Assessment of a Virtual Laboratory for Geotechnical Engineering

Timothy Robert Wyatt, Pedro Arduino, Emir Jose Macari
Georgia Tech / University of Washington / Georgia Tech

Abstract

In the study of engineering science phenomena, there is no substitute for hands-on experience opportunities. However, despite the extent to which laboratories are commonplace in engineering education, many obstacles stand in the way of achieving satisfactory hands-on experience. The cost of laboratories and associated experiments, in terms of time, space, and finances, limits the complexity of experiments that can be performed and limits the extent of any lab test series. At some smaller schools, these costs can result in the elimination of laboratory experiences altogether. Additionally, because many undergraduate students have only a basic level of technical ability, lab experiments must be limited to demonstrations of phenomena that are physically obvious (e.g., that a soil sample will deform under load). Virtual reality environments have been proposed as a partial solution to these obstacles. After the initial software development, the cost of preparing and performing laboratory tests is negligible. Multiple tests can be performed, with variations in loading conditions, material types, and boundary conditions, enabling students to observe the more specific details of material behavior as well as general deformation behavior. In addition to serving as an augmented laboratory experience, the virtual environment has potential both as a lecture tool, to present concepts that can not be demonstrated on a two-dimensional blackboard, and as a vehicle for individual student exploration. However, the application of virtual environments always sparks arguments that a simulation is not reality, and that it may have the potential to mislead students about real-world material behavior. In this research project, a virtual-reality geotechnical laboratory is introduced into a graduate-level soil mechanics course. The software is made available to students for individual experimentation, and is assigned for use to complement lecture material about critical-state soil mechanics. Log files are used to identify student usage patterns, and to correlate individual student performance with exploratory use of the environment. Preliminary observations and conclusions based on this pilot project are presented.

I. Background

The Georgia Tech School of Civil and Environmental Engineering incorporates laboratory testing into both its undergraduate and graduate soil mechanics curricula. Graduate students in the Geosystems program at Georgia Tech are required to take four core courses: a course in fundamental soil mechanics (CE 6150), two lab testing courses (CE 6151 and 6161), and a course in field testing and measurement (CE 6162). At the culmination of the lab testing series, each student (as a member of a four-person team) performs two triaxial strength tests, one under drained conditions and one under undrained conditions. These are performed on identical soil specimens; typically a sandy material so that excess pore pressures will dissipate quickly in the drained test and thus the test can be performed in a short time. Comparing results from the two tests allows the student to observe firsthand the effect of large excess pore water pressures (which are generated in the undrained test). However, the limited number of tests does not permit the student to observe variations in behavior among different soil types, nor does it permit the student to explore the effect of different levels of density, confinement, or overconsolidation. Due to time and cost constraints, it is unlikely that a more extensive lab testing program could be incorporated into the existing framework.

To meet this need, a virtual reality geotechnical laboratory[1] has been developed. The virtual reality environment being employed is the interactive visualizer (IV)[2]. IV provides the developer with an extensive set of modular entities, including cameras, lights, and user-defined static, kinematic, and dynamic objects. The modularity of IV makes it particularly powerful for the development of virtual environments for specific engineering problems. The IV framework supports detailed modeling of physical systems and allows visualization of relevant features of the problem under study. It has been implemented in the C programming language and makes use of the OpenGL graphical library. The current version runs on 32-bit Windows platforms.

The virtual geotechnical laboratory, shown in Figure 1, consists of a conventional triaxial testing device containing a cylindrical soil specimen, and a blackboard to record lab data. The test device is typically used to consolidate the soil specimen under a given level of confinement. The soil is then sheared under the application of an axial load, using either drained or undrained conditions. Soil response is monitored with the aid of electronic instrumentation such as load cells, linear variable differential transducers (LVDTs), and pressure transducers. During undrained conditions the generation of excess pore water pressure is monitored, and during drained conditions the volume change of the specimen is monitored. It is expected that additional test equipment will be made available to the virtual lab in the future.

In the virtual environment, the student can move freely about the lab and control his viewing direction, angle, and lens magnification through the use of keystrokes. A Soil Properties dialog box allows the user to define the soil by providing values for six material parameters, including the shear modulus (G) and the slope of the critical state line (M). These parameter values are used by the program to compute soil response according to the Modified Cam Clay constitutive model; however, the computational process is hidden from the user and understanding of the model is not required in order to use the program. Also, due to the modularity of IV, it is relatively simple to substitute the MCC model with alternate constitutive relations. A Test Parameters dialog box allows the student to set test conditions, including the initial confining cell pressure (σ_c), the load increment by which shear stress is increased or decreased, the consolidation increment by which cell pressure is increased or decreased, and the preconsolidation pressure (p'_0), which is the maximum past pressure experienced by the soil. This window also allows the student to specify how results are to be displayed on the blackboard; up to four graphs can be shown at once. Loading or unloading the specimen in either shear or confinement is controlled by the student at the keyboard; one keystroke corresponds to one load increment. Drainage valves are also controlled from the keyboard.

Thus the student is not confined to the use of traditional stress paths, where the specimen is consolidated under drained conditions, drainage valves are closed (for undrained tests), and then the specimen is loaded to failure in shear, then unloaded. Instead, the student may at any time during the test open or close the drainage valve, increase or decrease the cell pressure, and increase or decrease the shear stress. The student may also reset the test at any time. While the results obtained from a non-traditional stress path may not be suitable for a physical experimental test series, where the goal is to explicitly determine the material properties, it is entirely suitable for this educational setting, where the goal is for the student to gain an intuitive understanding of soil behavior under different conditions.

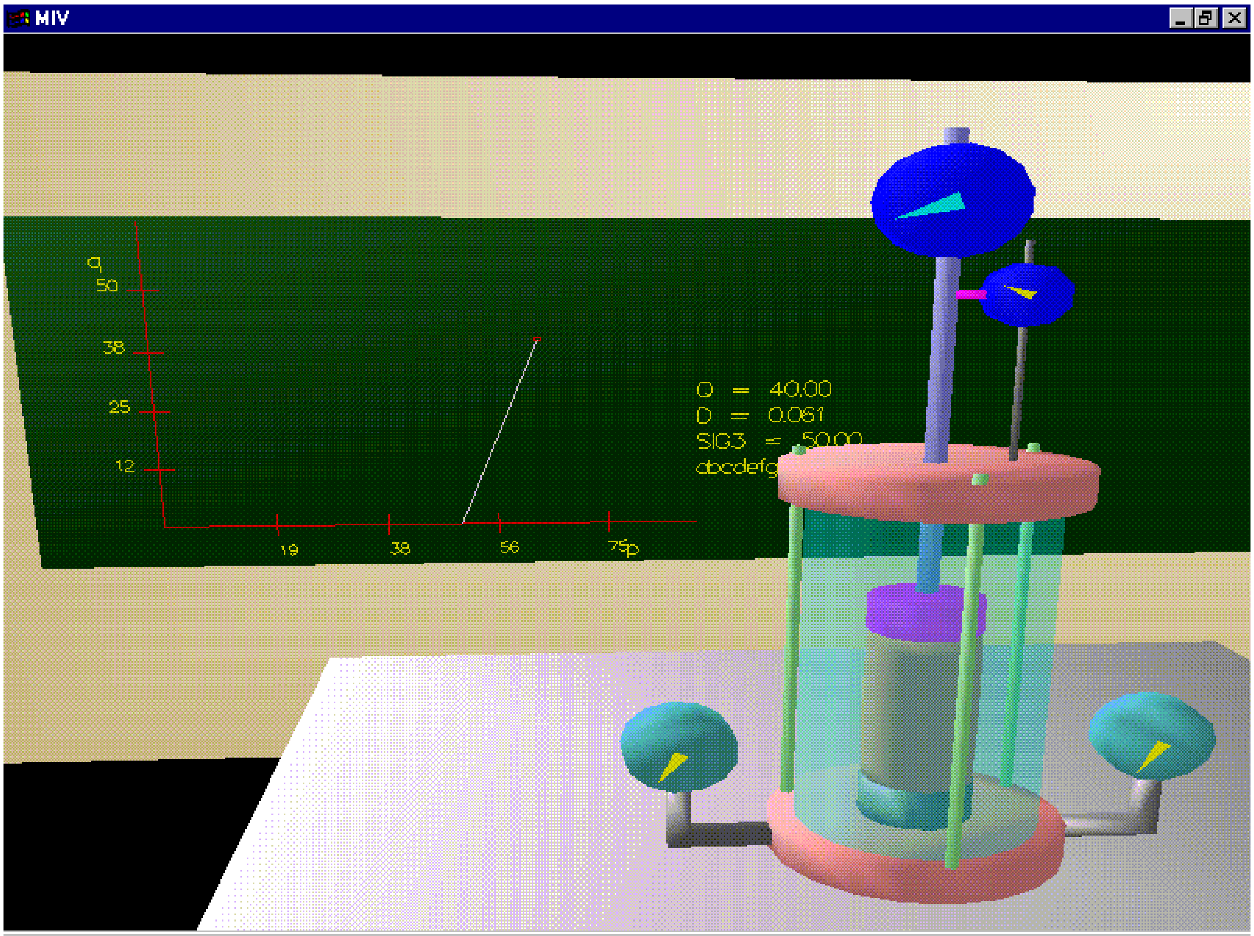

Figure 1. Virtual reality geotechnical laboratory.

II. Formative Evaluation Study

The goal of the study presented here was to assess the potential of the virtual lab as an educational tool, and to define the direction for future development. At this time, the lab is not an instructional environment, with specified lesson plans and required tasks. Rather, it is a situated learning environment where the student has complete control over the testing process. The virtual lab software was given to graduate students in the CE 6150 class, along with a brief tutorial explaining its capabilities. An accompanying written assignment was provided, with little detail of how the software was to be used in order to complete the assignment. Student usage patterns were recorded in order to identify different learning styles. Future development will focus on steering the student to usage patterns that result in more effective learning.

Students were given the software on a floppy disk along with installation instructions, so that they could install the virtual lab on their personal computers. Along with the installation instructions were included operational instructions, with corresponding key commands for movement (e.g., side-to-side, up-and-down, forward-and-backward), view control (zooming, rotating, shading, etc.), and test control (cell pressure, shear loading, etc.). The operational instructions also described how to open the Soil Properties and Test Conditions windows in order to edit the associated parameters. Also accompanying the software was a short tutorial intended to demonstrate the features of the virtual lab. The text of the tutorial is in the Appendix.

The assignment required the students to answer the following three questions:

1. Perform a series of drained tests on one soil type at various overconsolidation ratios (e.g., OCR = 1, 1.5, 2, 4, 8) by changing the initial cell pressure. Do the same for undrained conditions. Describe the effect of OCR on ultimate load, ultimate axial strain, and excess porewater pressure (undrained case only).

2. Repeat the test series from Question #1, but change the OCR by modifying the preconsolidation pressure and keeping the initial cell pressure constant. Explain any differences between these results and those in Question #1.

3. Parametric studies: What is the effect of increasing the shear modulus (G)? What is the effect of increasing the slope of the critical state line (M)? Support your conclusions with numerical values such as ultimate shear load and ultimate strain, from drained and undrained tests.

Students were asked to complete the assignment within two weeks of receiving the program. They were asked to submit a written response to the questions, along with the log file that the program created on their personal computers.

This was a *formative evaluation*; the assignment was designed primarily to identify potential problems with the software as well as its potential uses. The assignment questions thus did not correspond to specific learning goals, but rather was designed to prod students into independent exploratory use of the software. There was also no specific guidance concerning the appropriate length of response. However, there were some general phenomena that should have been noticed by the students and that should be reflected in their responses. The following discussion provides some necessary background information in order to give the reader an idea of the general responses that were expected:

The overconsolidation ratio (OCR) is defined as the ratio of preconsolidation pressure to the *in situ* isotropic pressure (or initial cell pressure, in the case of a lab test). An overconsolidated soil (OCR > 1) can be considered to have previously experienced greater pressure than it does presently and will experience less deformation under a given load than will a normally consolidated (NC) soil with the same initial confinement. The assignment requires students to determine the impact of OCR (as well as certain material parameters) on ultimate strength, strain, and excess pore water pressures:

Ultimate strength: The ultimate strength at a given level of confinement is the deviator stress at which the soil specimen reaches the critical state (where it will deform as a frictional fluid under any additional load)[3]. "Similar sets of tests on soil samples with different peak maximum consolidation pressures would produce similar loci of peak deviator stresses, with normally compressed and lightly overconsolidated samples still ending on the critical state line," although "heavily overconsolidated samples pass through a peak value of deviator stress followed by a subsequent drop in deviator stress to a critical state."[4] That is, the ultimate strength is controlled not by the preconsolidation pressure but rather by the slope of the critical state line (M), although overconsolidated soils may experience higher peak strength before reaching the ultimate state.

Ultimate strain: When the stress state on a soil is increased, as long as the isotropic stress remains below the preconsolidation pressure, deformation should be "much less than if the soil were normally consolidated. If the added stress … exceeds the preconsolidation stress, then much larger [strain] would be expected."[5] A highly overconsolidated soil, therefore, should experience less strain than a normally consolidated soil under similar loading conditions. The amount of elastic strain under a given shear increment is controlled by the shear modulus (G). Because soils that are lightly OC to NC rarely experience purely elastic deformation, the effect of G is much more noticeable in the highly overconsolidated soils.

Excess pore water pressures: While the volume change measurements under drained tests are used to estimate long-term settlement of constructed facilities, the measurements of excess pore water pressure in undrained tests are also important to estimate pore pressure response in the field under rapid construction or short-term conditions. Increases in pore water pressure decrease the effective confinement of a soil and consequently may result in instability. It has been shown[6] that lightly OC to NC soils produce positive excess pore water pressures at failure under undrained conditions; but the ultimate values become negative when OCR ≈ 2.

III. Log File Analysis

In the version of the software used in this study, a log utility was used to record all user actions to a text file. Students were required to "log in" to the program with a specific user name and password, in order to differentiate between user actions from multiple students using the same computer. All user actions (modifying soil properties, changing test conditions, increasing the shear stress, opening drainage valves, moving to the right, zooming in, etc.) were recorded and stamped with the date and time of the action, along with any action-specific details (e.g., the modified value of an input parameter). Upon completion of the assignment, students were asked to submit the log files.

The log files contain approximately 44 hours of program usage among 18 students. Figure 2 presents the total distribution of program usage over time. The program was distributed to the students two weeks before the assignment was due, but there is very little activity recorded until three days before the due date ("D -3"). This can partially be attributed to a school holiday that fell during the two-week period. The small amount of activity recorded after the due date is from students who submitted late assignments.

The distribution of usage time for individual students is plotted in Figure 3. The log file recorded the time that each student logged in and out of the program. Typically this occurred over multiple sittings. Periods of inactivity of greater than 15 minutes are disregarded in this analysis. The smallest time of total usage was 51 minutes, the largest was 5 hrs. 14 minutes, and the average (mean) time of use was 2 hrs. 27 minutes. There was wide variation in usage times among individual students, but approximately 40% of the class falls in the range from 1 to 2 hrs.

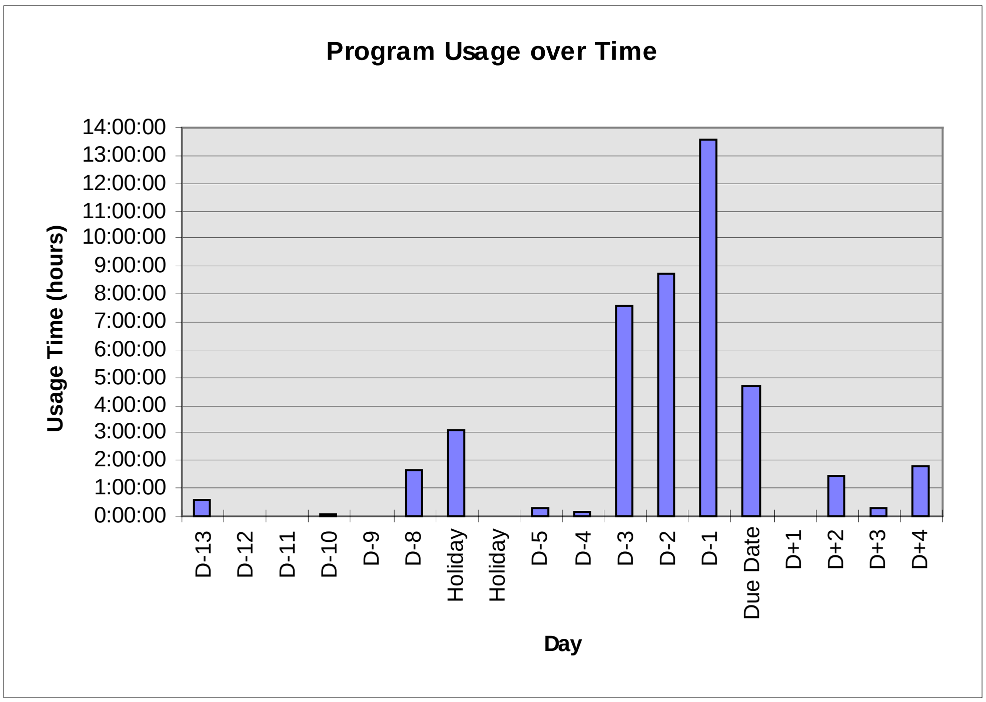

Figure 2. Program activity as logged by the software.

Because the log utility recorded all user actions and date-time stamped the information, another measure of individual student usage is the disk size of the logged activity. Figure 4 shows the distribution of recorded activity among the students in terms of file size. The smallest file size was 273 kilobytes, the largest was 3.86 Megabytes, and the mean file size was 1.61 Megabytes. While there was again wide variation in file sizes among individual students, there appears to be a cluster in the range from 400 to 800 kilobytes; approximately 30% of the class falls in this range. Because of the large variation in recorded activity, in terms of both time and disk usage, it is evident that students used a number of individual approaches to complete the assignment.

Interestingly, among the two clusters identified, there are only two common students. That is, only two of the seven students who used the program from 1-2 hours also had file sizes in the range from 400 to 800 kilobytes. The other four students in that block had a file size of 1.6 Megabytes, on average. This indicates wide variation in the way the program was used. There could be several explanations for the non-correlation between usage time and logged activity. For one thing, the students with fewer logged actions over a given time could be considered to be more cautious, taking time to reflect on the observed behavior resulting from each load increment and judiciously considering their next action. Students with many logged actions over that time can be seen as more exploratory, performing actions quickly and observing the response, but not necessarily taking the time to try to understand the underlying meaning. Other explanations for the variation in time and activity include differences in type of predominant action (recording of movement used very little disk space, whereas load increments recorded the action as well as the initial and final states of stress and strain) and the student's preference for load increment size (smaller load increments would require more steps to reach failure for a given test, and would thus consume more disk space). Analysis of the log files reveals no common explanation for the deviation between recorded time and recorded activity; rather, each student had an individual style of working with the program which precludes much generalization.

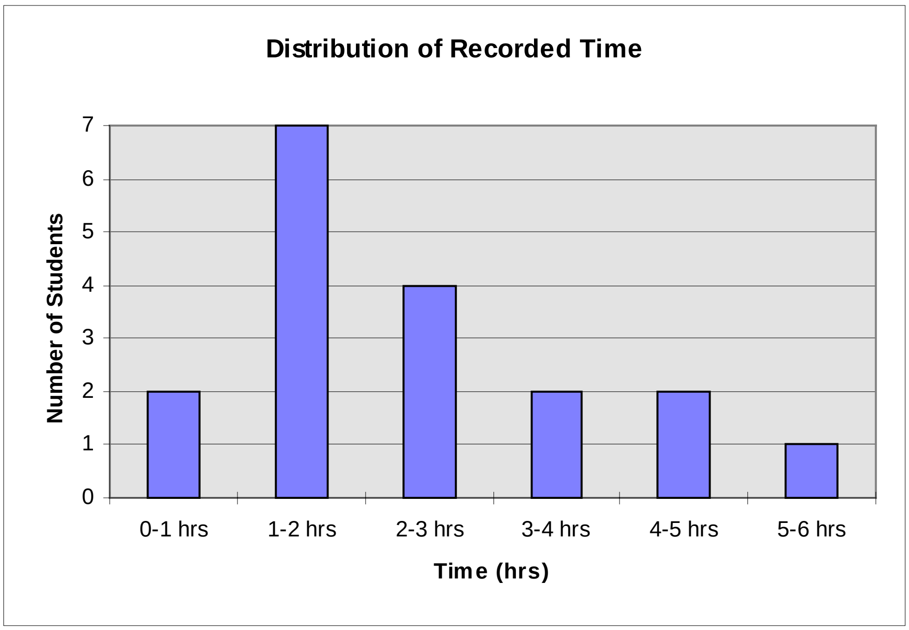

Figure 3. Distribution of program activity in terms of usage time.

Further evidence of the wide variation in individual styles is shown in Table 1. The individual students are listed in order of increasing time using the program. Column 2 indicates the disk space required to store the text description of their activity. Column 3 indicates whether or not the log files revealed that the student performed the test series prescribed in the tutorial (see the Appendix). Because all student actions were recorded in the log file, it was simple to scroll through the text of the log file and determine whether or not the tutorial was followed. Ten students attempted to follow the short tutorial procedure from beginning to end; two of these (G and M) made the mistake of changing the preconsolidation pressure (instead of the initial cell pressure) to 70 kPa. Eight students did not attempt to follow the complete tutorial procedure properly. In some cases, there was evidence that the student began to perform the tutorial test series, but quickly deviated from the prescribed path and never completed it.

Column 4 indicates the number of times the student "moved" about in the lab. Keystrokes corresponding to forward, backward, left, right, up, and down permitted the student to take a "step" in each direction, and thus move about the laboratory to view the experiment from different angles. (Rotations of the viewing direction or magnification of the viewing lens from a static position are not included in this total.) At one extreme, four students (D, E, L, P) did not move about the lab at all, choosing to stay at the original location. At another extreme, two students (M and R) took over 500 "steps" about the scene.

Column 5 contains the number of times the student "reset" the soil specimen. This is an indication of the number of tests performed, since the student would need to reset after attaining failure under a single test. Approximately half of the students reset the specimen between 60 and 80 times. Two students (R and T) reset the specimen over 150 times.

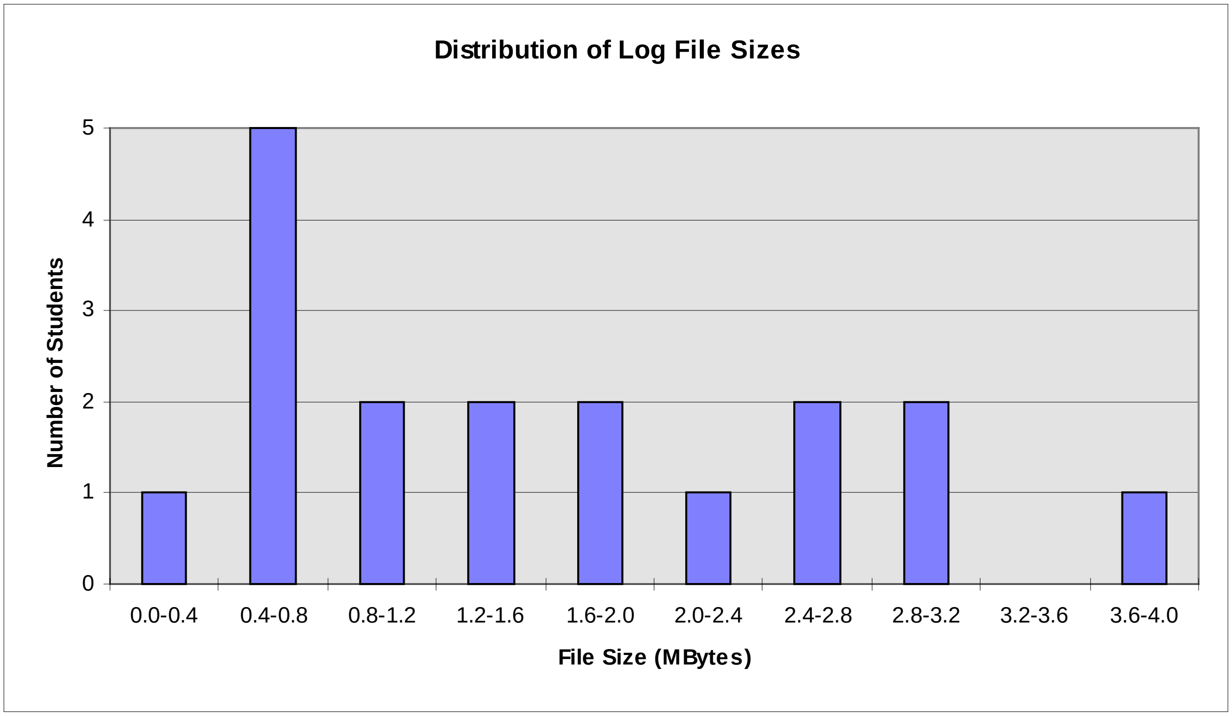

Figure 4. Distribution of program activity in terms of recorded disk space.

Columns 6 and 7 contain the number of times the student edited the cell pressure and the preconsolidation pressure, respectively. The value in column 6 is an indication of the effort expended on Question #1, which required the student to study the effect of OCR by varying cell pressure. Similarly, the value in column 7 is an indication of the effort expended on Question #2, which required the student to vary preconsolidation pressure. Student R edited the cell pressure three times as often as the preconsolidation pressure (110 vs. 37), indicating much more relative effort on Question #1. Student N edited the preconsolidation pressure three times as often as the cell pressure (30 vs. 9), indicating much more relative effort on Question #2. Other students fell within these two extremes, but there was wide variation in the relative levels of effort.

The sum of columns 6 and 7 should not exceed column 5, because that would indicate that the student performed tests without varying cell pressure and preconsolidation pressure independently, and thus the student would not be able to isolate the effect of each condition. Only in one case (Student J) does this happen. Because column 5 indicates the total number of tests performed, and the sum of columns 6 and 7 indicates the number of tests corresponding to the first two questions, then the difference is one indication of the effort expended on Question #3. In order to isolate the effects of specific material parameters, the student would need to edit soil properties without changing the test conditions. Five students (D, E, G, H, T) appear to have expended about half of their total effort on this question, whereas Student M appears to have spent about two-thirds of his effort on it.

Table 1. Summary of individual usage styles.

STUDENT	(1) Time of Use	(2) Logged Activity (kB)	(3) Follow Tutorial?	(4) # Moves	(5) # Reset	(6) # Changes in σ'_c	(7) # Changes in p'_0
A	0:50:54	715	N	19	31	12	9
B	0:54:16	273	N	35	40	12	14
C	1:02:50	507	Y	125	38	13	22
D	1:03:33	2344	N	0	74	18	16
E	1:19:15	1636	N	0	70	17	18
F	1:44:19	1193	Y	100	78	42	30
G	1:48:01	1258	Y*	28	59	13	13
H	1:49:59	2905	Y	126	97	21	26
J	1:57:00	431	Y	170	69	28	47
K	2:19:38	1796	Y	157	59	18	35
L	2:36:37	507	Y	0	71	27	15
M	2:46:09	2465	Y*	514	53	10	9
N	2:57:16	1556	Y	386	59	9	30
P	3:02:02	817	N	0	69	19	43
Q	3:29:24	2405	Y	156	75	28	34
R	4:27:45	2839	N	1054	175	110	37
S	4:34:01	635	N	29	73	31	29
T	5:14:06	3860	N	113	151	43	28

IV. Correlation with Performance

As previously stated, this was a formative evaluation. The assignment was intentionally open-ended, and was designed to prod students into independent exploratory use of the software. As was hoped, this resulted in wide variation in the way that the program was used by individual students. The submissions typically consisted of about one page of written response to the three questions, with several supporting graphs and tables. The lack of a consistent user approach, as well as the open-ended nature of the assignment, makes it difficult to develop numerical correlations between performance and style of use. However, it is instructive to examine the submissions on a student-by-student basis and draw conclusions based on their individual approach to the problem. In general, students submitted written responses corresponding to the expected material behavior described in Section II. The log file analysis of student activity in the previous section revealed a few "red flags" that indicate marked differences in individual learning styles, and it is interesting to see how these individual styles are borne out in the responses.

---

* Attempted to perform tutorial test series, but accidentally changed p'_0 to 70 kPa instead of changing σ'_c to 70 kPa.

As seen in Table 1, Student M moved about the lab much more than most students, indicating that he relied heavily on visual observation and chose to view the test apparatus from many positions. However, he performed fewer tests than the average. In addition to performing few tests, only a small portion of those tests appears to have been devoted to the first two questions. As expected, his text response for Question #3 is about twice the length of that for the first two questions combined. His response to Question #3 is insightful: He correctly recognized that the ultimate load and pore pressures are independent of the shear modulus, and that strain decreases with increasing shear modulus. He also recognized that in a drained test, failure in a conventional triaxial test will never occur when the slope of the CSL exceeds the slope of the stress path. However, his responses to the first two problems are less encouraging. He correctly recognized that the excess pore pressure decreases with increasing OCR, eventually becoming negative, and that the ultimate strain tends to decrease with increasing OCR. However, because the level of confinement was not held constant in the Question 1 test series, he drew the false conclusion that the ultimate strength generally decreases with increasing levels of overconsolidation. He also made the mistake of confusing ultimate strength with peak strength, and thus drew the false conclusion that ultimate strength may increase with OCR for highly overconsolidated soils. In fact, if the initial cell pressure were held constant, he should have realized that the ultimate strength is independent of the level of overconsolidation. It is clear that he did not expend enough effort on the first two problems, and instead drew false conclusions after performing only a few tests. Also, he concentrated far too heavily on visual inspection of the test when the assignment clearly required more quantitative analysis; this is reflected in the fact that his total text response to the assignment covers about one-half page.

The logged activity of Student N closely approximates that of Student M in terms of usage time and total number of tests, and both moved about the laboratory much more than did the average student. The difference in disk usage can be attributed to the fact that Student M performed about 33% more movements than did Student N. Note, however, that Student N modified the preconsolidation pressure approximately three times as often as the cell pressure, indicating that she spent more time on Question #2 than on Question #1. This indicates that she probably performed the test series prescribed in Question #1 and initially drew the same false conclusion that increasing degree of overconsolidation resulted in decreased ultimate strength. Presented with conflicting information in Problem #2 (where initial confinement is held constant), she expended more effort to uncover an explanation. Accordingly, she reported that the ultimate load was dependent not on OCR but rather on initial cell pressure and the slope of the critical state line.

Student R performed more tests than any other student. However, his effort seems to have been disproportionately expended on Question #1 (he modified the confining pressure 110 times). As a result, he never reached the conclusion that the ultimate strength depends primarily on the initial confining pressure and the slope of the critical state line. He did not test over a wide range of OCR values, and thus he observed no negative excess pore water pressures. It appears that he began the assignment with “good intentions,” performing several tests under Question #1. However, he became distracted with his freedom to move about the lab area, and his effort on subsequent problems decreased markedly as he concentrated more on visual inspection than quantitative analysis.

Student J had a very typical usage style in many respects: her time of use and recorded disk activity both fall into the large clusters shown in Figures 3 and 4, and she performed an average number of tests (69 resets). However, she does not appear to have had a structured test plan to edit parameters independently (the total number of modifications to cell pressure and preconsolidation pressure alone are greater than the total number of tests). As a result, it is difficult for her to isolate the effects of specific parameters. In describing the effect of the shear modulus G, she says, "Increasing the shear modulus … did not affect the strain in the drained case, and only slightly affected the undrained strain results (as G $\uparrow$, ε $\uparrow$)." Of course, with all other parameters held constant, the elastic portion of strain will decrease as the shear modulus increases. But Student J did not attempt to isolate the effects of one parameter by holding all others constant, and thus did not observe this phenomenon.

V. Conclusions and Future Direction

The virtual geotechnical laboratory has been shown to be a very flexible environment that accommodates a wide variety of learning styles. It allows the student to visualize concrete physical phenomena (e.g., the bulging of a soil specimen) as well as abstract quantities (e.g., plots of excess pore pressure vs. effective isotropic stress) simultaneously, thus supporting the link between observation and intuitive understanding of soil behavior. The student has control over material properties, test parameters, and view properties.

As with any situated learning activity, when the student is given a great deal of control over the learning environment, there is increased potential for mistakes and misinterpretation of results. A log utility to record user actions is helpful to identify potential problems with an individual student's style of use. Disproportionate levels of effort spent on specific tasks or lack of attention to specific details can be quickly identified through log file analysis, and the student can be corrected as necessary. Eventually this should take the form of an intelligent tutoring system, where certain "red flags" in a student's logged activity will instigate helpful guidance directly from the software. For example, if the student moves around too much he or she would be advised to focus more on performing the test. If the student starts changing the preconsolidation pressure in the middle of the test, he/she would be advised that such a change is unrealistic.

Rigorous assessment of the virtual lab will require the program to be incorporated into a more structured learning situation. We plan to incorporate the software into the second lab testing course (CE 6161) with the same student group used in the formative evaluation. Students will use the program in conjunction with actual physical testing over the entire academic quarter, comprising a number of different tests (consolidation, unconfined compression, unconsolidated-undrained, consolidated-drained, and consolidated-undrained). For each physical lab report, students will be expected to compare their physical test results with results in the simulated tests, and use the virtual lab to discuss the effect of specific parameters.

APPENDIX

The following is the main text of the tutorial that was provided to familiarize students with the capabilities of the virtual laboratory.

Click on all the arrow keys to get a feeling for how to change the viewing direction. Also try moving up, down, left, and right.

Click on the right mouse button, then select "Modify soil properties." This brings up a dialog box with default soil property values. Note that the default preconsolidation pressure is 100 kPa. Click Cancel to close this box without changing values.

Click on the right mouse button, then select "Modify test conditions." This brings up a dialog box with default test conditions. Note that a drained test is selected by default. The default consolidation pressure is 50 kPa, which corresponds to an overconsolidation ratio (OCR) of 2. Pe the shear loading increment from 5 kPa to 1 kPa, then click OK to save your changes.

Load the specimen by clicking the 1-key. Load it all the way to failure (the machine will stop loading when failure is reached). For a drained test, with cell pressure = 50 kPa and preconsolidation pressure = 100 kPa, this occurs at q = 50 kPa. The axial strain at this ultimate state is about 0.5. You should have noticed a dramatic increase in strain at about q = 35 kPa when the material yielded. After this point the soil experienced plastic deformation. You can verify this by unloading the specimen (the minus key). There is very little elastic rebound.

Go back to the Test Conditions dialog box. Click on the q-vs.-p plot type, then click OK. You now should see two plots, one with a linear stress path and the other with a very non-linear stress-strain curve.

Reset the specimen by clicking the Home key. Go back to the Test Conditions dialog box and click the Drainage checkbox OFF to run an undrained test. Also change the initial consolidation pressure to 70 kPa. This corresponds to an OCR of about 1.4. Click OK to save your changes.

Load the specimen to failure by clicking the 1-key. This time, in addition to the total stress path, the effective stress path is seen as a yellow curve. Both curves are very linear up to the yield stress (again, this occurs at about q = 35 kPa). There is much less axial strain in this test because volume changes are not permitted. However, there is a noticeable amount of excess pore water pressure generated.

Reset the specimen by clicking the Home key. Open the Soil Properties dialog box. Pe the preconsolidation pressure to 400 kPa, then click OK to close the window and save your changes. This corresponds to an OCR of (400/70) = 5.7. Again, load the *specimen to failure. This time, it will yield at a much higher shear stress (about 100 kPa). At the ultimate load, there will be a large amount of negative pore pressure. The plot of Δu-vs.-strain (available on the Test Conditions dialog box) graphically demonstrates the variation in porewater pressure.*

Bibliography

[1] Arduino, Pedro, Augusto Op den Bosch, and Emir Jose Macari, "Geotechnical triaxial soil testing within virtual environment," *Journal of Computing in Civil Engineering*, ASCE, vol. 11, no. 1, January 1997.

[2] Op den Bosch, A., and W. Rodriguez, "Interactive visualizer: object and view manipulation algorithms," *Theoretical Graphics and Computing*, 6(1), pp. 48-57, 1993.

[3] Schofield, Andrew, and Peter Wroth, *Critical State Soil Mechanics*, McGraw-Hill Book Co., New York, 1968.

[4] Wood, David Muir, *Soil Behaviour and Critical State Soil Mechanics*, Cambridge University Press, Cambridge UK, 1990.

[5] Holtz, Robert D., and William D. Kovacs, *An Introduction to Geotechnical Engineering*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981.

[6] Bishop, A.W., and D.J. Henkel, *The Measurement of Soil Properties in the Triaxial Test*, William Arnold Publishing, London, 1957.

TIMOTHY ROBERT WYATT

Tim Wyatt is a Ph.D. candidate in the Geosystems group of the School of Civil and Environmental Engineering at Georgia Tech in Atlanta GA, where his minor discipline is educational technology. He received B.S. and M.S. degrees in civil engineering from North Carolina State University in Raleigh NC. Before returning to graduate school, he spent three years as a staff scientist at Applied Research Associates, Inc. in Raleigh NC.

PEDRO ARDUINO

Pedro Arduino is an Assistant Professor in the Civil Engineering Department at the University of Washington in Seattle. His research interests include constitutive modeling of soils, mechanics of porous media, and numerical methods in geomechanics. He received M.S. and Ph.D. degrees in civil engineering (geosystems) from Georgia Tech in Atlanta GA.

EMIR JOSE MACARI

Emir Macari is an Associate Professor in the Geosystems group of the School of Civil and Environmental Engineering at Georgia Tech in Atlanta GA. He specializes in numerical modeling in geomechanics, and experimental and numerical analysis of partially saturated soils. He received M.S. and Ph.D. degrees in civil engineering (geomechanics) from the University of Colorado in Boulder CO.