AC 2010-592: DEVELOPMENT OF A GEOTECHNICAL EARTHQUAKE ENGINEERING TEACHING MODULE USING AN INSTRUCTIONAL SHAKE TABLE

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Abstract
Liquefaction, which is the loss of strength of supporting soil, is one of the major causes of destruction to permanent infrastructure (roads, buildings, and bridges). After being introduced to the concepts of compaction, permeability and effective stress in an introductory geotechnical engineering course, undergraduate students understand the basic concepts of liquefaction. In this research, an apparatus was built to provide hands-on experience to undergraduates to provide them with a greater understanding of the liquefaction mechanism, liquefaction induced damage to the built environment and the influence of various soil properties that trigger liquefaction. A geotechnical earthquake engineering teaching module was also developed for use with the apparatus. Subsequent experimentation indicates that the apparatus constructed in this research successfully demonstrated the mechanism of liquefaction, liquefaction induced damage and the influence of soil properties on the extent of the damage. The proposed experiments are repeatable and the teaching module can be included as one of the many geotechnical engineering laboratory experiments. These experiments will give students hands-on experience in sample preparation, instrument use and testing with various earthquake time histories.

Introduction
Earthquakes threaten millions of lives and property in both the United States and abroad. The US Geological Survey (USGS) estimates that several million earthquakes occur throughout the world each year, although most go undetected because they hit remote areas or have very small magnitudes. On average, only 18 of these earthquakes occur at a magnitude of 7.0 or higher annually[1]. One of these for the year 2010, being the January 12, Haitian earthquake which claimed over 200,000 lives and left millions more homeless. Because earthquakes are impossible to predict, preventive measures to reduce earthquake induced damage are critical to ensuring infrastructure integrity after such events, as the Haitian quake all too graphically illustrates. Introducing civil engineering undergraduates to the concepts of earthquakes and discussing the impact of earthquake induced damage to the built environment is one method for showing students some of the preventative measures. Fortunately, teaching undergraduates about earthquakes and engaging them in discussions on the damage they can induce to the built environment is not a new concept. One example of a successful initiative is the University Consortium on Instructional Shake Tables (UCIST)[2], the primary goal of which was to develop experiments that would provide undergraduates with a firm grounding in structural dynamics. Numerous teaching models that were used to achieve this goal are on the UCIST's website[3]. However, though the UCIST provided detailed structural dynamic experiments, they did not provide soil dynamics experiments particularly those related to liquefaction induced damage to the built environment.

Liquefaction, which is the loss of strength of supporting soil, is one of the major factors contributing to severe damage to the built environment in various forms such as ground settlement and movement, slope failure, damage to buried utility lines. Figure 1 shows a photograph of liquefaction induced damage to structures after 1964 Niigata earthquake. There was no structural damage observed but the structures tilted and settled due to ground liquefaction. Since liquefaction can be an abstract concept to many students, it is usually introduced through a demonstration with photographs and videos of case studies. Experiments are effective for demonstrating such basic concepts, and were used to great effectiveness in the UCIST work. A hands-on experiment can also effectively teach students how to develop new experimental procedures, build a simple experimental setup using knowledge from previous courses, conduct model scale testing and interpret results. This paper elucidates one such hands-on experiment: the design of a plexi-glass container used to hold a soil sample on a Quanser Instructional Shake Table II. The authors also detail procedures for preparing different sandy soil samples using a pluviation device similar to that used in preparing samples for geotechnical centrifuge tests and a funnel used to prepare very loose sand samples. The procedures for consolidating clay samples are also discussed. A sample of module experiments and the response captured using cameras is in the results. A discussion of future module experiments is also included.

Figure 1: Tilting and settling of apartment complex in Niigata, Japan due to 1964 Niigata earthquake (http://www.ce.washington.edu)

Experimental Set Up

In these experiments, the authors used a Quanser Shake Table II. The shake table is driven by a powerful motor that allows for an acceleration of 2.5 g's when upwards of 7.5 kg of mass is mounted on the platform. The load carrying capacity of the linear bearings is 131.5 kg. An accelerometer is mounted to the platform to measure the acceleration of the stage directly. The position of the stage is measured with an embedded high-resolution encoder, with an effective linear resolution of 3.10 μm. The stage has a length of 457 mm and a width of 457 mm. The shake table operates through the use of the software QuaRC on a PC, the Universal Power Module, and a data-acquisition card. Using QuaRC on the PC, the amplitude and frequency of a sine wave can be set between 0 and 50 mm and 0 and 5 Hz respectively or a scaled acceleration history of an actual earthquake can be programmed to run on the shake table through Matlab. Details of all shake table operations and peripheral devices are in the Shake Table II Manual[4].

A container was constructed to hold the soil samples on the shake table. The container has interior dimensions of 346 by 346 by 254 mm with plexiglass 12.7 mm thick. The container was constructed out of plexiglass to allow for a camera to record the effects of the dynamic loading on the soil structure. The robust container was designed to withstand the dynamic forces of a model seismic event, permit ease in saturation of the sand in a non disturbing manner, and also to meet the weight limits for this shake table.

In designing the box a spreadsheet was used to estimate the force that would be applied to the box walls during the dynamic loading of the soil sample. The sample mass was calculated by setting a reasonable target dry unit weight for a loosely packed sand sample with an estimated specific gravity of 2.67. Using weight-volume relationships, the amount of water to fully saturate the sand sample was also estimated. The mass of the water was added to the total mass acting on the walls. The estimated acceleration of the shake table was 1g. The amount of force on the walls helped determine the thickness of the plexiglass that was used to construct the tank. Other factors to determine thickness were the glue joint size, and the thickness needed to prevent significant deflection. Since the joints between the individual pieces of plexiglass were a concern, three 25.4 mm (1 inch) screws were evenly spaced along the joint.

In order to saturate the sand, two ball valves with diameters of 6.35 mm (1/4 inch) were installed on two parallel sides of the container. Clips were attached to the two small ball valves to allow for hoses to be attached to the valves for saturation. The hoses were attached to a sink, in which the minimum water pressure was applied.

Soil Model Preparation

Single Liquefiable Layer

Poorly graded sand with a specific gravity (G_s) of 2.685, was used as the single liquefiable layer. The sand also had a void ratio in the loosest state (e_{max}) of 0.811 and a void ratio of the soil in the densest state (e_{min}) of 0.492. Poorly graded sand is more susceptible to liquefaction, since the sand grains pack more loosely than well-graded sand. The gradation curve shown in Figure 2 was determined through sieve analysis. The specific gravity was determined using the procedure in the laboratory manual[5]. The maximum void ratio was determined in accordance with ASTM Test Designation D-4253 (2004). Sand was poured loosely into a mold with a volume of 2830 cm^3 from a funnel with a 12.7 mm diameter spout. The average height of the sand fall into the mold was maintained at approximately 25.4 mm. The minimum void ratio was determined by placing oven-dried sand into the same mold in 10 layers. After placing each layer, the mold was hammered on the sides until the surface was level.

In order to fill the tank with sand, two methods were devised. One method involved the use of a funnel with a 12.7 mm (1/2 inch) diameter spout. The other involved using a pluviation setup with the sand falling into the tank. Many tests were conducted to estimate the relative densities created with the two different methods. Results showed that the funnel created loose sand and the pluviation setup created dense sand. The average void ratios, relative densities, and porosity are recorded in Table 1 for both methods. The following two paragraphs explain how each method can be used to run a single layer and single density test in the plexiglass tank. Currently tests with different density layers have not been completed.

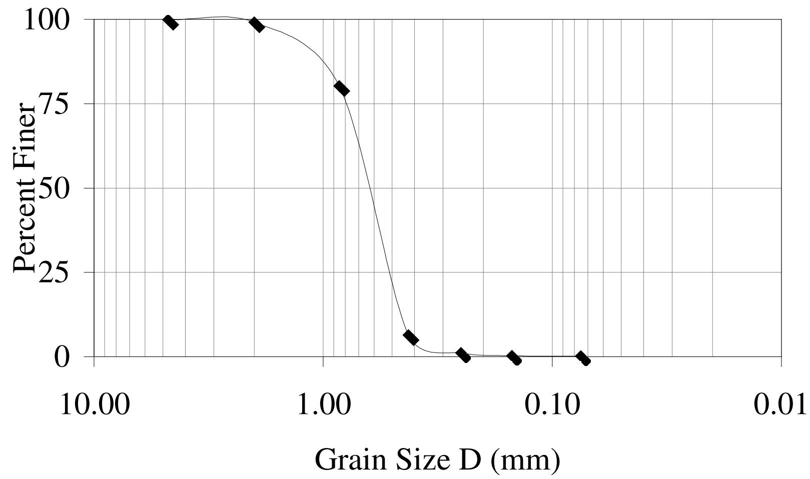


Figure 2: Gradation Curve of Sand

Table 1: Comparison of Pluviation Setup and Funnel

Parameter	Pluviation Setup	Funnel
Average Void Ratio	0.57	0.77
Average Relative Density (%)	76	12
Average Porosity	0.36	0.44

The method used to prepare the soil specimen with the funnel required approximately 35 kg of sand (Figure 3). The tank was filled by pouring sand slowly from the funnel at approximately 25.4 mm (1 in.) above the base of the container. To ensure the sand was poured evenly in rows, the funnel was moved at a rate at approximately 15 cm/s (6 in/s). Once 25.4 mm of sand covered the entire base of the tank, the funnel was raised approximately 25.4 mm to allow for constant falling distance. The funnel's direction of motion was also positioned perpendicularly to the previous direction of motion. This method was repeated until the container was filled to a level of 180.9 mm (7.125 in). Finally, the sand was saturated to prepare the single liquefiable layer.

The method used to prepare the soil specimen with the pluviation setup required approximatly 40 kg of sand. The seive was set at the lowest setting 304.8 mm (12 in) above the base of the container (Figure 4). After the sand reached a height of 25.4 mm in the container, the sieve was raised up a level, which is equivalent to the sand height of 25.4 mm. This method was repeated until the container was filled to a level of 180.9 mm (7.125 in). Finally, the sand was saturated to prepare the single liquefiable layer.

Since the main purpose of the module is to provide undergraduate students with a visually informative experience, considerations were made to make the results clearer for students. For example, in order for students to clearly see differences in settlement, colored sand was used at different layers in the sand sample. Another example involved using higher frequency loading on the shake table, compared to standard earthquake tests. This increase in frequency accentuates the liquefaction effects.

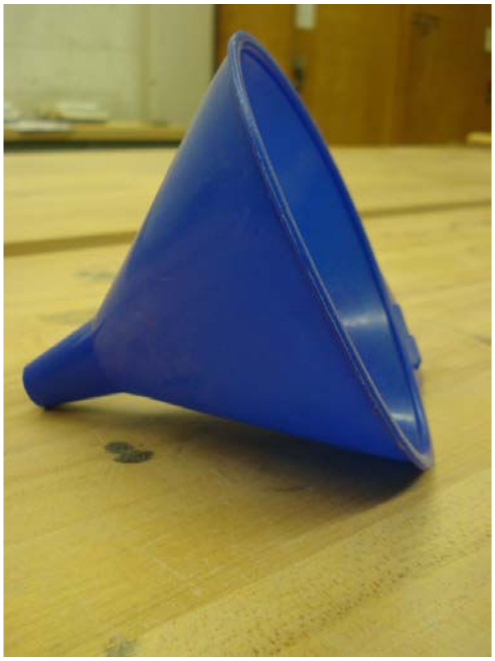


Figure 3: Funnel: .0127 m diameter spout

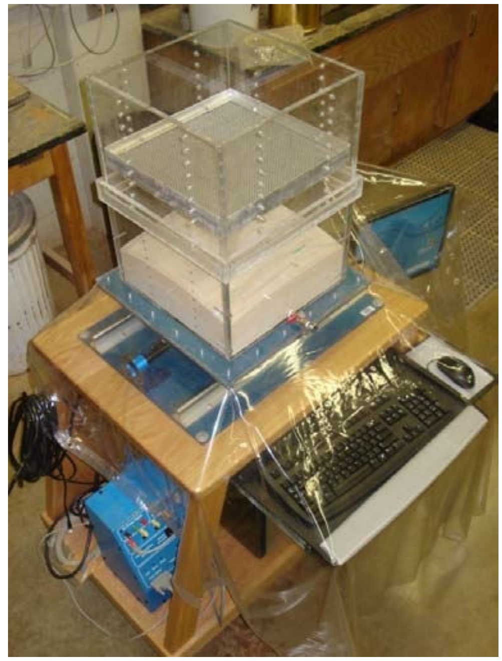


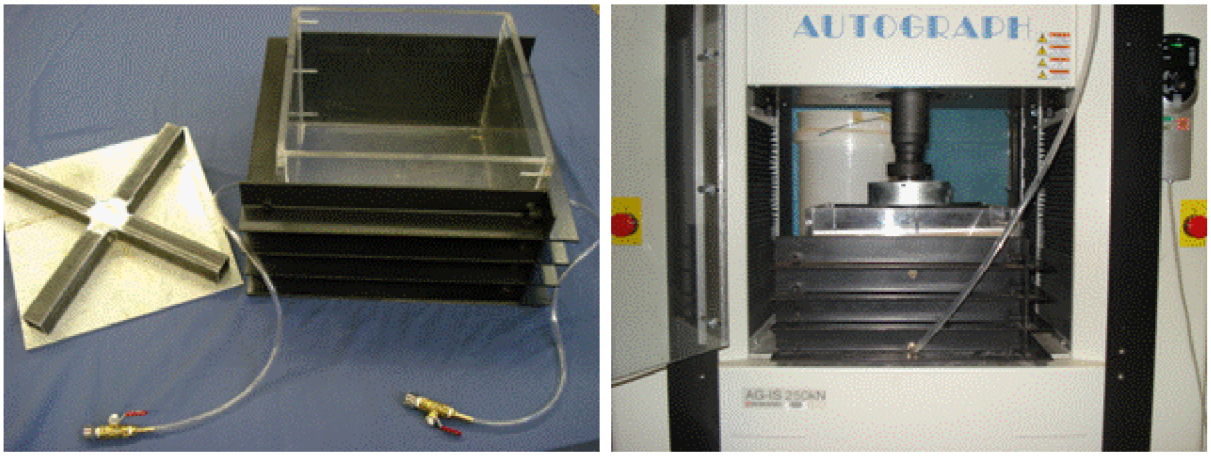
Figure 4: Pluviation Setup: US sieve number 20

Non-Liquefiable Layer on a Liquefiable Layer

In order to demonstrate how a non-liquefiable layer on a liquefiable layer affects both settlement and the liquefaction process, a non-liquefiable soil layer was formed. A ratio-by-weight of 50% ball clay and 50% sand passing through the US sieve #50 was mixed to create a uniform non-liquefiable layer. The clay-sand mixture had a liquid limit of 32.75 and a plastic limit of 21.96. The specific gravity of the clay was estimated to be 2.67. The clay-sand mixture had 1.5 times the liquid limit of water added by weight. This proportion yielded a very workable clay slurry that could be spread over the liquefiable layer with little disturbance. The funnel method was used to prepare the liquefiable layer, which was 135 mm (5.33 in) tall. Following the preparation of the liquefiable layer, the sand was fully saturated, and a 50.8 mm (2 in) clay layer was spread over the sand. A thin layer of sand was placed on top of the clay layer to allow for drainage in both directions when consolidation was performed on the clay layer.

In order for a clay-sand mixture to be consolidated in the liquefaction tank, it was necessary to reinforce the plexiglass tank to accommodate for the horizontal stress produced due to the vertical consolidation load. The reinforcement system is made of steel angles (see Figures 5(a) and (b)). The loading plate was aluminum reinforce with steel. The consolidometer was square, since consolidation had to be performed in which the same box tests were run. With a small load applied to the clay-sand mixture, there is little concern of stress concentrations affecting the quality of the clay layer on top of the sand layer.

Consolidation of the clay-sand mixture was conducted in a two-step process on a universal testing machine (UTM). Each step was performed by applying the load and the rate shown in Table 2. Once the loading for consolidation of the clay-sand mixture was completed, the steel reinforcement was removed and the plexiglass container was attached to the shake table.



(a) (b)

Figure 5: Reinforcement to the plexiglass box and consolidation setup for clay

Table 2: Consolidation of Clay-sand Mixture

Initial Load (kN)	Load Rate Increase (kN/min)	Final Load (kN)	Holding Period (hours)
0	0.2	6	22.5
6	0.2	42	20

Results

For Sample Test 1, the first sample module experiment was performed with the soil properties presented in Table 3. The sample was fully saturated sand, and the funnel method procedure was used to fill the tank. The shake table applied a sine wave with amplitude of 1.6 mm and a frequency from 1to 15 Hz. Figure 6 shows the test results.

Table 3: Soil Properties for Sample Module Tests

Sample Test	1	2	3	
Soil Type	Sand	Sand	Sand	Sand clay mixture*
Dry Unit Weight (kg/m^3)	1510	1760	1660	
Void Ratio	0.78	0.52	0.62	
Relative Density (%)	8.4	90	61	
Porosity	0.44	0.34	0.38	
Specific Gravity	2.69	2.69	2.69	2.67
Liquid Limit				32.75
Plastic Limit				21.96

* 50% Clay and 50% Sand by weight

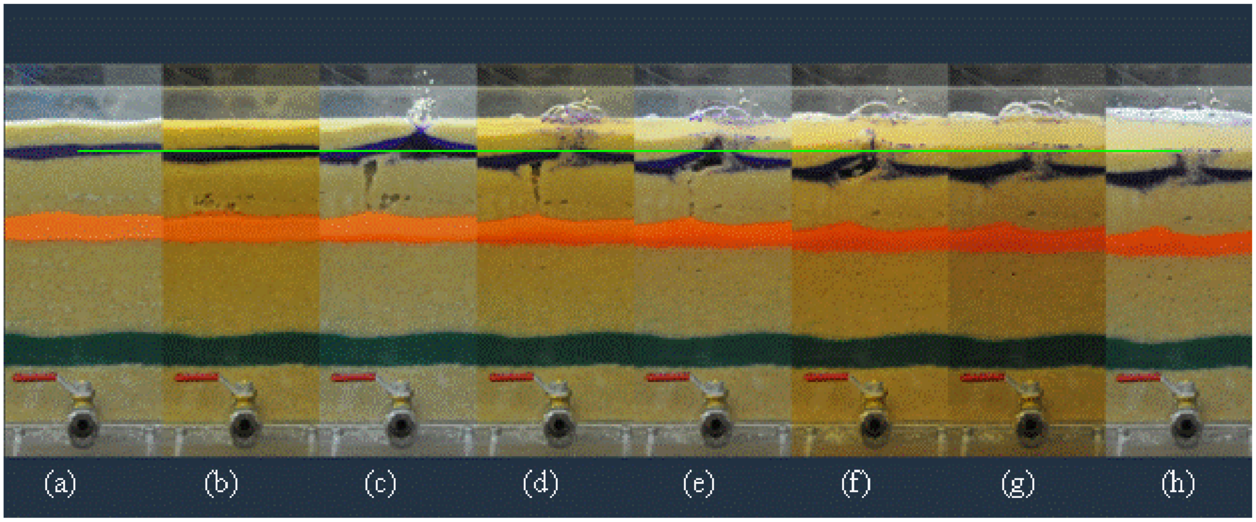


Figure 6: Sample Test 1 Showing Center of Tank Displayed Side by Side to Show Settlement, Photographed with Nikon D3

For Sample Test 2, the second sample module experiment was performed with the soil properties presented in Table 3. The sample was fully saturated sand, and the pluviation method was used to fill the tank. The shake table applied a sine wave with amplitude of 1.6 mm and a frequency from 1 to 15 Hz. Figure 7 shows the test results. For Sample Test 3, the third sample module experiment was performed with the soil properties presented in Table 3. The sample was fully saturated sand, and the funnel method procedure was again used to fill the tank. Following saturation, the procedure for creating a non-liquefiable layer on a liquefiable layer was used. A small layer of sand was placed above the clay layer to allow for drainage. After consolidation, the sand was again saturated due to an unintentional leak at the bottom of the tank caused by a faulty wearing seal. The second saturating caused a small disturbance to the clay sand layer interface. The shake table applied a sine wave with amplitude of 4 cm and a frequency of 4 Hz. Figure 8 shows the test results.

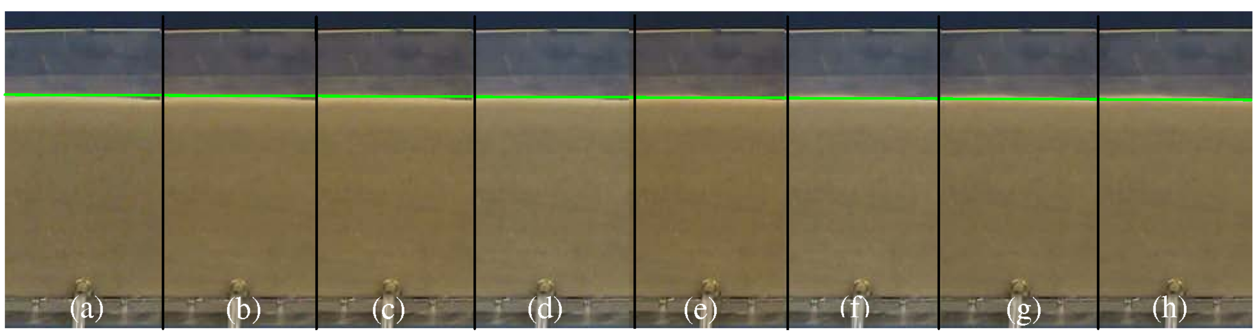


Figure 7: Sample Test 2 Showing Center of Tank Displayed Side by Side to Show Settlement, Photographed with Sony DCR-SX40

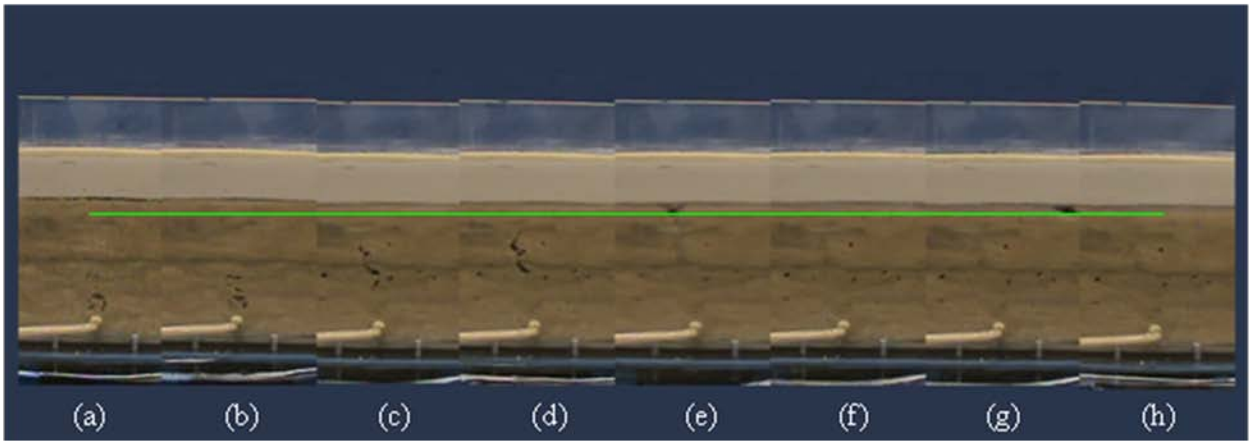


Figure 8: Sample Test 3 Showing Center of Tank Displayed Side by Side to Show Settlement, Photographed with Sony DCR-SX40

Discussion of Results and Future Module

The first sample module test yielded good results of the many different liquefaction phenomena. In Figure 6, the settlement of the sand is shown clearly. The dissipation of the water is also shown. Students involved in this work can learn to measure the exact settlement using available measuring instruments, and also observe the sand boiling, as shown in Figure 6(c). Small air pockets are clearly observed escaping through the sand with small bubbles forming in the water, as shown in Figure 6(d). The colored sand in Figure 6 also shows the divergence of settlement at different layers. Questions which may be asked of students are whether the finer colored sand caused a film of water to form beneath it and the subsequent effects in a sloping model. Such efforts can encourage them to further investigate the liquefaction effects in layered sand.

The second sample module test shows dramatically how different dense sand acts as compared to loose sand. The same earthquake shaking was applied to both the loose and the dense sand. As Figure 7 shows clearly, because there is no pore water pressure dissipation or sand settlement (see Figure 7 a-h), the dense sand neither liquefies nor settles. These two extremes provide students with opportunity to learn how density effects liquefaction.

The third sample module test provided a visual understanding of how a non-liquefiable layer on top of a liquefiable layer affects settlement and dissipation of pore-water pressure. As expected, Figure 8 shows that the sand settled and allowed the pore water pressure to dissipate. The water formed a layer between the sand and clay layer. Since the clay layer was very sticky it did not settle, thus the water pressure was not high enough to break through the clay layer, which is evident in Figure 8(h). Compared to the two previous tests, a different frequency was used and set amplitude was chosen. This change in loading was used to produce a clear clay, water, and sand layer. After repair, saturation only had to occur once, which prevented any damage to the sand layer.

The boundary conditions for each of these tests must be explained to students. In each case, ridged walls react with the soil when subjected to earthquake shaking. Naturally, these ridged walls do not simulate the flexibility that actually occurs in a natural soil boundary. The rigid boundaries in the direction of shaking causes a quicker breakdown of the soil structure along the walls, and reflects waves back into the soil sample. To mitigate this breakdown, a liquefaction box with flexible beams similar to those in the geotechnical centrifuge at the Network for Earthquake Engineering Simulation (NEES) facilities is recommended. A smaller size flexible beam box made of metal is available at the University of Colorado, Boulder. Though building a similar box with transparent sides may be difficult, the ability to explain the boundary effect makes such an effort worthwhile.

Further sample tests (e.g. tests to determine slope behavior and behavior of models built on sand) are required to add additional material to the teaching module. Results from the third sample module also show the benefits of building a sample model atop the clay layer to force the clay layer to settle. A in-depth understanding of how different properties in sand affect liquefaction is also possible by comparing our tests here with different sand types.

Student Engagement and Assessment

This proposed experiment is not yet part of the list of Geotechnical Engineering Laboratory experiments at Clemson University. However, research results were presented in two separate sections of the CE321-Geotechnical Engineering class in Spring 2009. During the 50 minute lecture period, the authors demonstrated the settlement of saturated sand and sand boiling during shaking. Though the actual sample preparation occurred outside of the classroom, students learned about the apparatus used to prepare these samples. Students were grouped around the shake table during the shake tests. While no formal evaluation was conducted, the number and quality of questions from students during the experiment and their interest in the response of saturated sand when subjected to shaking clearly mirrored their enthusiasm. Because some in the class had never felt an earthquake, this demonstration gave them an opportunity to see how the ground moves during such seismic events. Some suggested building structures in liquefiable soil to monitor structural performance during earthquakes. Because of the recent occurrence of severe seismic events (Haiti and Chile) students are now much more aware of their intensity and vast damaging impact. Geotechnical earthquake engineering modules like that described here will provide a vastly improved understanding of what actually occurs during earthquakes, and how to prevent such damage to save lives and property.

Conclusion

The experiments demonstrate that these module tests can provide students with a solid introductory understanding of liquefaction and its effect upon layered soils. These proposed repeatable experiments and teaching module can be included as one of the many geotechnical engineering laboratory experiments. In these hands-on experiments students prepare samples, use instruments and test results on an instructional shake table. In order to properly evaluate the addition of these laboratory experiments, students should be required to take a short quiz or write a summary lab report. They should also be encouraged to develop their own experiments, which are not part of the teaching module. Additional surveys to gauge student opinion on the benefits of the additional lab work are also recommended.

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