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Integration of centrifuge testing in undergraduate geotechnical engineering education at remote campuses

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We report the results of a pilot study aimed at developing, implementing, and assessing an educational module that integrates remote major research instrumentation into undergraduate classes. Specifically, this study employs Internet Web-based technologies to allow for real-time video monitoring and execution of cutting-edge experiments. The students’ activities within the module are centred on building a model of a shallow foundation on a sand deposit utilising a centrifuge facility and using this model for: (1) visual observation of the response of soil-foundation systems, (2) learning the use of instrumentation, (3) interpretation of acquired data, and (4) comparing experimental results to theoretical predictions. Testing a soil-foundation system helped the students identify the lab experiments needed to analyse and design the system. A survey was used to gauge students’ perceptions of learning as a result of introducing the module, which were found to be positive.

Keywords: civil engineering; engineering education; geosciences; Internet applications; remote access laboratories

1. Introduction

Geotechnical engineering is a major component in many education and research applications within the broader discipline of civil engineering. It builds on the basic knowledge acquired by students from introductory courses in mathematics, physics, chemistry, statics, dynamics, mechanics of materials, and computational methods. Within these areas, experimentation and computational analyses are currently the backbone of engineering education and research. In spite of the fact that geotechnical systems are relatively complex in nature, undergraduate students tend to struggle to link experiments performed in the lab on small soil elements to the theoretical part of the course that focuses on the response of larger geotechnical systems.

To overcome these shortcomings, physical modelling and testing has been recently incorporated in undergraduate geotechnical engineering. Wartman (2006) argues that a student’s understanding and retention of fundamental concepts would be enhanced if physical modelling is strategically integrated into coursework. Physical models have served important roles in engineering
research, practice, and education for hundreds of years (Ferguson 1992). In geotechnical engineering, reduced scale physical models tested under 1-g environment suffer from the limitation that soil behaviour is highly stress-dependent and small-scale 1-g models fail to mimic actual field conditions. Geotechnical centrifuge modelling overcomes this shortcoming by subjecting a small-scale model to a high gravitational field that produces stress levels in the small-scale model similar to those in the prototype. More details about geotechnical centrifuge technology are presented in the next section.

Laboratory instruction, which has traditionally played a prominent role in engineering education, allows students to develop skills in experimentation, data interpretation and synthesis, communication, and teamwork. According to Wartman (2006), physical modelling offers the following unique advantages pertinent to teaching geotechnical engineering: (1) physical models clearly portray complex, nonlinear geotechnical mechanisms and phenomena that are otherwise difficult to visualise; (2) by directly observing geotechnical systems at the model scale, students develop an intuition and physical sense for the fundamental mechanisms that govern the behaviour of these systems; (3) small-scale models may be tested to collapse, thereby allowing students to witness, first hand, failure mechanisms that are not seen in traditional soil mechanics laboratory sessions, which usually focus on element testing; and (4) through back-analysis of physical model experiments, students can directly assess the deviation between the predicted and actual performance of geotechnical systems.

The pilot study presented herein examines the impact of introducing an Internet-based course module that utilises major research instrumentation in the regular undergraduate curriculum in three different universities. The experimental learning module is a collaborative effort among Southern Methodist University (SMU) of Dallas, TX, Rensselaer Polytechnic Institute (RPI) of Troy, NY, and the University of North Carolina at Charlotte (UNCC) of Charlotte, NC. The module allows for real-time video monitoring, tele-control, and execution of cutting-edge experiments utilising the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) facility at RPI. The goals of the project are to actively engage students in a stimulating and informative educational environment. We aim to provide students with broader insight into advanced research equipment and increase their motivation to learn about geotechnical systems by creating a learning environment that integrates physical modelling into geotechnical engineering education. The educational activities and experiment are intended to enhance students’ ability to access, interpret, and evaluate relevant technical information in a timely and effective manner. The expected outcome of the project is that the activities will lead to a better understanding of the physical meaning of engineering principles and improve students’ capability to design and conduct experiments.

2. Centrifuge physical modelling and geotechnical engineering education

Geotechnical centrifuge model testing provides a valuable tool to the geotechnical engineer, enabling the physical study and analysis of design problems by using geotechnical materials (Taylor 1995). Centrifuge modelling has emerged as a valuable research and educational tool for geotechnical and geoenvironmental engineering. A centrifuge is essentially a sophisticated load frame on which soil models can be tested. Soil models are placed at the end of the centrifuge arm which is rotated at high revolutions per minute, thus subjecting the soil model to an inertial radial acceleration field, which is many times stronger than Earth’s gravity. The model is often a reduced scale version of the prototype. The two events should be similar and similarity is achieved by appropriate scaling laws where dimensionless groups are used to relate events of different scales (Taylor 1995). This concept is illustrated in Figure 1 where an actual field condition (prototype) is scaled to a model that is \(1/N\) the height of the prototype, where \(N\) is the intended g-level to
be achieved in the centrifuge. When the model is subjected to this high g-level in the centrifuge, the stresses at the corresponding heights between the model and the prototype will be the same (Figure 1). Thus, the use of the centrifuge enables modelling of complex soil behaviour and soil-structure interactions as opposed to standard geotechnical laboratory experiments where the focus is usually on a small element response. Centrifuge modelling is a very economical and effective method for studying the response of soil systems (slopes, dams, etc.) and soil-structure systems (shallow and deep foundations, tunnels, retaining structures, etc.). Contrary to actual soil systems, instrumented centrifuge soil models can be tested to failure for students and engineers to observe and analyse.

Instructional centrifuges with radii that typically range from 300 to 800 mm and centrifuge capacities between 400 and 500 g have been used by a number of researchers and educators. Craig (1989) notes that instructional centrifuges can be effectively used to illustrate concepts of slope stability, slope–foundation interaction, tunnel stability, and lateral earth pressure theory. Caicedo (2000) used an instructional centrifuge to perform simulations of shallow foundations, pile and pile groups, and earth retaining structures. He also discusses modelling in the context of a ‘learning by doing’ instructional module and describes a capstone course where student groups design a geotechnical system, test it to failure in the centrifuge, and later back-analyse the experiment. Newson, Bransby, and Kainourgiaki (2002) used educational centrifuge along with a digital video camera and stroboscope. The imaging system can be used to view and measure deformations during an experiment and several teaching applications of the centrifuge including back-analysis of experiments involving bearing capacity, lateral earth pressures, and interface friction in soils are described. Dewoolkar, Goddery, and Znidarcic (2003) discuss applications of educational centrifuge for undergraduate laboratory experiments involving slope stability and lateral earth pressures.

The use of small instructional centrifuges has contributed to the inclusion of physical modelling in undergraduate education. Building models for testing in instructional centrifuges is rather simple and multiple applications can be demonstrated in one course. However, because the model is so small, the focus is mainly on demonstrating failure mechanisms and trends in the behaviour. Large-size centrifuges (e.g. radii > 1000 mm) produce detailed results at the expense of a more
difficult-to-construct model. However, they allow use of several sensors that can monitor the system at multiple locations, providing the user with a wealth of data to better understand the behaviour of the different elements of the tested system. Mitchell (1994) discusses the use of a large-size (2250 mm radius) centrifuge to teach topics in geoenvironmental engineering such as unsaturated soil mechanics and contaminant transport. Mitchell (1998) reports that physical modelling activities often stimulate interest in geotechnical engineering among students. He also notes that modelling can be particularly valuable for student-independent projects.

3. Educational labs in engineering education

There are three types of labs that can be implemented in engineering education: physical (real) labs, remote labs, and simulation (virtual) labs. Web-based technologies allow students to work remotely on real equipment and instrumentation located at a distance. When compared to actual physical labs, both remote and simulation labs have advantages and disadvantages. Balamuralithara and Woods (2008) summarised key comparison elements between the three types of labs. Physical labs have the advantage of hands-on experience and providing real experiences and practical skills. Access to physical labs, however, is limited and they require costly equipment and large space. Remote and simulation labs share the drawbacks of not promoting support and teamwork as well as developing a feeling for lab safety. The cost of virtual labs is low and access to these labs is not limited.

The use of remote labs in which a Web-based technique provides an interface between students and a laboratory provide opportunities to address the inclusion of remote lab work in engineering education. Web-based communication technologies enable students to send commands that then go through a server and execute the experiment on equipment in the real lab. This technique was applied by Marc et al. (2002) to Control and Robotic labs utilising LabVIEW Web server.

Web-based technologies have been used effectively to demonstrate theoretical concepts using virtual (simulation) experimentation equipment. Internet availability of experimental set-ups and related computational simulations allow for: (1) efficient use of time and resources, (2) flexibility in accessing information, and (3) convenience of self-paced learning with the aid of physical models (Soh and Gupta 2000; Romero and Museros 2002). The interest in developing and implementing educational Web sites is increasing rapidly, including: (i) vibration of instrumented flagpole (Amaratunga and Sudarshan 2002), (ii) virtual experimentation in soil mechanics (Budhu 2002), (iii) simulation of shear waves in layered media, (http://octavia.ce.washington.edu/DrLayer/, Arduino, Miller, and Ogurinde 2002), and (iv) Webshaker live shaking table experiment (http://webshaker.ucsd.edu, Elgamal, Fraser, and McMartin 2005). Such a learning environment greatly facilitates deriving physical insight and knowledge, but clearly does not cover the experimental challenges of model construction, instrumentation, and data acquisition.

4. Course module

This pilot study employs Internet Web-based technologies to allow for real-time video monitoring, tele-control, and execution of cutting-edge experiments utilising the NEES facility at RPI. Engaging research experimentation in the typical geotechnical engineering classrooms provides undergraduate students with broader insight into advanced research equipment and motivates them by creating a new learning environment. The goals of this study are: (1) to build, organise, and test an online module for students across different campuses; (2) to test the viability of remote lab assignments taking advantage of NEES technology; (3) to introduce a unique physical
Figure 2. Elements of the proposed course module presented in a Kolb (1984) learning cycle as modified for teaching by McCarthy (1987) (adapted from Wartman 2006).

modelling experimentation environment and make it conveniently accessible to students, faculty, and other learners; and (4) to save instructors’ and educational institutions’ resources in terms of time, effort, and lab-space by providing Web-based, sharable lab resources.

The activities within the course module were mainly divided into four quadrants (I–IV) following the learning cycle proposed by Kolb (1984) and modified by McCarthy (1987) for teaching (Figure 2). Wartman (2006) suggests that the use of this model suits well course modules that incorporate physical modelling. Kolb (1984) argued that to be comprehensive, learning must occur in all stages of the learning cycle shown in Figure 2. Stice (1987) found that people learn most effectively when they develop learning skills in both their preferred and weaker learning stages. Thus, it is important to include a range of activities that appeal to all four of the learning styles when developing instructional modules. Research indicates that civil engineers will naturally gravitate towards Abstract Conceptualisation and Active Experimentation (AE) activities (Kolb 1981). However, overemphasis on quadrant III activities at the cost of less Concrete Experience (CE) and Reflective Observation (RO) will yield less than complete learning. Including CE and RO activities such as model demonstrations and analysis of model experiments into geotechnical engineering instructional modules will increase the likelihood that comprehensive learning will occur (Wartman 2006).

The students’ activities within the developed module were centred on building a model of a shallow foundation on a sand deposit utilising the RPI-NEES 3 m radius, 150 g-ton capacity centrifuge and using this model for: (1) visual observation of the response of soil and soil-foundation systems, (2) learning the use of instrumentation, (3) interpretation of acquired data, and (4) comparing the experimental results to theoretical predictions. Specifically, a centrifuge experiment was introduced in geotechnical engineering courses to examine the performance of a shallow footing constructed on a deposit made of dry, uniform sand. The readily available tools at the RPI-NEES facility were used in this project (see www.nees.rpi.edu for detailed description of NEES equipment). The following learning outcomes were set for the module. As a result of participating in the module/lab, students will be able to:

1. describe the actual stress distribution in the soil and the shape of the area loaded to failure;
2. design experiments using advanced procedures, instrumentation, and applications; and
(3) monitor, evaluate, analyse, and design soil and soil-foundation systems using appropriate instrumentation, electronic data collection, and state-of-the-art geotechnical engineering workplace applications and technologies.

The experiment was conducted in the spring of 2012 and included graduate and undergraduate civil engineering students at three campuses. Three graduate students participated in the class offered at SMU. Twenty-four students attended the class offered at RPI and 18 students took the class at UNCC. All students had taken at least one introductory course on geotechnical engineering prior to that semester and were familiar with topics such as soil phase relationships, compaction, permeability and seepage, effective stress and stress distribution, shear strength of soils, and bearing capacity of shallow foundations.

4.1. Pre-experiment assignment

The instructors at the three institutions collaborated in planning the learning activities for the project. The instructors faced a number of issues associated with synchronising the project tasks at the three schools. To accommodate different course schedules and start/end dates, students were informed at the start of each course that the project would require that they attend a remote lecture one late afternoon during a specified week. All students, regardless of the school they attended, viewed the experiment remotely. A lecture covering centrifuge concepts and scaling laws along with examples of their implementations was presented by RPI instructor, Dr Abdoun. The lecture was held live for RPI students and was streamed in real time over the Internet to SMU and UNCC students. Using video-conferencing technology, remote students were able to engage in a question and answer session towards the end of the remote lecture.

The module was introduced to the course as a term project composed of two assignments that mainly cover the topics of stress distribution and bearing capacity of shallow foundations, which are integral parts of the three courses offered at the three institutions. The activities in the first assignment focused on the RO part of the Kolb learning cycle (Figure 2). Specifically, it contained the following pre-experiment activities:

1. Gather information about centrifuge technology and associated scaling laws relevant to the problem under consideration,
2. review information pertaining to safety precautions and procedures involved in centrifuge modelling. These include safety of the personnel and ensuring that the designed experiment will not damage the utilised equipment, and
3. design the model of the test (define dimensions and materials) and specify what needs to be measured as well as the type and proper locations of sensors for the application. Students were also asked to identify the soil parameters needed to evaluate soil strength and the lab experiments needed for that. Students were then asked to predict the maximum column load that could be placed if the soil is known to be uniform Nevada sand with a specified relative density (shear parameters were not given).

The solutions to this assignment were due in 10 days from the day the assignment was given to the students. Discussion of students’ solutions took place in each school and students were shown the final design of the model (Figure 3). In general, the following observations were made by the instructors on the performance of students in Assignment 1:

- Many students felt the assignment was a challenge since it was not similar to typical homework problems.
Some students tended to propose more soil parameters and tests than actually needed. Students were provided with an explanation on how to define the soil parameters needed for a specific application.

Some students were not able to implement centrifuge scaling laws and accurately define the model dimensions. The instructors went over the solution of Assignment 1 so that students could understand how to apply scaling laws.

4.2. The remote experiment

RPI students built the physical model based on the final design (Figure 3). Students on the remote campuses were kept updated of the model progress and SMU students engaged in building a dummy model to learn how the soil deposit is created and how sensors are installed. The actual centrifuge experiment was conducted on 2 April 2012 at the RPI facility. To resolve scheduling issues, RPI students observed the experiment on the morning of 2 April and another experiment was performed in the late afternoon of that day for UNCC and SMU students. WebEx and NEES telecommunication tools were used so that students at the remote sites could observe the live experiment from different camera angles. The remote experiment broadcast also allowed questions and answers from students at SMU and UNCC.

The experiment consisted of two tests. In the first test, the model footing was positioned in the middle of the container (Figure 4) and loaded by means of an in-flight robot. The stresses on the four tactile pressure sensors shown in Figure 3 were monitored in real time and students were able to see the anticipated stress distribution with depth (Figure 5). The screenshot shown in Figure 5 shows the raw data the students observed during class, which were without magnitude or units. Note that the contour plots shown in Figure 5 show how the stress distribution differed from
being highest and localised at the sensor immediately underneath the footing to low and spread out for the lowest sensor, thus confirming the theory which shows that with depth stresses under a footing decrease in magnitude and tend to be distributed over a larger area. The second test was carried out to evaluate the ultimate bearing capacity of the footing and visualise the development of failure surface. For this purpose, the footing was relocated near the edge of the container where the side is made of transparent acrylic and the sand deposit was coloured in layers to help visualise and track the deformation of the underlying soil. The footing was loaded incrementally to failure and students were able to see, in real time, the shape of the load-displacement curve and the deformation of the soil underneath the footing (Figure 6).
4.3. Post-experiment assignment

Following the completion of the experiment, the recorded data were made available to all students and they were handed the second assignment on 5 April. This assignment focused on the AE activities of the learning cycle (Figure 2) and included the following activities:

(1) Quantifying the performance of the foundation. Included in this task was obtaining the physical and mechanical properties of the tested sand,
(2) running the experiment, using the tele-presence facility, under the supervision of the instructors,
(3) analysing the test results and producing relevant plots, and
(4) comparing the results from the centrifuge test to that obtained from theoretical calculations employing data from elementary geotechnical testing (e.g. direct shear and triaxial tests).

The second assignment was due two weeks from the day it was handed to the students. It should be noted that the students were directed in this assignment to obtain the ultimate footing load from the centrifuge test results (Figure 6) at the specific overall vertical strain magnitudes of 2% and 15% to define local and general shear failure modes, respectively. Just after students submitted their solutions, they were asked to complete a survey designed to assess the outcomes of the module. The students’ solutions were graded and a discussion of their answers took place along with statistical comparisons of the performance of students at the different schools. The project grade contributed differently to the overall course grade at each school. It was 20% of the course grade at RPI as the students had to build the physical model in addition to the assignments. It was only 15% at UNCC and 10% at SMU. The instructors observed that the students’ performance in Assignment 2 was better than that in Assignment 1, mainly because students were now more familiar with scaling laws and the fact that the assignment included theoretical calculations that directly relate to material covered in class.

4.4. Assessment

This paper focuses on the initial implementation of the online centrifuge experiment. The premise of the project is that student learning of geotechnical engineering concepts will be enhanced or improved through their participation in the centrifuge experiment. In this pilot project, no
comparative data were available given that the concepts covered by the experiment had not been
taught in prior versions of the courses. A qualitative approach to the assessment was employed
since the focus of the pilot project was to determine how to most effectively run a remote lab
such as this, and to gain insight into student learning based on student self-reports and reflections
regarding their learning, the assignments, and the technology used in the course. The survey
covered students’ prior experience with experimentation (online and in person), their opinions
regarding the experiment and associated assignments, the quality and ‘user friendliness’ of the
online experiment, and their opinions regarding the impact of the experiment on their learning.
All opinion questions were designed using a five-point Likert scale from ‘Strongly Disagree’ to
‘Strongly Agree’.

In this article, we report only on the results for undergraduate students as they are the prime
target group for this approach to online labs. Thirty-four undergraduate students from RPI and
UNCC completed the survey; a paper version of the survey instrument was used with students at
UNCC; students at RPI completed the online version of the survey instrument. Fifty per cent of
the students were seniors and 50% were juniors. The majority of students (79%) had completed
only one course in geotechnical engineering. Twelve per cent of the students reported that they
had conducted an experiment with a centrifuge prior to taking this class. These students, all
undergraduates from RPI, had previously had the opportunity to see or work with the centrifuge,
while students from the other schools had not. Few of the students (15%) had observed a live
experiment over the Internet and only 6% had ever performed a live experiment over the Internet.
Students were also asked to rate their confidence in designing and running experiments in general.
Fifty-six per cent of the undergraduates reported high levels of confidence in this area, with a
large portion (44%) reporting they were ‘neutral’ or less than ‘confident’. These response patterns
were also consistent when comparing responses by school.

Students were asked to describe their general opinion about the experiment and associated
assignments. Overall, students felt they were ‘just about right’ (80%); however, 12% noted that the
experiment and assignment were ‘too challenging’. The range of responses among the students
most likely reflects the diversity of these students’ abilities. Students were also asked to rate
the helpfulness of specific pre-experiment activities and assignments (see Table 1). In general,
students felt that the pre-experiment activities were quite useful in preparing them to conduct
the experiment. However, they also rated the activities lower with regards to preparing them to
analyse the results of the experiment. Students’ responses to the open-ended question about the
kinds of problems they encountered in interpreting the results of the experiment indicated several
types of problems, including: the assignment was unclear, the data returned were confusing (in

<table>
<thead>
<tr>
<th>Regarding the assignments and classes prior to conducting the centrifuge experiment:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>The in-class lectures and discussion prepared me for conducting the experiment ($n = 34$)</td>
<td>0</td>
<td>20.6%</td>
<td>23.5%</td>
<td>50.0%</td>
<td>5.9%</td>
</tr>
<tr>
<td>The remote lecture(s) and discussion(s) prepared me for conducting the experiment ($n = 33$)</td>
<td>0</td>
<td>3.0%</td>
<td>30.3%</td>
<td>48.5%</td>
<td>18.2%</td>
</tr>
<tr>
<td>The in-class lectures and discussions prepared me for analysing the results of the experiment ($n = 34$)</td>
<td>0</td>
<td>17.6%</td>
<td>35.3%</td>
<td>35.3%</td>
<td>11.8%</td>
</tr>
<tr>
<td>The remote lecture(s) and discussion(s) prepared me for analysing the results of the experiment ($n = 33$)</td>
<td>0</td>
<td>6.1%</td>
<td>36.4%</td>
<td>45.5%</td>
<td>12.1%</td>
</tr>
</tbody>
</table>
Table 2. Percentage and mean ratings of the effectiveness of the centrifuge experiment in learning geotechnical concepts.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
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<tbody>
<tr>
<td>The centrifuge experiment was an effective way:</td>
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<tr>
<td>To learn about the actual stress distribution under a</td>
<td>0</td>
<td>2.9%</td>
<td>0</td>
<td>29.4%</td>
<td>67.6%</td>
<td>4.6</td>
<td></td>
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<td>loaded foundation (n = 33)</td>
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<tr>
<td>To learn about the actual bearing capacity of a shallow</td>
<td>0</td>
<td>2.9%</td>
<td>2.9%</td>
<td>41.2%</td>
<td>52.9%</td>
<td>4.4</td>
<td></td>
<td></td>
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<tr>
<td>foundation (n = 33)</td>
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<tr>
<td>To visualise the failure mechanism under a shallow foundation</td>
<td>0</td>
<td>2.9%</td>
<td>8.8%</td>
<td>35.3%</td>
<td>52.9%</td>
<td>4.4</td>
<td></td>
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<tr>
<td>(n = 33)</td>
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<tr>
<td>To link field conditions, traditional lab experiments, and</td>
<td>0</td>
<td>0</td>
<td>9.1%</td>
<td>30.3%</td>
<td>57.6%</td>
<td>4.5</td>
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<tr>
<td>centrifuge physical modelling (n = 32)</td>
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</table>

Table 3. Percentage and mean ratings of the quality of the remote experiment.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate the following aspects of the centrifuge experiment</td>
<td></td>
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<tr>
<td>Being able to view the live centrifuge was important to the</td>
<td>0</td>
<td>2.9%</td>
<td>5.9%</td>
<td>44.1%</td>
<td>47.1%</td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>experiment (n = 33)</td>
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</tr>
<tr>
<td>The image of the centrifuge was clear (n = 32)</td>
<td>3.0%</td>
<td>3.0%</td>
<td>6.1%</td>
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<td>The live demonstration was too long to view (n = 33)</td>
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display and because they were unfamiliar with this type of data), and that they had problems with specific concepts such as determining strain or the failure criteria.

Students also responded to a series of questions regarding how the experiment affected their learning. Since none of the courses had included this experiment previously, student self-reports on their own learning served as a proxy for direct measures such as test or assignment grades. Table 2 describes the findings for all responses. Overall, students found the experiment to be a very effective way to learn concepts about stress and load-bearing capacities associated with different foundations. Students also reported that the experiment helped them visualise and better link field conditions, experiments, and physical modelling.

One of the goals of this project was to learn what works and does not work in terms of adapting or adopting live remote experiments in a class or course. To determine the ‘workability’ of the experiment, students rated a series of questions that related specifically to the experience of watching the experiment (Table 3). The high ratings indicate the importance of being able to view the experiment (not just read about it) and that the quality of the images and experience of watching the experiment in real time was not an impediment to the experience.

Questions were also asked to determine students’ interest in various aspects of the experiment such as the use of technology, collaboration with other students at their own campus or with students from other campuses, and their desire to be more involved in building or testing their own models. It appears the students wanted to conduct more experiments using technology regardless of whether they did it alone or in teams (Table 4). Eighty-two per cent of the students reported that they had a strong desire to build the physical model to be tested.

To confirm students’ opinions regarding the experiment, they were asked if they would recommend it to their friends or colleagues. Ninety-eight per cent of the students said they would do so, noting in their comments that they thought it was interesting and enjoyable, that they learned a lot because it was new material that was not included in previous courses, or that access to the
After conducting the centrifuge experiment, I would like to conduct more experiments using this technology \( (n = 33) \)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
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I would like to conduct more experiments like this working online by myself \( (n = 34) \)

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<thead>
<tr>
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I would like to conduct more experiments like this working online with only students from my school \( (n = 34) \)

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I would like to conduct more experiments like this working online with students from other schools \( (n = 34) \)

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I would like to experiment with building the physical model that is tested \( (n = 34) \)

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I would like to have more online sessions that include students from the other schools who are also working on the assignment \( (n = 34) \)

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<th>Rating</th>
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centrifuge made it possible. A number of students commented about the real-world nature of the experience and how practical it was. The main reasons they would not recommend it was because their friends or colleagues were not involved in geotechnical engineering.

5. Conclusions

Incorporating an educational module that for the first time integrates remote major research instrumentation into an undergraduate class appears to have been successful. Students’ perception about the module and online lab was very positive. Additionally, many students showed interest in interacting with students from other schools and in seeing more experiments like this one for other applications in geotechnical engineering.

The implemented course module appears to have enhanced students’ understanding of geotechnical systems and the link between elementary soil testing and system design. Testing a soil-foundation system helped the students identify the lab experiments needed to conduct the design of the system. Students acquired actual system test data that are similar to field data and compared it against the outcome of using theoretical analysis that is based on element testing. Such a comparison appears to stimulate the thinking necessary to identify the approximations in the theory and/or the setting of the experiment that may lead to differences between computed values and measured data. The module introduced a unique physical modelling environment to the course and lab and the results suggest that remote facilities such as the centrifuge used in this pilot study can be made conveniently accessible to students and faculty, thereby helping to save scarce institutional educational resources.

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References


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