# Advancing Undergraduate Geotechnical Education through Multiphysics-Enriched Mixed Reality Games (IUSE)

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## Abstract

This work presents the continued development and evaluation of MERGE (Multiphysics-Enriched Mixed Reality for Geotechnical Education)—an immersive learning platform that integrates classroom theory, field observation, and laboratory simulation through the mixed-reality game EarthTrek. Designed around the sustainable engineering challenge of geothermal pile design, EarthTrek enables students to visualize subsurface processes, perform virtual experiments, and apply geotechnical design principles within a realistic digital environment.

Over the past year, several key improvements have been made: a text-driven knowledge map for structured navigation, a bearing capacity calculator for real-time parametric exploration, a toggleable flow guide with automatic progress saving, and migration to Unity's Universal Render Pipeline (URP) for enhanced cross-platform fidelity. A controlled classroom study ($N = 30$) showed significant gains in conceptual understanding ($F(1,28) = 10.02$, $p = .004$), with the treatment group outperforming the control by an effect size accounting for 26% of variance in test scores.

Qualitative findings indicated strong engagement and inclusivity, while also highlighting areas for improvement such as technical stability and curriculum alignment. The results demonstrate that integrating MR-based, multiphysics-informed simulations can strengthen undergraduate students' metacognition, problem-solving, and ethical reasoning.


## Introduction

Geotechnical engineering is facing increasing pressure from climate change, energy related issues, and the aging of existing infrastructure. Under these conditions, education in geotechnical engineering needs to help students better understand how soil behavior, laboratory testing, and engineering judgement are connected. However, in many courses, these parts are often taught separately. Students may learn the basic concepts and equations, but still have difficulty using laboratory results to support design decisions. As a result, the learning process can appear fragmented and not closely related to real engineering practice.

Game based learning and serious games provide a possible way to address this problem by allowing students to learn through actions, decisions, and feedback. Previous studies point out that an effective educational game should integrate learning objectives directly into the game tasks and feedback, instead of adding learning content on top of gameplay [1]. When students have different backgrounds and learning speeds, adaptive serious games offer useful methods through player modeling and adjustment of task difficulty [2]. In addition, recent discussions on future education emphasize the role of technology integration and well structured learning environments in supporting student learning [3].

Based on these considerations, we develop MERGE, a Multiphysics Enriched Mixed Reality platform for geotechnical engineering education. The platform combines site exploration, experimental learning, data interpretation, and design reasoning into a single learning process focused on geothermal pile design [7]. In this paper, the main attention is given to learning assessment and analysis of results. Therefore, the description of the platform itself is kept brief, in order to better support the discussion of the educational outcomes.

## Overview of the merge platform and earth trek

Earth Trek structures learning as a clear task pathway. Students enter a map based scenario, receive a design oriented goal, and progress through exploration, sample collection, preparation, experimentation, and design interpretation. The workflow is designed to repeatedly surface one central idea: different soils and conditions lead to different parameters, and those differences matter for engineering decisions.

Short interactive activities are placed within the workflow to build intuition before formal testing. For example, simple interactions can illustrate that deeper excavation becomes slower and harder to maneuver, which is used as an entry point to discuss how material and environmental conditions affect transport and resistance processes. Map guided exploration also supports engagement by asking students to move to specific locations, collect tools, and gather samples as part of the learning rhythm.

After sampling and preparation, students enter the virtual laboratory phase. The platform centers on two common undergraduate geotechnical experiments that represent thermal and mechanical soil properties. In the thermal module, students perform a steady state style measurement procedure, explore how measurement setup affects readings, and record thermal conductivity as an input for geothermal pile performance reasoning. In the direct shear module, students adjust normal stress and water condition, observe shear response, and interpret stress displacement information to understand shear strength parameters and related concepts.

Following experimentation, the platform connects results to interpretation and design reasoning through scaffolded tools. A calculator component allows students to map measured parameters to bearing capacity related quantities and observe sensitivity to inputs. A knowledge mapping component presents key concepts and parameter relationships in a structured view, helping students keep a coherent conceptual frame across multiple steps and connect experimental outputs to engineering meaning. Earlier versions of this mixed reality, multiphysics enriched educational game approach have been introduced in prior conference work [4], and subsequent classroom oriented refinements and deployment focused discussions have also been reported [5].

## Study design and methods

Currently, this study is being conducted through ongoing classroom deployments of Earth Trek, with continued data collection and iterative refinement. The study includes two classroom implementations that are assessed using the same 18 item knowledge test, enabling direct comparison on a common scoring scale. The first implementation used a single group pre post design ($n = 35$) to establish a baseline learning gain under a control classroom setting. The second implementation used a controlled design (total $n = 30$), with two groups ($n = 15$ per group), to compare learning gains and post test performance under different classroom conditions. In addition to the group comparison within the second implementation, we also compare its control group against the baseline results from the first implementation to examine how outcomes under control conditions may vary across deployments.

Both implementations followed the same activity chain in the learning platform. Students entered a map based scenario, completed exploration and sample collection, experienced short interactive activities to build intuition, engaged with the virtual experiment learning modules, and then used scaffolded tools to support interpretation and design reasoning. The workflow is intended to repeatedly reinforce a coherent loop: changes in conditions lead to changes in parameters, which in turn affect engineering judgement, providing a basis for conceptual understanding and transfer to the assessment.

The assessment consists of 18 items, including 8 items related to thermal conductivity and 10 items related to direct shear, with a total score out of 18. Students completed a pre test (Pre) before the learning activity and a post test (Post) after the activity. We define the total score gain as Gain = Post − Pre. For the first implementation, sub scores for the two topic areas are also retained to support interpretation of where improvements may originate. Results are presented primarily through distribution based visualizations. We use boxplots with overlaid individual points to compare the three groups in terms of gain and post test performance (Figure 1), highlighting both average changes and individual variability, including dispersion and negative gains.

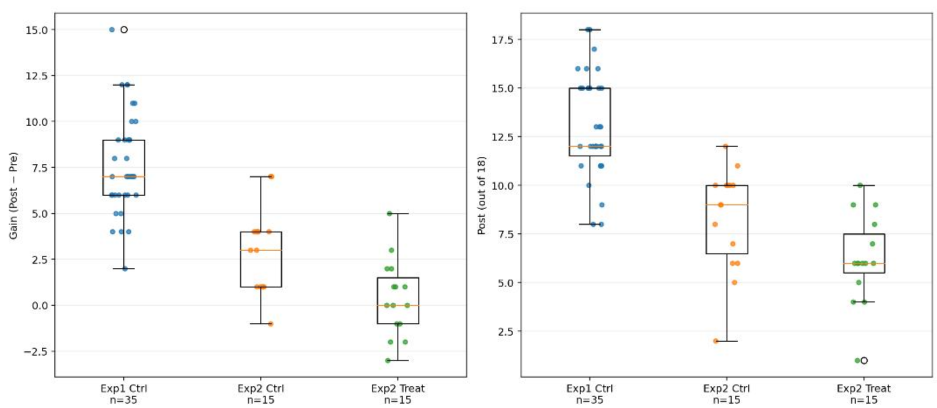


Fig 1. Statistics of correct answers before and after the game.

**Result**

Figure 1 summarizes total score gain distributions (left) and post test total score distributions (right) for three groups: the baseline cohort from Implementation 1 (n = 35) and the two groups from Implementation 2 (n = 15 per group). The baseline cohort in Implementation 1 shows a larger and more consistent positive gain, with the distribution shifted upward and very few, if any, negative gains. This pattern suggests that under the baseline classroom setting, the platform supported a stable improvement on the knowledge test.

In Implementation 2, both groups show pre post changes, but the overall magnitude and stability are weaker than the baseline cohort. The control group shows a modest positive gain with a more dispersed distribution, while the treatment group shows gains that cluster closer to zero and exhibits a higher share of negative gains. The post test distributions show a consistent pattern, with both Implementation 2 groups achieving lower overall post test levels than the baseline cohort, and the treatment group exhibiting the lowest overall post test performance. Together, the gain and post distributions indicate that the group difference in Implementation 2 is not only a difference in mean gain, but also a difference in stability, namely whether gains consistently translate into an upward shift in assessment performance.

When viewed on the same 18 point scale, Figure 1 provides a clear joint observation: the two implementations start from similar baseline levels but diverge substantially in gain and post test outcomes under control conditions. The baseline cohort from Implementation 1 shows higher and tighter gains and a higher post test distribution, while the control group in Implementation 2 shows smaller, more variable gains and a lower post test distribution. This suggests that learning benefits under a control setting may be sensitive to deployment conditions and learning pathways, which remains one of the key issues that the ongoing study aims to explain and validate.

You also noted that Implementation 1 may have benefited from student level differences. At the current stage, this can be expressed more appropriately as differences in learner engagement and task completion consistency. In Figure 1, the concentrated positive gain distribution in Implementation 1 is consistent with more uniform engagement and more complete completion of critical learning steps. The larger dispersion and the presence of negative gains in Implementation 2 suggest that some students may have had lower engagement, incomplete progression through key steps, or weaker alignment between experimental outputs and conceptual interpretation, making gains less likely to transfer into assessment performance. Future work can validate this interpretation using process data, such as task chain completion rates, time on experiments, and scaffold usage patterns, to separate learner factors from deployment condition factors.

## Conclusions and future work

Earth Trek has been developed as the first learning experience within the MERGE platform, and our current study provides initial evidence that the platform can support measurable learning gains when deployed in undergraduate geotechnical courses. By combining map based task progression, short interactive activities, virtual laboratory experiments, and scaffolded interpretation tools, MERGE connects experimental procedures with engineering meaning and design reasoning in a single workflow, helping students engage with concepts that are often difficult to experience in conventional instruction.

Future work will expand this ongoing study through additional classroom deployments at multiple universities, allowing us to evaluate the robustness and generalizability of the observed outcomes across different regions, course structures, and student populations. In parallel, we will continue to refine the game based on classroom feedback and process data, with particular attention to supporting consistent learning pathways and improving usability in real course settings. Together, these efforts aim to establish MERGE as a scalable, evidence informed tool for geotechnical engineering education and to better understand how implementation conditions shape learning impact.

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