Development of Multiphysics Enriched Mixed Reality Game for Geotechnical Engineering Education

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ABSTRACT

This study aims to develop a multiphysics-enriched mixed reality game system that provides an integrated geotechnical learning experience with visualization, collaboration, and simulation tools. This paper summarizes the game development works. Essential game components, such as player characters, geotechnical testing devices and tools, and laboratory environment, were created for the virtual game. Multiple mini-games incorporating geotechnical concepts are designed to further encourage the players to play the game. The thermal conductivity and direct shear tests will be performed in a virtual walk-in environmental chamber with controllable temperature. Using these experimental results as modeling inputs, finite element simulations are integrated to support the geothermal pile analysis under field conditions. Players will be able to visualize the simulation results through the augmented reality technique. The entire game is created as a mobile game platform which enables players to use personal smartphone or tablet devices. The work is expected to improve undergraduate students' interests and success in geotechnical engineering coursework, as well as provide developmental insights and educational background to inform researchers who seek to develop similar games.

INTRODUCTION

Geotechnical engineering plays a critical role in addressing today's global issues covering energy demand, environmental protection, infrastructure sustainability, and hazard mitigation (Cannon and Gartner, 2005; Tang et al., 2020). The next two decades are expected to witness substantial increase of the world population, as well as subsequent increase of today's power consumption. These challenging concerns raise pressing needs for the education of next-generation geotechnical engineers who are capable of identifying, preventing, and solving emerging multiphysical geotechnical problems. To achieve this goal, students are expected to gain a broader range of knowledge than previously provided in a typical geotechnical course, as well as an improved understanding of the underlying science and governing mechanisms, making the possession of an integrated background of knowledge essential for the future geotechnical workforce.

The current geotechnical engineering education often lacks connection with students, as many students see the work as uninteresting, challenging, and unrelatable (Ferentinou and Simpson, 2019; Shidlovskaya and Briaud, 2016; Welker, 2012). This challenges outreach work to recruit new students and workers in the field. Development of updated, interactive educational materials is needed to engage students in engineering education. Research has begun into replacing traditional group projects in geotechnical engineering courses with innovative, project-based participatory games, such as mixed reality games, to demonstrate engineering principles with real-world examples. In previous studies, Bennett et al., (2020) utilized the teaching technique of mixed reality games to teach geotechnical students with Cone Penetration Testing (CPT) and it was found that the learning interest and efficiency of students had been significantly fostered; Harteveld et al., (2020) conducted a survey on 362 undergraduates and found the evidence of positive outcomes and equitable learning environment from the transformation of traditional educational model to a more student-centered and experiential paradigm (i.e., game-based learning); Budhu, (2020) proposed interactive animations and (game-based) virtual geotechnical laboratory tests that had significantly enhanced the presentation of these concepts and improve learning and retention for students. In this competitive and fun game environment, students will be motivated to develop skills to tackle challenging geotechnical problems at their own pace (Agrawal and Dill, 2008). Such mixed reality game systems help to further stimulate students' learning across the contexts established by time, space, and social arrangement, and offer students unprecedented access to learning resources. Therefore, the current study will be conducted to achieve three educational goals: 1) To engage students with an innovative solution from geotechnical engineers to tackle global energy issue; 2) To lead students to master a systematical design of a geotechnical infrastructure from theory to practice; 3) To develop an educational paradigm for enhancing the learning experience and interest b using the teaching technique of mixed reality games.

METHODOLOGY

A mixed reality game was developed through this study to promote geotechnical engineering education. Mixed reality games include gameplay where objects can be superimposed into "reality" through a camera in addition to the virtual reality format one would normally expect from a gaming experience. This game format was chosen to help promote learning, as well as improve the virtual learning experience. This study would convert a simple practical design of a geotechnical infrastructure into an example for virtual Multiphysics-enriched mixed reality game. A design of geothermal piles was chosen due to its interdisciplinary study and innovative and sustainable solution to the global issue of climate change. The educational purpose could be achieved by engaging students with metaphysical problems (i.e., thermal-mechanical interactions) beyond the traditional teaching and the role of geotechnical engineering in solving global issues. The geothermal pile is an emerging technology that utilizes the underground geothermal energy for cooling or warming infrastructures through heat exchange. A geothermal pile majorly consists of a pile foundation, a heat exchanger, and a heat pump (Lyu et al., 2020). This suggests that the bearing capacity of a geothermal pile is determined by the load-transferring on the soil-pile interface under both mechanical and thermal loadings. Determining both mechanical and thermal properties of geomaterials is of importance for the design, analysis, and evaluation of the performance for a geothermal pile. Figure 1 shows the design process of a geothermal pile, from site investigation, determination of engineering properties, structural design, and construction. The designed game includes laboratory measurement of mechanical and thermal properties of geomaterials and structural design of geothermal piles using finite element method. Students would be led to apply the measured shear strength and thermal conductivity of soils to the design of a geothermal pile under various boundary conditions. The geotechnical engineering education is systematically conducted from laboratory testing, structural design, numerical modelling, and performance evaluation. Students should be having a better understanding of geotechnical engineering from theory to practice.

Game Development

The mixed reality game developed through this study was inspired by Niantic Inc.'s mixed reality game, Pokémon GO. Pokémon GO includes a player's avatar, which used the phone or tablet's GPS location to show the avatar within the game. The game developed focuses on laboratory experiments involving the study, construction, and implementation of geothermal piles, which are special foundations that utilize the earth's temperature to heat and cool the associated building. Targeting this application of geotechnical engineering allows the game's players to be informed about the energy crisis and current sustainability efforts. There are two main experiments included in the game: thermal conductivity experiment and direct shear test. These experiments were implemented as a series of learning-based mini-games which will ideally keep the player attentive to the learning process. The implementation of a points and achievement system is also to promote continued gameplay. Storyline chapters developed throughout the game include: Becoming an Intern, Finding a Plot, Soil Sampling, Thermal

Conductivity Experiment, Direct Shear Experiment, Experiment Results, Foundation Determination, Pile Design, Simulation, and Construction.

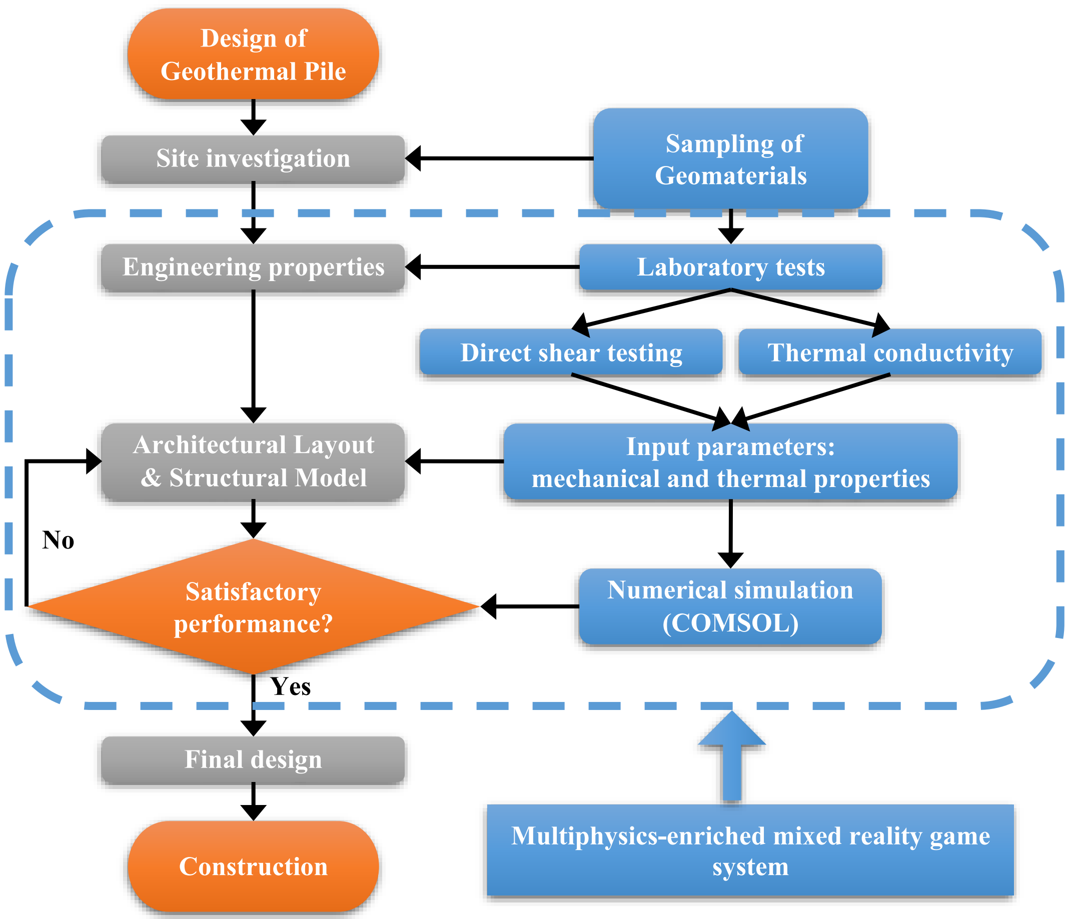


Figure. 1 A flowchart showing the whole design process for a geothermal pile and the role of Multiphysics-enriched mixed reality game system in the design.

Mini-Game Development

A series of learning-based mini-games were developed for the game intended to provide background information and context on the concepts and tools the players will need while playing the full game. Mini-games include word search, connect the dots, spot the difference, and dig dug games. The Dig Dug game is inspired by the 1980's game, Dig Dug as shown in Figure 2, where the player collects soil types (i.e., sprites of different colored rocks) as the player digs below the surface. Once the player collects a certain amount to fill their meter, the player wins the mini-game. In the Connect the Dots game, the player will trace the dots in order to reveal a picture related to the experiment being performed.

The mini-games developed work with a point system for the player to gradually gain points throughout the game. Points can be earned and collected so that the player can use them as a form of in-game currency, which can be used to alter their avatar, such as changing its clothes or making certain upgrades throughout the game.

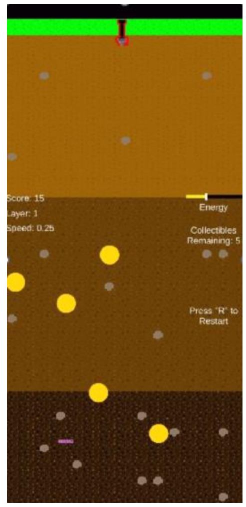


Figure 2. Dig Dug game built in this platform.

RESULTS AND DISCUSSION

The mixed reality game developed through this study focuses on laboratory experiments involving the study, construction, and implementation of geothermal piles, which consist of a series of pipes that are built within a concrete pile. Essential game components, such as player characters, geotechnical testing devices, and laboratory environment, were created for the virtual game. A knowledge map was also developed to guide the player throughout the pile design and analysis processes within the game. The knowledge map serves as a metacognitive intervention technique to improve students' metacognitive awareness and strategic learning of geotechnical concepts.

Pile Design Game

The mixed reality game platform was developed to expose students to the geotechnical engineering concept of geothermal piles. First, the player focuses on the creation of the player's avatar which will walk the map throughout the main game. Figure 3 shows examples for a male and female avatar created for the game.

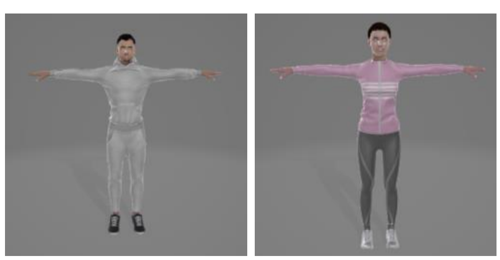
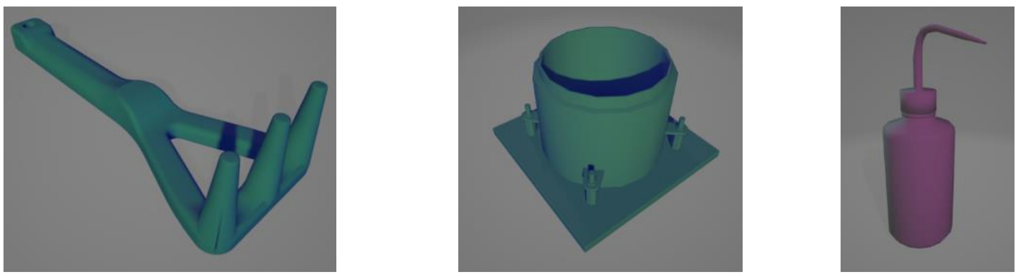


Figure 3. Example male and female avatar characters created for the mixed reality game.

Similar to the avatar in Pokémon Go, the player's avatar will represent where the user is in the virtual world and will follow the path as the player walks to collect the different tools (e.g., hand rake, mold, wash bottle, and pickaxe) needed for the experiments as shown in Figure 4, the mini-games, and other activities. We use the phone's GPS location to give students the experience of viewing their local area as shown in Figure 5, an example map around Rowan University. Within the game, there are two experiments chosen for the players to construct, which are detailed below.



(a) Hand Rake (b) Mold (c) Wash Bottle

Figure 4. Example 3D models of tools for experiments.

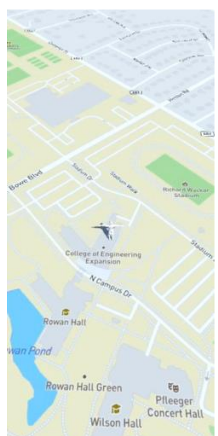


Figure 5. Example map around Rowan University

Thermal Conductivity Experiment

Within the gaming platform is the thermal conductivity experiment. The thermal conductivity experiment determines how well a material conducts heat under steady state conditions, which is necessary when developing a design of underground power transmission systems, for example. For this experiment, a thermal conductivity device is inserted into a soil sample to determine the temperature of the soil, which is used to calculate the k-value (known as the thermal conductivity) of the soil. This laboratory experiment was translated into gameplay, where the player will choose to enter the "laboratory", known as the environmental chamber, where the temperature is able to be controlled. In front of the player is the thermal conductivity device and multiple cylinders containing the sample soil. Figure 6 shows an example of the 3D model of the thermal conductivity device used in this gameplay experiment.

Figure 6. Example 3D model of the thermal conductivity device created for the mixed reality game.

The player will select the cylinder containing the soil sample to test and will click on a spot in the soil to insert the probe. Once the probe is fully inserted into the soil, the player will click to determine the temperature of the sample. After the temperature is determined, the k-value will appear within the game, and the player has concluded the experiment. The k-value measured in this thermal conductivity experiment can be used as an input parameter in the following thermal pile simulation.

Direct Shear Test

Within the gaming platform, there is also the Shear Stress Test Experiment. The Shear Stress Test is an experimental procedure conducted in geotechnical engineering to determine the shear strength of soil materials. Shear strength is defined as the maximum resistance that a material can withstand when subjected to shearing. In a shorter shear stress test, the shear is often applied between the top and bottom portions of the shear box. In a longer shear stress test, water can be used to help keep a saturated condition (like it would be under most buildings). The normal stress or the downward pressure simulates the loading above the soil as well. This laboratory experiment was translated into gameplay, where the player will choose to enter the laboratory and locate an even surface to start assembling the shear box. To start, the player must put the square plate into the water table with the ribbed side down. Then, the player must fit the circular bottom plate into the hole of the square plate with the ridged side up and add the filter paper on top. Next, the player can add the selected soil sample and then add the top plate to the shear box. Next, the player must add another piece of filter paper, followed by the porous stone. Finally, the player adds the coned plate on top of the porous stone with the small Iron Ball in the small recess on top of the coned plate.

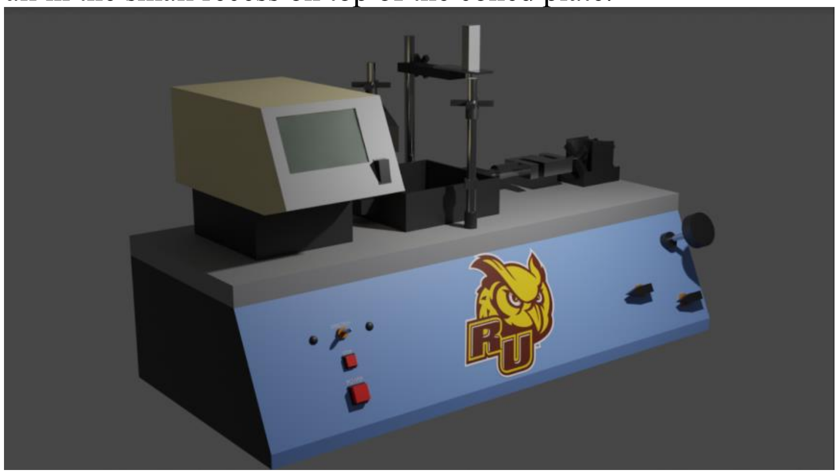
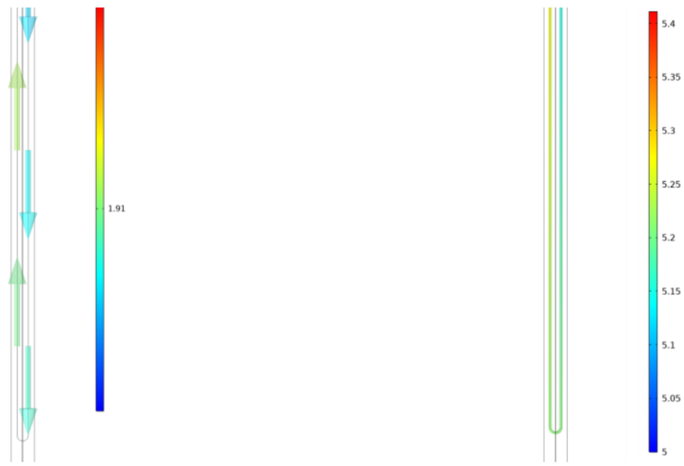


Figure 7. Example 3D model of the shear stress machine created for the mixed reality game.

Moving back to the apparatus as a whole, the upper bracket must be slid down so that the arm is over the top of the iron ball. All the load and pressure knobs must be turned off. Next, the player can turn the apparatus on by clicking the controller box button. The player can then change the knob on the right to adjust the pressure. Once done, the player can hit the designated load, and then hit the apply load switch. Finally, the player must hit the direction flip to the left for the apparatus to start moving. The results can then be obtained from the display screen on the top left of the apparatus. Figure 7 shows an example of the 3D model of the shear stress machine used in this gameplay experiment.

Geothermal Pile Simulation

Geothermal piles are concrete piles containing a series of pipes, which can meet the requirements for loading and energy extraction (Lyu et al., 2020). Several meters below the earth’s surface the temperature remains relatively constant all year long. During the summer, the temperature under the surface is often colder than the weather above, and warmer than the surface during the winter. Because the temperature of these piles remains constant in relation to the weather outside, it helps to efficiently heat/cool the structure. The geothermal piles save money in the long term for the building. The biggest disadvantage of geothermal piles is their expensive cost and the scarcity of tested data on the piles themselves. The geothermal piles are connected to a pump system, which aids in the movement of fluids via the pipe network. Pipes placed in concrete piles can be designed a variety of forms (e.g., spiral, U, and UU shapes). The heat exchange mechanism in a geothermal pile was explored using COMSOL, a FEM (finite element technique) program. The students can alter the design of the pipes and concrete piles, as well as the temperature gradient of the ground and the water temperature, to obtain varied simulation results that will assist players in understanding the process of geothermal piles. For example, we injected 5 ℃ water into the U pipe as shown in Figure 8(a). After 1 hour, we can observe the water was heated by the surrounding ground as shown in Figure 8(b). As further information is learned about geothermal piles, it is a good idea to add boundary conditions (such as configuration of pipes and piles, underground temperature gradient) as a potential option in our game since it has high promise for future buildings that are looking to build using green technologies.



(a) Velocity distribution (b) Temperature distribution

Figure 8. Velocity and temperature distribution in U pipe.

CONCLUSIONS AND FUTURE WORK

This work aims to create a fun learning experience for students who are studying the field of geotechnical engineering. Through playing this game, players experience tests that geotechnical engineers conduct in the real world in order to evaluate and characterize soils. Within the game, players have the opportunity to customize their characters and gain knowledge about the engineering concepts.

To expand upon this work, the next steps in the development of this game include the players determining how geothermal piles will be implemented into their design, as one of the goals in this game is to show the players the benefits of geothermal piles. Once the players have chosen their ideal pick of foundation type, they will need to test them out in a simulated environment, which will help teach the players how important checking their work is when it comes to engineering design. This portion of the game will conclude with a simulation of their structure being built and a reward for successfully completing the mission. A post-game survey will be also conducted to assess the learning interest, learning retention curve, academic performance of students. The work will help improve undergraduate students' interests and success in geotechnical engineering coursework through an interactive learning experience. This work will provide developmental insights and educational background to inform researchers who seek to develop similar games.

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