data in accordance with the student ordering. These data are generated by introducing some random noise consistently with the observed variability.

Subsequently, the user is guided to the Moodle LMS space to retrieve the results of the ordered investigation campaign. He/she is invited to check the data, to point out any inconsistency and to make the necessary interpretation to define the ground model attributing values to the design parameters for each soil layer. This final phase ends up with uploading a complete geotechnical investigation report on the Moodle LMS space to be evaluated by the professors. Once the feedback is given, the student can eventually repeat the whole process to improve the site investigations.

To engage students and enhance their skills in designing optimized site investigations, they are encouraged to iterate the process by varying the number and types of investigation points. For instance, students might start with three boreholes and two types of tests, then adjust to four boreholes and three types of tests based on initial findings. This approach helps develop an awareness of the importance of balancing the quantity of boreholes and tests with the required accuracy for the project at hand, while also controlling the cost of the reconnaissance.

Figure 6. Sceenshot from the simuation showing the virtual meeting room during project introduction

6 Future developments

GeoSim was designed as a prototype to demonstrate the feasibility and effectiveness of the concept. An enhanced version is planned, and further development perspectives include but aren't limited to:

- Adding growing complexity geological/geotechnical complexity;
- Adding different types of construction projects, in particular, linear projects as roads, railways, embankments and tunnels;
- Incorporating a built-in data generation module which will automatically generate test results considering lithology and soil parameters variability in accordance with the settings specified by the professors.

The effort needed to enrich GeoSim with additional sites of increased complexity, and to include new construction projects beyond foundation design, such as embankments, slope stability, and retaining structures, is relatively moderate. The resources library is quite complete; only the project material needs to be developed, and the data generation module must be updated to handle the new lithology.

7 Conclusion

In this paper, the GeoSim simulator concept, objectives, development steps and expectations in terms of future usefulness as an educational resource were presented. This tool is dedicated to enhance teaching geotechnical site investigation to engineering students.

The first objective was to develop several resources to be used as educational material for teaching geotechnical routine testing methods. The second objective was to develop a VR tool to simulate a real-world investigation project for the construction of a building. The chosen scenario for this tool was to allow the students to iteratively sharpen their knowledge and develop their skills in choosing the appropriate number of boreholes and the useful testing methods, to properly define the ground model for the foundation design while optimising the investigation cost. This project is a prototype that can be enriched with moderate efforts, to include new sites and new construction projects with increased complexity.

At the moment of writing the manuscript, the project was not finished and the development phase is scheduled to end in June 2025. The final product will be shared to everyone who might be interested in trying and using it under a Creative Commons (CC) open licence. The main language is French but text translations and video subtitling in English will be systematically added.

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Dr. Adel ABDALLAH is an Associate Professor of Geotechnical Engineering at Nancy Engineering School of Geology, Université de Lorraine, France, since 2000. He holds a Civil Engineering BEng from ENI Gabès, Tunisia (1993), a MSc in Civil and Mining Engineering (1995), and a PhD in Geotechnical Engineering (1999) from Lorraine's National Polytechnical Institute in Nancy, France. His research is focused on coupled THM behaviour of natural, compacted and treated soils. He is particularly interested in numerical modelling and model parameter calibration, and in applications of machine learning and artificial intelligence in Geotechnical Engineering. He teaches soils mechanics at graduate and undergraduate levels, numerical modelling, geotechnical design and machine learning. He served as the Academic Dean of his Engineering school from 2012 to 2018.

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Prof. Olivier CUISINIER is Professor of Geotechnical Engineering at Nancy Engineering School of Geology, Université de Lorraine, France, since 2008. He earned his PhD from the Université de Lorraine in 2002 before joining the Laboratoire Central des Ponts et Chaussées (LCPC) as a Researcher, where he worked until 2008. That year, he transitioned to academia as an Associate Professor at the Université de Lorraine, and in 2020, he was promoted to Professor of Geotechnical Engineering. Dr. Cuisinier's research focuses on the fundamental behavior of soils and the advanced laboratory characterization of fine-grained soils. With nearly 20 years of experience in soil mechanics, his expertise covers unsaturated expansive soils, naturally and artificially cemented soils, with a particular emphasis on their long-term behavior. Beyond his research, Dr. Cuisinier actively contributes to the geotechnical community. He serves since 2024 as the Chair of the Scientific Committee of the French Association for Soil Mechanics and Geotechnical Engineering.

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Prof. Farimah Masrouri holds a doctorate in Geotechnics and Civil Engineering from INSA de Lyon, as well as a Habilitation à Diriger des Recherches (HDR) from the Institut National Polytechnique de Lorraine. She is currently a Professor at the University of Lorraine, École Nationale Supérieure de Géologie in Nancy, France, where she teaches both theoretical and applied soil mechanics, geotechnics, and the modeling of thermo-hydro-mechanical behavior in saturated and unsaturated soils, alongside structural design and natural risk management. Her research primarily focuses on the multiphysical and multiscale behavior of saturated and unsaturated clayey soils. This research approach integrates micro- and macroscopic properties with chemo-thermo-hydro-mechanical behavior, as well as phenomena related to time and durability. The applications of her work span various structures, including the storage of high, medium, and low-level radioactive waste, energy geostructures, shallow and deep foundations, retaining walls, and embankments. Since 2007, she has been an active member of the International Society for Soil Mechanics and Geotechnical Engineering, participating in the activities of three international technical committees: 106 (Unsaturated Soils), 306 (Geo-engineering Education), and 308 (Geo-Energy).