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Design and Implementation of Experiential Learning Modules for Geotechnical Engineering

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Design and Implementation of Experiential Learning Modules for Soil Mechanics and Foundation Design

Introduction

Geotechnical engineering undergraduate curricula typically consist of courses in soil mechanics and foundation design that include a variety of topics that are difficult for students to understand and master. Behavior of the below grade geomaterials discussed in these courses can be difficult for students to visualize. Typically, the mechanisms of behavior are demonstrated using small-scale laboratory tests, two-dimensional sketches, simple table-top models, or video simulations in the classroom. Students rarely have the opportunity to observe large-scale behavior of foundations in the field or laboratory, particularly since deformation is often small and they do not fail often. The authors from Rose-Hulman Institute of Technology (RHIT), a small, private, masters-terminal university, and St. Louis University (SLU), a large, private, doctoral-granting university, designed and implemented a large-scale foundation testing system to address several topics that students tend to struggle with the most, including 1) the difference in strength and service limit states in shallow foundation design, 2) soil-structure interaction associated with lateral behavior of deep foundations, and 3) the influence of near-surface soil on lateral behavior of foundations. This paper provides a detailed overview of the design, fabrication, and implementation of two large-scale experiential learning modules for undergraduate courses in soil mechanics and foundation engineering. The first module utilizes shallow foundations in varying configurations to demonstrate the differences in strength and service limit state behavior of shallow foundations. The second module utilizes a relatively flexible pile foundation embedded in sand to demonstrate the lateral behavior of deep foundations. The first module was used in the soil mechanics courses at RHIT and SLU to compare theoretical and observed behavior of shallow foundations. The second module was used in the foundation engineering course at RHIT to illustrate the concepts of soil-structure interaction and the influence of near-surface soil on lateral behavior of foundations.

The following sections provide some background about the overall project along with the design and implementation of the experiential learning modules. There is also a brief discussion about assessment efforts on the project and lessons learned by the project team.

Project Background

The project as a whole includes several experiential learning modules covering four courses: structural analysis, reinforced concrete, steel design, and geotechnical engineering (soil mechanics and foundations) as described by Carroll et al. [1]. This paper is the third in a series and focuses on the design and implementation of the experiential learning modules for soil mechanics and foundation design [4], [8].

RHIT is a small, private, four-year, highly residential university without doctoral programs, classified as special focus four-year: engineering schools; SLU is a large, private, four-year, highly residential university with doctoral programs and high research activity (R2). Both geotechnical related modules require the use of a self-contained load frame. Neither institution had a large-scale structural engineering laboratory prior to this implementation, but both focus heavily on the undergraduate learning experience. The project utilizes the Modular Strong-block Testing System [2] when needed to test larger-scale specimens. While a full structural engineering lab would be ideal to conduct such tests, the self-contained system provides an economical solution for smaller programs. Figure 1 (a) and (b) show the system in use.


(a)


(b)

Figure 1—Modular Strong-block Testing System setup for (a) a beam test and (b) a frame test.

All junior-level civil engineering students at RHIT and SLU take an introductory geotechnical course called Soil Mechanics and Geotechnical Engineering, respectively. The RHIT course takes place in the fall quarter and includes roughly 35 students each year. The course meets 3 times per week over the course of ten weeks for 50 minutes each time. The course at RHIT also includes a separate lab section that meets one time per week for two hours and 30 minutes. The non-lab portion of the course is taught in a classroom equipped with flattop tables and is arranged in a traditional lecture format: chalkboards at the front and side of the room and tables in rows. Case studies are typically used to introduce primary topics, and subsequent class periods utilize a variety of active learning techniques including lectures with skeleton notes, group problem sessions, and facilitated discussions. The laboratory portion of the course consists of a short introductory lecture prior to the hands-on activities that take place in a traditional soil mechanics laboratory or in a field setting on campus.

The SLU course takes place in the spring semester and includes roughly 20 students each year. The course meets three times per week over the course of fifteen weeks for 50 minutes each time. The course at SLU also includes a separate lab section that meets one time per week for one hour and 50 minutes. The non-lab portion of the course is taught in a classroom equipped with desks and tables and is arranged in a traditional lecture format: whiteboards at the front of the room and a podium upfront with full AV projector capabilities for online learning. The main topics of the course are often framed around case studies and field examples. The modality of the course is lecture based with regular homework assignments and the occasional problem solving in class. The group activities and collaborative learning are conducted during the weekly lab period. For example, a proposal for field investigations is scoped and budgeted, and the sketching of subsurface cross-sections and groundwater flow nets. For the experiments conducted in the lab (mainly ASTM test standard) a short video and instructions are previewed prior to the hands-on activity. Occasionally and weather permitting the class goes on a field trip to observe local geotechnical works underway.

The content of geotechnical courses varies widely among universities and may include topics ranging from basic geology to deep foundations. However, most courses include a core list of topics such as soil composition, compaction, groundwater, consolidation, and shear strength. Some applications to slope stability and foundations are also typically included towards the end of the course. The prerequisite material for geotechnical courses mainly includes mechanics of solids, fluid mechanics, and civil engineering materials.

Foundation Engineering is a senior-level elective course at both RHIT and SLU. The RHIT course takes place in the fall quarter and includes roughly 15 students each year. The course meets 4 times per week over the course of ten weeks for 50 minutes each time. The course is taught in a classroom equipped with flattop tables and is arranged in a traditional lecture format: chalkboards at the front and side of the room and tables in rows. Case studies and real-world example problems are used extensively along with a variety of active learning techniques including group problem sessions and facilitated discussions.

The SLU Foundation Engineering course takes place in the spring semester and includes roughly 10 students each year. The course meets two times per week over the course of fifteen weeks for 75 minutes each time. The course is taught in a classroom equipped with desks and tables and is arranged in a traditional lecture format: whiteboards at the front and a podium upfront with full AV capabilities for online learning. The course has two sections, one for undergraduate credit and the other for graduate credit. The graduate students do additional work: advanced problems, read journal papers, and present a few advanced topics to the rest of the class. The undergraduate students are all seniors and appreciate the interaction with grad students.

The content of foundation engineering courses varies among universities and may include topics ranging from bearing capacity and settlement of shallow foundations, axial and lateral capacity of deep foundations (driven, drilled), retaining walls, structural design of foundations and walls, and sometimes ground modification. The prerequisite material for foundation engineering courses mainly includes soil mechanics/geotechnical engineering and reinforced concrete design.

Among the topics that students learn in soil mechanics/geotechnical engineering and foundation engineering, the authors have noted some students struggle with analysis skills that require deeper understanding and judgement. Some of the particular topics are 1) the difference in strength and service limit states in shallow foundation design, 2) soil-structure interaction associated with lateral behavior of foundations, and 3) the influence of near-surface soil on lateral behavior of foundations. [1].

Students at both RHIT and SLU were asked to take a course content survey near the end of the course to evaluate their perception of the topics most difficult to understand. The survey used a standard five-point Likert scale where 1 = Very difficult, 2 = Difficult, 3 = Neutral, 4 = Easy, and 5 = Very easy. Over the course of two years, 109 students at the two schools participated in the soil mechanics and foundation design course content survey, the results of which are shown in Table 1. Eleven topics had an average response less than or equal to 3.0.

Topic 10 was the only topic with a mode of 2, indicating that a significant number of students selected "Difficult" on the survey. Topics 12, 13, 15, 24, and 25 had some of the lower averages, which was not surprising. Overall, the results were fairly consistent across universities. Topics 17-25 are taught in a separate course at RHIT that was not consistently taught at SLU during the project duration, so those topics were not included at SLU.

Table 1—Students' perception of the most difficult topics in soil mechanics and foundation design [1].

#	Topic	SLU			RHIT			Total		
		Mode	Avg.	SD	Mode	Avg.	SD	Mode	Avg.	SD
1	Engineering geology	4.00	3.92	0.89	3.00	3.52	0.74	3.00	3.62	0.79
2	Subsurface sample and characterization methods	4.00	3.77	0.91	3.00	3.48	0.68	4.00	3.55	0.75
3	Soil phase relationships	4.00	3.89	0.80	3.00 & 4.00	3.47	0.77	4.00	3.58	0.79
4	Soil plasticity and clay mineralogy	4.00	3.58	0.95	3.00	3.32	0.69	3.00	3.38	0.76
5	1-D and 2-D groundwater flow	3.00	3.33	0.96	3.00	3.16	0.79	3.00	3.21	0.84
6	Earthwork engineering and compaction	4.00	3.48	0.94	3.00	3.41	0.75	3.00	3.43	0.79
7	Total and effective stresses	4.00	3.48	0.98	4.00	3.65	0.84	4.00	3.61	0.87
8	Mohr's circle and states of stress	3.00	3.30	1.17	3.00	2.89	1.04	3.00	3.00	1.08
9	Induced stresses and superposition	3.00	2.93	0.92	3.00	3.12	0.71	3.00	3.07	0.77
10	Consolidation settlement of shallow foundations	2.00	2.96	0.98	3.00	3.11	0.77	3.00	3.07	0.82
11	Consolidation time rate	3.00	2.96	0.90	3.00	3.26	0.76	3.00	3.19	0.80
12	Shear strength of soils	3.00	2.70	0.72	3.00	3.33	0.78	3.00	3.17	0.81
13	Bearing capacity analysis of shallow foundations	3.00	2.85	0.86	3.00	3.34	0.79	3.00	3.22	0.83
14	Elastic settlement of shallow foundations	-	-	-	3.00	3.13	0.74	-	-	-
15	Lateral earth pressures	3.00	2.89	0.88	3.00	3.26	0.74	3.00	3.18	0.78
16	Retaining wall types and uses	3.00	3.00	0.79	3.00	3.07	0.87	3.00	3.05	0.84
17	Shallow foundation design charts	-	-	-	3.00	3.15	0.81	-	-	-
18	Structural design of shallow foundations	-	-	-	3.00	3.25	0.77	-	-	-
19	Deep foundation load test interpretation and use	-	-	-	3.00	3.13	0.89	-	-	-
20	Deep foundation axial load transfer	-	-	-	3.00	3.09	0.82	-	-	-
21	Static analysis of deep foundations	-	-	-	3.00	3.14	0.89	-	-	-
22	Dynamic analysis of deep foundations	-	-	-	3.00	2.95	0.91	-	-	-
23	Lateral capacity of deep foundations	-	-	-	3.00	2.98	0.86	-	-	-
24	Structural design of deep foundations	-	-	-	3.00	2.89	0.84	-	-	-
25	Downdrag of deep foundations	-	-	-	3.00	2.76	0.89	-	-	-

Note: Shaded rows denote topics with an average response less than or equal to 3.0 (Neutral)

Design and Implementation of Experiential Learning Modules

The primary objective of this project is to develop and implement experiential learning modules that allow students to visualize the deflection and failure mechanisms associated with shallow foundations and piles. This paper focuses on two experiential learning modules for soil mechanics and foundation design courses that illustrate geotechnical service and strength limit state behavior. The two modules focus on 1) settlement and bearing capacity of shallow foundations and 2) lateral behavior of pile foundations. The following sections contain a description of each module's design, fabrication, and their implementation at RHIT and SLU during the third and fourth years of the project.

Design and Fabrication

Both modules described below utilize a soil test box, so design and construction of the box was the first step in the module design process. The size of the box was governed by three primary considerations. The first consideration was that the box needed to be large enough to conduct the shallow foundation tests with minimal boundary effects from the edges of the box. As described in the sections below, the shallow foundation was modeled as a continuous (strip) footing with a width (B) of 8 in. According to Terzaghi's theoretical shape of a general shear failure beneath a shallow foundation, the failure surface extends a maximum lateral distance of about 1.5B laterally from the outside edge of the foundation and a distance of about B vertically from the base of the foundation [3]. In addition, according to Schmertmann's method of calculating settlement for a shallow foundation on granular soils, the depth of influence for settlement of a continuous footing is 4B below the base of the footing [3]. Based on the criteria from the two primary theories for strength limit state and service limit state of shallow foundations that are covered in the introductory soil mechanics and geotechnical engineering courses, the soil test box would need to be at least 32 in. long by 8 in. deep.

The second design consideration was that the box needed to be large enough to conduct the pile foundation tests with minimal boundary effects from the edges of the box. According to the FHWA Driven Pile Manual [6], a laterally loaded pile in sand has a zone of influence up to about 8 times the pile width in the direction of lateral load and 2.5 times the pile width measured from the center of the pile perpendicular to the direction of loading. These approximate correlations would indicate that the soil test box would need to be at least 32 in. long and 20 in. wide (for a 4 in. wide pile).

The third practical consideration was that, within the limitations of the first two considerations, we tried to minimize the volume of the box to minimize the amount of sand required and the soil box set-up time each year. Our final soil test box dimensions were approximately 48 in. long by 18 in. wide by 60 in. deep at RHIT and 72 in. long by 18 in. wide by 48 in. deep at SLU. The exact dimensions differed between the two campuses because of availability of construction materials and practicality of construction. Figure 2 shows the final design along with the overall approximate dimensions.

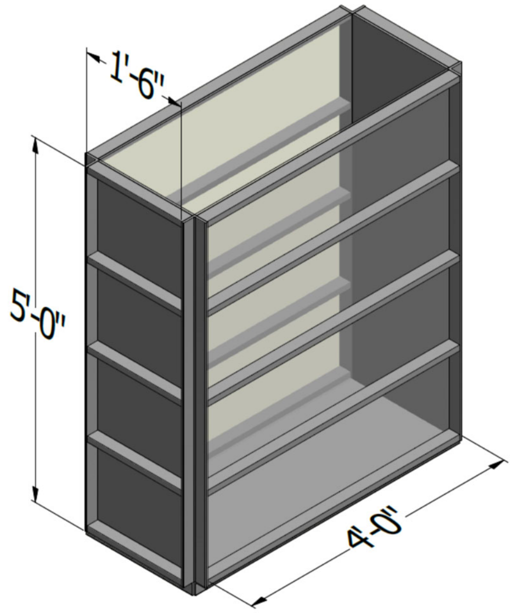


Figure 2—Soil test box at RHIT with approximate dimensions.

Pre-fabricated concrete formwork was used to construct the soil box because it can withstand the anticipated soil and applied stresses with minimal deformation, and it is easy to assemble and disassemble. The plywood facing in the forms was replaced by 1/2-inch-thick clear polycarbonate so the soil and structures in the box could be seen. Because the soil box is accessible from all sides at RHIT, polycarbonate was installed along the two long sides of the box. Space constraints at SLU only allow viewing of one side of the soil box, so polycarbonate was only installed on one side. To provide a solid base on which to mount the formwork and to aid in moving the box, a concrete pedestal with forklift cutouts was designed and constructed. The completed soil test boxes are shown in Figure 3.

(a)

(b)

Figure 3—Soil test boxes at (a) RHIT (b) SLU.

The next step of the design process was selection of the test soil. A fine to medium, uniform, clean sand (#12 Flint Silica, manufactured by U.S. Silica Company) was selected. The primary reason for choosing sand was that it is much easier and quicker to prepare an artificial granular sand subgrade compared to a silt or clay subgrade specimen. The uniformity and lack of fines in the sand were chosen for several reasons, including: (1) prevention of segregation of the material during transport and placement, (2) reduced potential for the soil to retain moisture and create a moisture gradient throughout the prepared soil mass, (3) reduced dependence of soil properties on placement method, and (4) reduced dust during placement [7]. Although the tests described herein are not intended to be research-level scale model tests, a fine to medium sand was selected to better match the small size of the foundations and reduce the effects of individual particle behavior on the tests. Manufactured sand was chosen to ensure a product with consistent properties.

Laboratory tests were completed at RHIT to classify the soil and determine strength properties. Laboratory testing included grain-size distribution and direct shear testing. Mechanical grain-size analysis indicated that the #12 sand is fine to medium (75% passing #30 sieve), clean (less than 0.1% fines), and uniform (poorly graded, $C_u = 1.25$, $C_c = 0.95$). The direct shear tests were conducted on dry sand in both a loose and dense condition. The results of the direct shear tests are presented in Table 2. Note that the variation in soil parameters between the loose and dense conditions is minimal.

Table 2-Laboratory Direct Shear Test Results

Soil Condition	**Unit Weight (pcf)**	**Friction Angle (degrees)**
Loose	103.9	31
Dense	110.9	33

Note: No measurable cohesion intercept

The soil was placed in the soil test box using air pluviation techniques. The sand was stored in hopper bags prior to placement. The bags were lifted above the soil box and the bottom spout was slightly opened to allow the sand to slowly funnel out into the box. The bag was moved around the box to uniformly fill the soil box. A more elaborate air pluviation technique was not developed because of the small variation in soil properties between the loose and dense conditions.

Module 1—Shallow Foundation Failure Modes

The purpose of the *Shallow Foundation Module* is to demonstrate the difference between the service limit state and the strength limit state and how either could be considered a failure condition depending on performance requirements. The module design was developed with several guiding considerations. First, the students should be able to see the foundation, even if it is buried, and be able to see deformation and shear develop within the soil. To accomplish this, the foundation would need to be placed directly adjacent to the plexiglass where the close proximity of the foundation element to a fixed boundary would influence the behavior of the foundation. To account for this influence and more accurately model free-field conditions, we designed the shallow foundation for plane strain conditions. Specifically, the finite length of the foundation models an infinitely long continuous (strip) footing because it traverses the entire width of the soil box (18 in.). The fixed boundary at each end prevents longitudinal movement of the foundation such that stress distribution in the soil would be similar to a continuous footing and shear failures in the soil could only occur in a 2-D plane (plane-strain) perpendicular to the footing. Second, the anticipated loads and response should be reasonable within the limits of the system and available equipment. We wanted to maximize the size of the foundation so that it looked and behaved like an actual foundation. We also wanted the foundation movement to be seen with the naked eye. Third, the measured displacement of the foundation should primarily be a result of soil settlement rather than structural displacement. To achieve this goal, we chose reinforced concrete as the foundation material and fabricated a thick concrete section that would be stiff enough to resist bending for the anticipated loads. Figure 4 shows the final design of the shallow foundation.

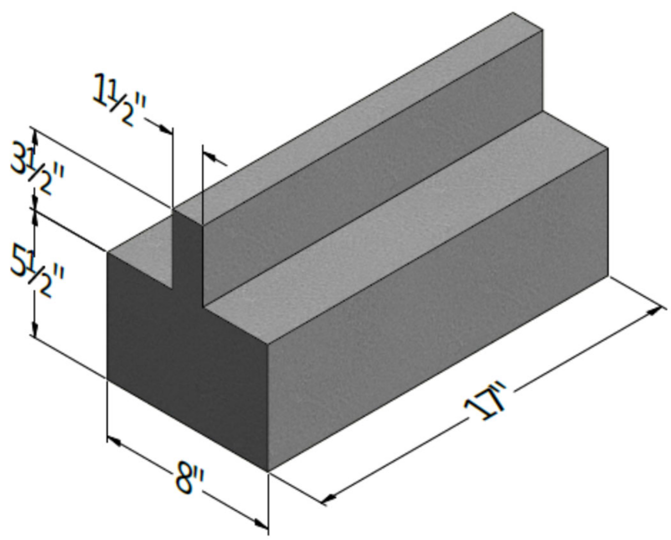
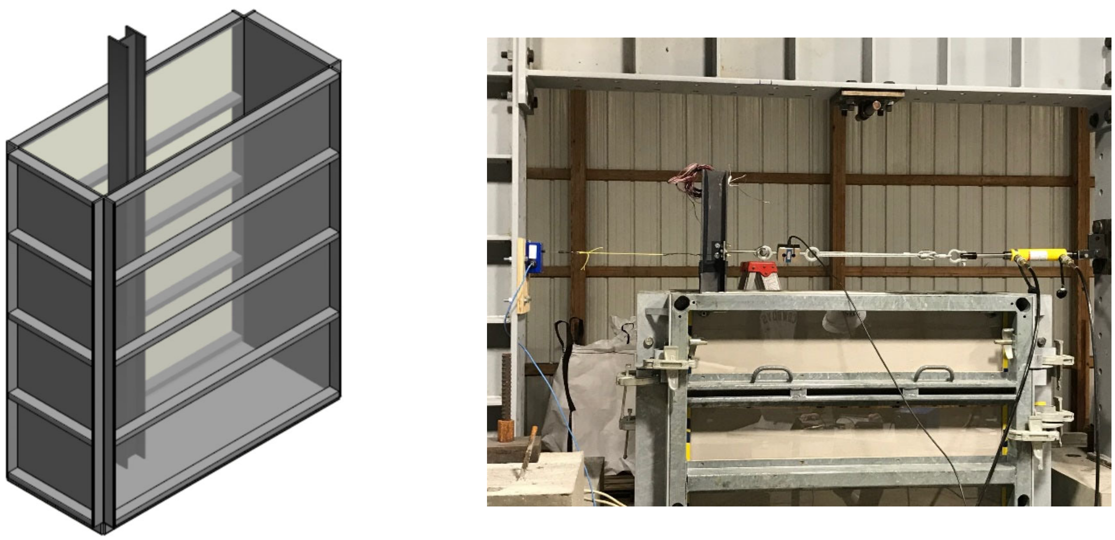


Figure 4—Shallow foundation schematic.

Module 2—Lateral Pile Capacity

The purpose of the *Lateral Pile Capacity Module* is to demonstrate the soil-structure interaction that occurs during lateral pile loading and the outsized effects of the near-surface soils on lateral behavior of piles. Because of difficulties with implementing a near full-scale deep foundation test, the design of the module had to balance the physical limitations with the objectives of the module. First, it was not possible to install the test pile via typical driving methods. Because of the minimal changes in soil properties with changes in relative density, it is unlikely that driving the pile would significantly alter the lateral behavior. Second, an ideal lateral pile test would be completed on a pile that is long enough to naturally achieve fixity (zero lateral movement) through embedment in the soil. Because we wanted to utilize a pile size and shape that was close to full-scale conditions, the depth to fixity would be larger than the soil test box depth. As discussed previously, the depth of the box was limited by practical constraints, including the ability for students to observe the behavior and the difficulty of placing and exhuming large volumes of sand. To remedy this conflict, the pile was attached to the bottom of the soil box to impose a point of fixity. This configuration is meant to model a pile that is driven into a hard soil or intermediate geomaterial (soft rock) below the surficial sand layer. Third, it was important for the students to be able to see the pile movement while applying reasonable lateral loads. The module utilized a 4"x4"x1/4" EXTREN® structural shape made of a flexible fiberglass reinforced polymer (FRP). While this material is regularly used for the design of structural members, it also has advantageous properties for the purpose of this module in an experiential setting. EXTREN® FRP materials are much more flexible than steel at much lower stresses. The modulus of elasticity is roughly 10% steel's modulus of elasticity (E = 2600 ksi). Its ultimate strength reaches 30 ksi. It is strong and lightweight, yet flexible enough to illustrate structural behavior [2]. The final design of the module is shown in Figure 5.



(a) (b)

Figure 5—Lateral pile test (a) schematic (b) photograph.

The test pile was fabricated to be 6 ft. long so that at least 1 ft. of pile stick-up above the top of the box was available to apply the lateral load. It was connected to the base of the soil box near the end of the long direction of the soil box to maximize the lateral distance between the face of the pile and the end of the soil box in the direction of loading. The pile was oriented for bending in the strong direction of the structural shape. Fixity at the base of the soil box was achieved using two 3"x3"x1/8" steel angles cut to a length of 4 in. and attached to each flange. Two concrete anchor bolts connected each angle to the base and two 3/8 in. Grade 5 bolts connected each angle to the flange.

Implementation

As was stated previously, neither program was equipped with large-scale testing equipment prior to implementation of this project. Although the applied loads used for the two soil mechanics and foundation engineering modules was not overly large (approximatey 2,000 lbs maximum), a reaction frame is necessary. The reaction frame used for these modules utilizes the Modular Strong-block Testing System [4], a versatile, large-scale testing alternative. Figure 6 shows the system in use for the soil mechanics and foundation design modules. Because the students were involved with running the tests and collecting data, they were in close proximity to the tests. Therefore, there were several safety considerations for these modules. Students were required to wear hardhats and safety glasses during testing and were not allowed to stand within the direction of loading during a test. In addition, the loaded connections were designed to be redundant and all connections are checked immediately prior to running the test.

(a) (b)

Figure 6—The Modular Strong-block Testing System setup for (a) a beam test and lateral foundation test and (b) a shallow foundation test.

Module 1—Shallow Foundation Failure Modes

Shallow foundation analysis was covered near the end of the term at both institutions. Prior to the shallow foundation portion of the course, students should have a good understanding of stress distribution and shear strength of soil. At RHIT, the instructor spent a day introducing Terzaghi's bearing capacity equation using a case study and traditional lecture. Elastic settlement of shallow foundations using Simplified Schmertmann's method was also covered in one class period using an example to introduce the concept. During the same week that settlement and bearing capacity were introduced in the lecture section, a single lab period was used as a studio class where the students were tasked with predicting the behavior of the shallow foundation that was tested the next week. The students worked in groups to develop a load-settlement curve and a bearing capacity failure prediction. Each group used a different combination of soil properties (loose vs. dense) and shallow foundation embedment (ground surface vs. 5.5 in. embedment) so that the class could see the range of possible behaviors.

For the following lab period, the students met at the structures lab where the soil test box was set up for the first shallow foundation test. The test set-up included a hydraulic actuator that was used to apply a point load to the stem of the shallow foundation. At RHIT, the load was applied to a small button load cell on a swivel that allowed the foundation to rotate without binding or applying a moment. Settlement of the shallow foundation was measured using string potentiometers that were attached to the outside edges of the foundation, in line with the actuator. At SLU, the actuator was attached to the footing stem via a pin connection that was allowed to rotate perpendicular to the long axis of the foundation. Settlement of the foundation was measured using dial gages on both sides of the shallow foundation. The load application and displacement measurement set-up for both institutions is shown in Figure 7.

(a) (b)

Figure 7—Test set-up for Module 1 at (a) RHIT and (b) SLU.

Prior to beginning the first test, the instructor gave a brief introduction to the test set-up and instructed the students on how to operate the actuator and how to read data from the load cell and string potentiometer. Students were then assigned tasks for the first test, including operating the actuator, reading instrumentation, recording data, and plotting data. The load was then incrementally applied until a bearing capacity failure was reached. In most tests run to date, the bearing capacity failure was apparent when excessive rotation occurred such that additional load could not be applied. After the test was finished, the students made notes about the observed behavior, including orientation of the foundation throughout the test and visual displacement of the soil. The foundation was exhumed and the soil beneath the foundation disturbed to get it back to the pre-test condition. The foundation was then re-set into the box and the test was run again with a different embedment condition. Photographs of the failed foundation condition are shown in Figure 8.

(a) (b)

Figure 8—Shallow foundation failure condition for (a) an embedded foundation at RHIT and (b) a non-embedded foundation at SLU.

Following the second test, students were asked to reflect and then discuss the following questions:

1. Did your load-deflection curve accurately predict the early behavior of the shallow foundation? Why or why not?
2. Did your bearing capacity analysis accurately predict the failure load? Why or why not?
3. At what design loads would bearing capacity control or settlement control?
4. How did your observations of foundation orientation and soil displacement compare with what you answered for #3?

Module 2—Lateral Pile Capacity

Because the foundation engineering course at SLU is offered infrequently, module 2 is only being implemented at RHIT. The course content regarding lateral capacity of deep foundations was covered approximately two-thirds of the way through the course following axial capacity of deep foundations. Three class periods were spent discussing the theoretical concepts and methods of lateral analysis. Specifically, the topic was introduced with a case study and then the interaction between the soil and the foundation structural elements was discussed. Several methods of analysis were then introduced including p-y analysis where the students utilized the Evans and Duncan's charts [3] and RSPile software from Rocscience, Inc. The students then completed a homework assignment in which they analyzed the pile and soil conditions that they were to encounter in the experiential learning exercise. They were required to develop a predictive lateral load vs. deflection curve that they brought to the laboratory with them for the lateral load test.

After the assignment was completed, the students spent a 50-minute class period in the structures lab. Prior to their arrival, the lateral load test was set up and ready to begin. Because the experiential testing portion of modules 1 and 2 occurred within about a week of each other and because the soil test box is long enough to accommodate the pile without interfering with the shallow foundation test, it was possible to prepare the sand one time for both tests. Only minor adjustments to the test setup were necessary, including removing the shallow foundation from the test pit, disturbing and replacing the upper layer of sand, and moving the string potentiometers to measure lateral rather than vertical displacement. Because the applied loads for the lateral load test were smaller than the shallow foundation test loads, a smaller hydraulic actuator was used. The actuator was mounted to a column of the load frame and set up to pull the pile laterally. The actuator was attached to a load cell and then a cable that was attached to the pile. The string potentiometer was attached to the back side of the pile. The lateral load test set-up prior to loading is shown in Figure 9.

Figure 9—Module 2 lateral load test set-up.

Prior to beginning the lateral load test, the instructor gave a brief introduction to the test set-up and instructed the students on how to operate the actuator and how to read data from the load cell and string potentiometer. Students were then assigned tasks for the test, including operating the actuator, reading instrumentation, recording data, and plotting data. The lateral load was then incrementally applied until a maximum load was reached so that the pile was not damaged during testing. After the test was finished, the pile was unloaded and the students made notes about the observed behavior. The final condition of the tested pile is shown in Figure 10.


Figure 10—Module 2 completed lateral load test.

Following the test, students were asked to reflect and then discuss the following questions:

1. Did your load-deflection curve accurately predict the lateral behavior of the pile? Why or why not?
2. How would the results vary if the pile was steel rather than EXTREN® FRP?
3. How would the results vary if the pile was installed in full-depth sand rather than fixed at the base of the soil box (modeled as hard soil)?

Lessons Learned and Recommendations

The foundation experiential learning modules provided excellent interactive opportunities for the students to participate in near full-scale testing of foundations that are not typically possible in introductory soil mechanics or foundation engineering courses. However, there were many lessons learned that can be used to modify future iterations of the modules and to help other institutions that may consider adding the modules.

- A significant amount of time was required to set up each round of tests. The most time-consuming activity was emptying and then properly refilling the soil test box. It was important to recruit student helpers that are motivated and willing to do the hard work of preparing the soil specimen.

- Student retention of module concepts could likely be increased using a reflection activity in a class period after testing is complete or a reflection assignment. Students were engaged in the in-class activities and gathered data and notes, but they did not have the opportunity to further discuss their observations and the implications of those observations.

- It was important for the instructors to assign students with active roles during testing. Some students left to their own means tended to withdraw and not participate.

- Soil deformation during the module 1 shallow foundation test is much easier to see if markers are placed in the soil profile. On the SLU soil box, red marker lines were drawn on the outside of the plexiglass and blue yarn was placed inside the box at the interface of the sand and the plexiglass. It worked well as a visual aid and will be used for subsequent tests at both institutions.

- Additional data can be gathered from the module 2 lateral pile test that may aid in student learning. Specifically, strain gages can be installed at regular intervals on both sides of the pile so that a bending moment profile can be developed. The students could also develop a predicted bending moment profile using p-y analyses to compare to the collected data.

- During the Spring of 2020, courses at both RHIT and SLU were shifted to remote learning because of the COVID-19 pandemic. Because the pivot to remote learning was abrupt, all testing associated with this project was cancelled. During the 2020-2021 academic, both institutions were at least partially in-person and the exercises were completed with students in the lab. However, the required masking and face shields made communication during the test difficult. To be prepared for future remote learning periods, the team plans to recorded the tests from several different angles and obtain data sets for analysis.

Future Assessment

Assessment of the project includes both qualitative and quantitative assessments. The qualitative assessment includes the Student Response to Instructional Practices (StRIP) survey [4], a course content survey, and a series of open-ended questions about the experiential learning modules (post-test only). The quantitative assessment includes a series of exam questions related to each module: 1) two questions about bearing capacity failures of shallow foundations, 2) a question about settlement of shallow foundations, and 3) a question about combining results of bearing capacity and settlement analyses for foundation design. The students at both universities in Year 1 and 2 were the control group and the students in Year 3 and 4 will be the intervention group. The students at SLU from Year 3 will be excluded because the experiential learning modules could not be implemented in class as a result of the COVID-19 pandemic. The intervention groups are currently in progress at both universities and full assessment is beyond the scope of this paper. However, future dissemination efforts will highlight the effect of the experiential learning modules on student learning, perception of topic difficulty within the course, and instructional practices.

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References

1. Carroll, J.C. and J.W. Benton, *Design, Construction, and Performance of the Modular Strong-block Testing System.* Journal of Performance of Constructed Facilities, 2018. **32**(5).
2. Carroll, J. C., Lovell, M. D., Kershaw, K., Sipes, S. M., Luna, R., Aidoo, J., Hanson, J. H. (2020, June), *Rationale and Design Approach for Full-scale Experiential Learning Opportunities in Structural Engineering* Paper presented at 2020 ASEE Virtual Annual Conference Content Access, Virtual On line . 10.18260/1-2--35119
3. Coduto, D.P. (2001), Foundation Design: Principles and Practices, 2nd Edition, Prentice Hall, New Jersey.
4. Derks, A. C., Carroll, J. C., Hanson, J. H., Lovell, M. D., Kershaw, K. (2020, June), *Design and Implementation of Experiential Learning Modules for Structural Analysis* Paper presented at 2020 ASEE Virtual Annual Conference Content Access, Virtual On line . 10.18260/1-2--34393
5. DeMonbrun, M., et al., *Creating an Instrument to Measure Student Response to Instructional Practices.* Journal of Engineering Education, 2017. **106**(2): p. 273-298.
6. Hannigan, P.J., Rausche, F., Likins, G.E., Robinson, B.R., and Becker, M.L. (2016, July), Geotechnical Engineering Circular No. 12 - Volume I, Design and Construction of Driven Pile Foundations, Report No. FHWA-NHI-16-009.
7. Kershaw, K.A, and Luna, R. (2018, April), *Scale model investigation of the effect of vertical load on the lateral response of micropiles in sand.* DFI Journal - The Journal of the Deep Foundations Institute, 12:1, p. 3-15.
8. Lovell, M., et al., *Rationale and Design Approach for Full-scale Experiential Learning Modules for Reinforced Concrete Design*, in *2021 ASEE Annual Conference*. 2021, American Society for Engineering Education.