Learner-Centered Educational Software for Constitutive Modeling of Soils

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Abstract

An educational software package has been developed and tested for its potential to convey aspects of constitutive modeling of soils to civil engineering undergraduate and graduate students. The software accounts for tenets of learner-centered design (LCD): (1) the software is intended to encourage individual exploration; and (2) students are expected to experience personal growth through use of the package, and thus the software itself adapts to accommodate this growth. Individual motivation is enhanced through interactive visualization of constitutive modeling concepts such as effective stress states and their corresponding yield surfaces. The student begins with fundamental mechanics concepts (stress invariants conversion) and must demonstrate proficiency in each topic, by performing an associated task, before moving to more advanced topics. Using the LCD concept known as intrinsic scaffolding, as the student moves to increasingly complex topics, he/she is given more powerful visualization tools and increased control over material parameters, loading conditions, and options for display of the results. The difficulty of the required proficiency task also increases accordingly. After completing the final topic (calculation of incremental strains), the student is given full capability to simulate a variety of stress and strain paths, such as true triaxial soil tests, including three-dimensional display of test results. Preliminary post-test evaluation has revealed that the scaffolded approach allayed student concerns and increased student motivation.

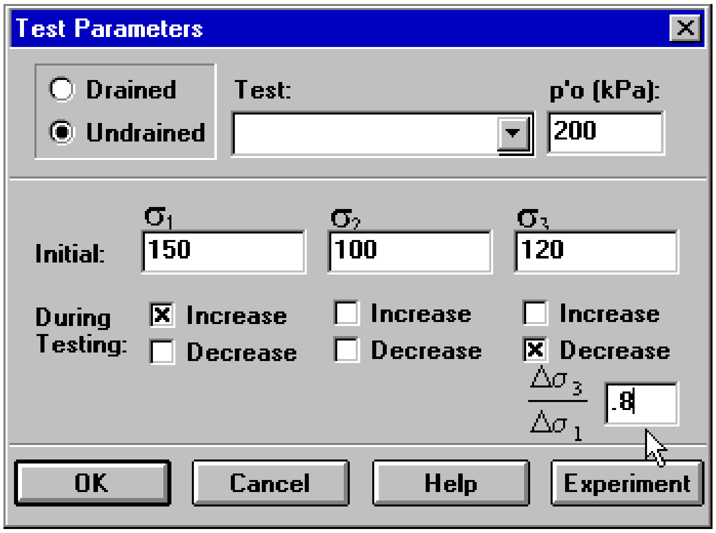
I. Background

The Geosystems graduate program at the Georgia Tech School of Civil and Environmental Engineering offers both M.S. and Ph.D. degrees. Students in both degree tracks 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). A number of other courses are offered in topics such as advanced soil mechanics and constitutive modeling, practical design (such as foundations and retaining walls), and geo-environmental engineering. Upon completion of the core courses, most students pursuing M.S. degrees elect not to take the advanced mechanics courses such as *Constitutive Modeling of Soils* and *Computational Soil Elasto-Plasticity* due to a fear that the concepts may be too complex for them to understand. Despite the fact that the purpose of the classes is to instill a more complete understanding of soil behavior, M.S. students generally consider the mechanics concepts too abstract for practical application. Thus, M.S.-level students tend to focus their research and study plan into areas that they view as more practical. The problem is that a strong understanding of mechanical concepts is important in all aspects of geotechnical engineering. In engineering practice, design procedures often make use of mechanics-based equations that have been derived for use in the general case. However, real life typically presents not the general case but some variation thereof; a strong background in mechanics is required to know how to modify the general equations for application to the specific conditions.

Geotechnical engineering education typically includes both classroom instruction in soil mechanics theory and hands-on experience in laboratory testing of soils. The Soil-MIST (Model Instruction and Simulated Testing) program was developed to combine the two, by teaching theoretical concepts of constitutive modeling in the more familiar context of laboratory strength tests. It is an outgrowth of a proposed "virtual reality" soil testing environment[1]. As such, a beta version of the software was first developed in Summer 1997 as simply a test simulator, where the user supplied data to define the soil to be tested, to specify the loading and drainage conditions, and to control how results were displayed. The Modified Cam Clay (MCC) constitutive model was used to predict results.

The initial version of Soil-MIST had three data input screens: Material Parameters, Test Parameters, and Plot Parameters. On the Material Parameters screen the user could define the material to be tested by typing in values for six independent parameters: initial specific volume (N); shear modulus (G); the slopes of the critical state line (M), the isotropic compression curve (λ), and the unload-reload curve (κ); and the eccentricity parameter (e), which is the ratio of the shear strength in extension to that in compression. On the Test Parameters screen, shown in Figure 1, the user could define the test to be performed by typing in values for the initial stress state and preconsolidation pressure (p'_0), and specifying drainage conditions and loading conditions. Finally, on the Plot Parameters screen, the user specified how results were to be plotted by selecting from a number of potential axes, including three-dimensional principal stress and stress invariant spaces. This screen also gave the user the option of displaying the MCC yield surface along with the total and/or effective stress paths on the chosen axes. After providing all three types of data input, the user could "perform the test" by clicking a button, and the resulting stress path predicted by the MCC model would appear on the screen.

The initial version of Soil-MIST was thus a situated learning tool: its purpose was to provide a context through which students could gain an intuitive understanding of soil behavior and critical state soil mechanics. That context – laboratory testing – has long been used as an educational tool in geotechnical engineering. However, "soil mechanics laboratories have been the home of some very traditional equipment and procedures. … Electronics and software may have been late arriving, but they are here and they are influencing the way industry will function, therefore education must be responsive."[2] The Soil-MIST program offered advantages over traditional physical lab testing by overcoming time and fiscal constraints normally associated with performing multiple tests, enabling the user to modify individual soil property values, and by providing the flexibility to vary stress values independently in three directions. It was hoped that through repeated use (a luxury not normally available to students in traditional labs) students would develop an intuitive understanding of complex soil behavior. However, the program did not present students with any description of the underlying constitutive model and computational process through which test results were computed. It is unlikely that students would "discover" the underlying theoretical formulation by repeated simulation alone[3].



Test Parameters

○ Drained

● Undrained

Test:

p'o (kPa): 200

Initial: σ_1 150, σ_2 100, σ_3 120

During Testing:

σ_1: ☒ Increase ☐ Decrease

σ_2: ☐ Increase ☐ Decrease

σ_3: ☐ Increase ☒ Decrease

$\frac{\Delta\sigma_3}{\Delta\sigma_1}$ .8

Figure 1. Test Parameters data input screen, showing initial stress state, preconsolidation pressure, drainage conditions, and loading conditions.

Therefore, during the Fall of 1997, three "investigation" screens (Stress Invariants, Yield Surface Geometry, and Incremental Strains) were added to provide more interaction with the underlying mechanics. There was a one-to-one link between the investigation screens and the data input screens; each investigation screen offered hands-on interaction with a portion of the constitutive model closely related to a particular type of data input. For example, because the user-specified material parameters define the shape of the yield surface, the Yield Surface screen was accessible from the Material Parameters screen. Investigation screens allowed the user to interactively observe the impact of his/her choice of input values, and thus permit more insight into the eventual test results. For example, on the Yield Surfaces screen, the MCC yield surface, corresponding to the user-provided values of M, e, and p'_0, was plotted in a two-dimensional q-p′ space, and would change size/shape instantaneously as the user edited the input. The user was not required to access these investigation screens in order to perform a test simulation. It was believed that students would be naturally curious to learn more about the impact of their data input on the overall test results, and would be independently motivated to access the investigation screens. By clicking the Help buttons, the user could view the underlying equations for each investigation screen. The program structure including investigation screens is presented in Figure 2.

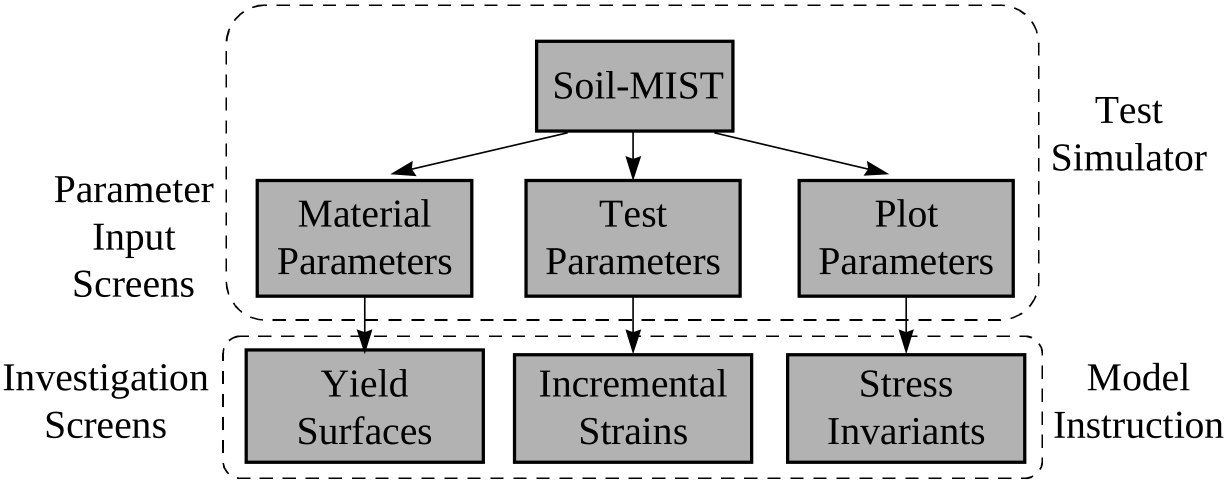


Figure 2. Soil-MIST program structure at the time of its initial evaluation.

One problem that was recognized early on was that the screen arrangement may not be optimal, because the lower-level investigation screens were inter-related, and in some cases, the theoretical concepts presented on one screen were dependent on an understanding of the concepts presented on other screens. For example, the Stress Invariants screen allows the user to convert between general three-dimensional states of stress values (e.g., vertical and lateral components) and the corresponding isotropic and deviatoric components, thus demonstrating that there is a one-to-one correlation between these sets of stress invariants. The stress invariant formulation used in this program is an extension of the Cambridge formulation for independent three-dimensional components (true triaxial formulation):

$$p = 1/3 \text{ trace}(\vec{\sigma})$$
$$q = [3/2 \text{ trace}(\bar{s}^{\,2})]^{1/2}$$
$$\theta = 1/3 \cos^{-1}(\chi)$$

where:

$$\vec{\sigma} = [\sigma_1, \sigma_2, \sigma_3]$$
$$\bar{s} = \vec{\sigma} - p\hat{\delta}$$
$$\chi = 9 \text{ trace}(\bar{s}^{\,3}) / (2q^3)$$

The Yield Surfaces screen, shown in Figure 3, displays a yield surface, corresponding to the user's choice of material property values, on a graph with q-p' axes representing the deviatoric and isotropic stress components. The equation of the MCC yield surface for true triaxial conditions[4] is:

$$q^2 g^2(\theta) - M^2[p'(p'_0 - p')] = 0$$

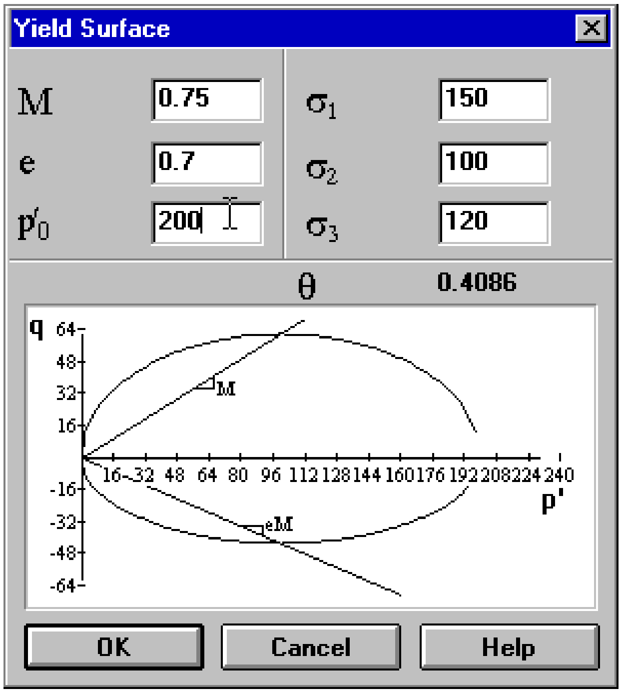
where

$$g(\theta) = \frac{4(1-e^2)\cos^2\left(\frac{\pi}{3}-\theta\right) + (2e-1)^2}{2(1-e^2)\cos\left(\frac{\pi}{3}-\theta\right) + (2e-1)\sqrt{4(1-e^2)\cos^2\left(\frac{\pi}{3}-\theta\right) + 5e^2 - 4e}}$$

For $\sigma_2 = \sigma_3$, $\theta = 0°$ and $g(\theta) = 1$, resulting in the original MCC yield surface formulation.

Thus the student must have a clear understanding of the concept of stress invariants in order to understand the meaning of the yield surface geometry. Likewise, the student must have a clear understanding of both stress invariants and yield surface geometry in order to understand the incremental strains calculation process. The procedure for computing strain components under load increments is described in detail elsewhere[5].

Because of the recognized deficiency in the screen arrangement (that lower-level investigation screens are inter-related but are not accessible from one another), and also because of the limited "Help" capabilities available, a tutorial was developed to briefly introduce the user to the program and its capabilities. Every step, every button click, and every action was prescribed in the tutorial, so that each student would receive an identical introduction to the program and its capabilities. The tutorial walked the student through the simulation of a conventional drained compression test, a conventional undrained compression test, and produced results in q-p' space. All of these concepts should have been familiar to the user group. The tutorial then walked the user through an unconventional test case, beginning with anisotropic consolidation and loading the material in three independent directions (true triaxial test). The test results were displayed along with the initial yield surface on two sets of 3D axes, principal stress space and stress invariant space, both of which were unfamiliar to the user group. Figure 4 shows typical output, in the form of a stress path and the initial yield surface plotted in (p′, q, θ) space. Each of the three investigation screens were introduced. Users of the tutorial would access the three investigation screens in the preferred order (Stress Invariants → Yield Surface → Incremental Strains). The tutorial was provided to participants in the initial software evaluation.



Yield Surface

M 0.75

e 0.7

p'_0 200

σ_1 150

σ_2 100

σ_3 120

θ 0.4086

Figure 3. The Yield Surfaces investigation screen, demonstrating the interrelationship of material parameters and stress state.

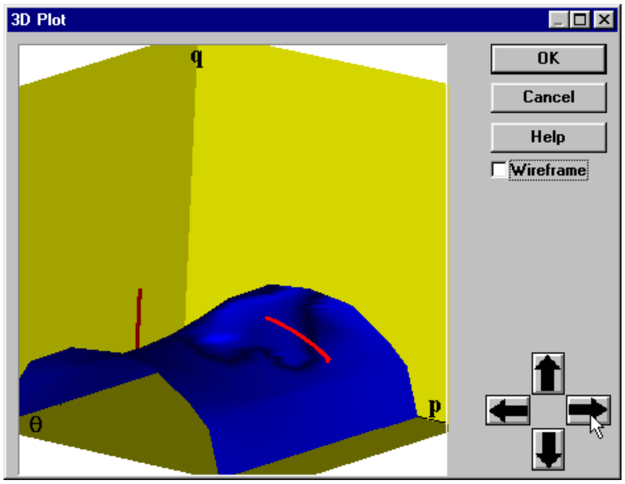


Figure 4. Plot of yield surface and stress path in three-dimensional stress invariant (p,q,θ) space.

II. Initial Evaluation

All of the evaluation participants met a target profile: students working on MS degrees in geotechnical engineering, who had completed the core courses at Georgia Tech, but who had not taken advanced soil mechanics courses, and did not plan to do so. This target necessarily limited the size of the participant group. All students meeting the targeted profile were invited to participate; four agreed to do so. All participants had nearly identical lab experience: the lab course series at Georgia Tech. Even when students had lab experience from a previous job, the experience included only simple tests and never triaxial strength tests. Triaxial strength testing is the culmination of the lab course series at Georgia Tech, and each student, as part of a three- to four-person group, performs one undrained test and one drained test. Assuming that each participant was exposed to one other triaxial test as part of an undergraduate soils lab course (which is sometimes required of civil engineering undergraduates), then each participant had been previously exposed to only three triaxial strength tests. However, the fact that student exposure to lab testing is limited is one of the problems that the Soil-MIST software was intended to address.

Explicit learning goals were established. This paper focuses on the following two concepts that were identified as new information that could be learned using the software:

- The concept of a third stress invariant, the lode angle θ, which indicates variation of the intermediate principal stress from the conventional case of axisymmetry.
- The concept of a yield surface, within which loading produces only elastic deformation, beyond which elasto-plastic deformation occurs.

The initial evaluation focused on other concepts as well, such as understanding the difference between shear and volumetric strain, and the difference between drained and undrained behavior. These concepts posed no problem for graduate geotechnical students, as should be expected, so the focus of the paper is on some of the most complex learning concepts. The evaluation stage of this study was composed of three different portions, as follows:

a) Log Files: By clicking on the "log file" radio button, participants acknowledged that their actions were being recorded to disk. The participant always had the option to suppress the recording of his/her actions. This was considered an important feature in case the student was uncomfortable having his/her every move recorded; however, no students suppressed the recorder at any time (an action that would itself have been recorded in the log file). The log file recorded every button click, and date-time stamped the information. The purpose of the log file was twofold: To determine the extent to which each participant followed the tutorial, and to see what kind of experimentation the user performed on his/her own. The premise was that recorded differences in user actions could be used to explain differences in learning.

b) Questionnaire: Students were assigned a questionnaire after having used the program for several days. The questionnaire was divided into three sections: Background Information (to assess the participant's background, in both mechanics and lab testing), Constitutive Model Concepts (to assess the effectiveness of the program in teaching the MCC constitutive model), and Evaluation Comments (to assess, among other things, the user interface). Students were given one day to complete the questionnaire and return it, along with the log file. Completed questionnaires were obtained from all four participants.

c) Results: The Constitutive Model Concepts portion of the questionnaire was designed to assess the program in relation to the pre-defined learning goals. This paper will focus on the questions related to the two goals stated earlier: an understanding of the physical meaning of a yield surface, and an understanding of the lode angle and its importance:

    - *"Explain your understanding of the concept of a yield surface, and its relationship to preconsolidation pressure."* Students basically understood that the yield surface is the boundary between elastic and elasto-plastic behavior. However, none of the students understood its relationship to preconsolidation pressure. Judging from their academic background, these students are familiar with the concept of preconsolidation stress in a one-dimensional sense, from Terzaghi's consolidation theory, and they understand that preconsolidation pressure increases when the material undergoes plastic deformation. The yield surface can be viewed as a three-dimensional extension of this concept.

    - *"Explain, to the best of your understanding, the meaning and importance of the third stress invariant, θ."* On this question the participant group split evenly. Half did not respond, while half understood that the value of θ indicates deviation in the lateral plane ($\sigma_2 \neq \sigma_3$). None of the participants had previously been introduced to the concept of a lode angle, so the correct responses indicated that the program had the potential to teach this concept. Participants were not asked to explain the meaning of the isotropic and shear components (p' and q, respectively) because these are concepts with which they should be familiar. However, it became apparent in follow-up interviews that some students did not have a clear understanding of the meaning of these invariants. They questioned why, for the unconventional test that began under anisotropic loading conditions, the stress path had an initial value of $q > 0$. While such a condition would be unfamiliar to students who are accustomed to analyzing test data for initially isotropic conditions, the student with a fundamental understanding of p' and q should not have a problem with it. The same students who did not learn the meaning of θ were those who were confused by this somewhat unusual initial value of q.

The log files were analyzed to determine if differences in understanding corresponded to differences in program usage. Two statements can be made about the log files:

- The students who followed the initial tutorial step-by-step demonstrated the most understanding of constitutive modeling concepts in the post-test questionnaire.
- The users who deviated from the tutorial procedure quickly realized that the program could be used to examine a wide range of material behavior and they soon became lost in its complexity. They were unable to grasp the more complex concepts without first gaining a solid understanding of basic concepts, which the tutorial procedure was intended to provide.

III. Scaffolded Redesign

The original design of Soil-MIST was *user-centered*: it provided the user significant flexibility to experiment with various soil types under various loading conditions, with the option for the user to get additional experience at the more elemental theoretical level when he/she desired. However, it failed to account for two tenets of *learner-centered design* as defined by Soloway *et. al.*[6]: a student is often not motivated to learn (and thus will not experiment with the underlying theory), and a student can be expected to experience personal growth through use of the software (and thus the software should adapt to accommodate this growth).

Soloway *et. al.* proposed using *scaffolding* to convert a user-centered design to a learner-centered design. Scaffolding is defined as providing support to learners while they are being introduced to new material, by helping the learner do a task that he/she can not do alone. As the learner demonstrates proficiency, the scaffolding "fades" and the user gains more control. One form of this technique is *intrinsic scaffolding*[7], which is a method of support in which the task itself is changed in order to reduce the complexity of the task: "As the scaffold fades, the task is changed, but associations should remain so that the learner can progress from simpler, more structured, or more concrete tasks to variations in which more of the underlying complexity or abstractness is introduced."

The Soil-MIST program was redesigned to meet these criteria; the new main screen (as seen at program start-up) is shown in Figure 5. Links to the three investigation modules are now in a prevalent position on the main screen. In fact, the beginning user is now *required* to pass through the three modules in the preferred order to reach the test simulator module. At program start-up, the user's only option (identified by the only active button) is to experiment with the Stress Invariants module. As the learner successfully "passes" each module, the next progressively complex module becomes available. While the "task" completely changes from module to module, the underlying associations are always clearly evident. For example, on the Stress Invariants screen, the learner's task is to provide values for a three-dimensional stress state, and then convert those values to (p, q, θ) invariants. On the next screen, Yield Surface Geometry, the task is to create a yield surface by providing material parameters. The resulting yield surface is displayed in q-p′ space, for a specific value of θ that corresponds to the user-provided stress state. After completing this task, the student has access to the Incremental Strains investigation screen, shown in Figure 6. Here the student has complete control to increment the load in each principal direction independently. As he does so, the resulting individual strain components (shear and volumetric, elastic and plastic) are computed and displayed on the screen, as are incremental changes in excess porewater pressure and preconsolidation pressure. The student's task is to load the material so that the yield surface is expanded and plastic strains are computed, under both drained and undrained conditions.

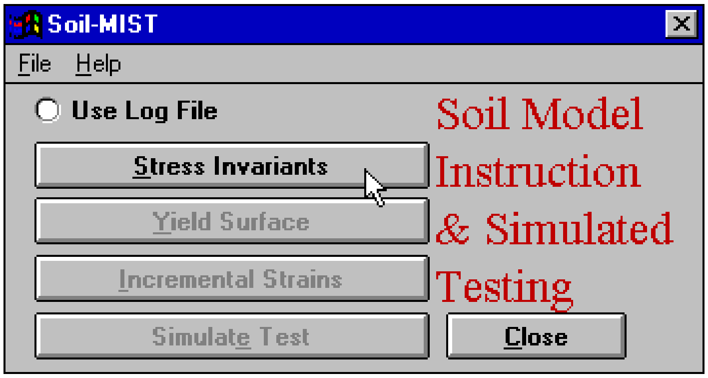


Figure 5. New main screen for scaffolded version of Soil-MIST program; user initially has limited capabilities, with more becoming available as learner gains proficiency.

In order to "pass" each investigation module, the user is required to perform the task associated with the screen. If the user clicks "OK" to close the screen without completing the associated task, a warning message appears stating that the task has not been completed, and is told what is required in order to complete that step. For example, on the Stress Invariants screen, if the user has not completely filled in stress state values, he is told to do that. If he has provided those values, but has not clicked the conversion button, he is told to do that. Extensive "Help" screens are available, which describe the screen operation as well as the underlying theoretical concepts.

The user is always able to return to a screen that has been previously completed. For example, the one-to-one links between the data input screens (for the test simulator) and the associated investigation screens are still in place. However, the scaffolding at each level, in terms of warning messages and expert guidance, is no longer in place after the learner has advanced to the next level; it has since *faded*. The "Help" screens are still accessible at user request.

IV. Second Evaluation

In order to evaluate the program with its scaffolded re-design, four additional geotechnical graduate geotechnical students were selected, with nearly identical background to the original evaluation participants. They were likewise asked to use the program over a period of a few days, *but this time were given no tutorial*. In lieu of the tutorial, each participant was simply asked to perform at least one drained test and one undrained test; thus it was implied that the student's goal was to access the test simulator, which is inactive at program startup, and can be accessed only after completing the tasks associated with the three investigation screens. Again, the students' usage was recorded in log files, and the identical post-test questionnaire was assigned after a few days.

a) Log File Analysis: In addition to recording user actions, the log files (in the scaffolded version) record whenever a participant's actions stimulated warnings or guidance from the program. Analysis of the log files shows that scaffolding, in the form of warnings and guidance messages, was effective both in guiding users through the lower-level tasks, as well as in modifying student behavior. Students who proceeded through the program "blindly" encountered scaffolding tips more frequently than students who accessed the on-line help. After receiving repeated warnings from the scaffolding support, students became more likely to access "Help" screens and their ability to use the program improved considerably (as measured by declining occurrence of scaffolding messages).

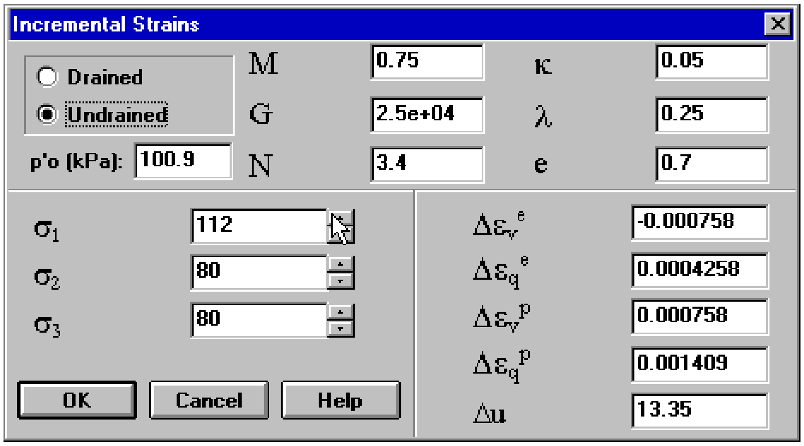
Another marked difference from the initial evaluation, as measured with log files, was in student motivation. In the initial evaluation it was noted that students who followed the tutorial procedure were generally content to stop after performing the two tests described in the tutorial. Students who did not follow the tutorial procedure were more likely to experiment with multiple tests but were also more likely to become frustrated at their inability to interpret results or to obtain meaningful results. In the second evaluation, due to the scaffolded re-design of the program, students were required to become reasonably proficient with constitutive modeling concepts before obtaining test simulation capabilities, but then were provided little guidance as to how to set up and run a test (beyond what was available in online help). The result was that all students performed more than ten tests with various loading/drainage conditions and soil types.

b) Questionnaire Results: The same questionnaire was given to participants in both evaluation periods. Again, all four participants in the second evaluation completed the questionnaire. The results relating to the previous learning goals are presented for comparison:

- *"Explain your understanding of the concept of a yield surface, and its relationship to preconsolidation pressure."* Unlike in the initial evaluation period, all students understood that the preconsolidation pressure and yield surface were related. Half of the students identified the relationship correctly as the value of the yield surface along the p'-axis. One student stated that the stress path reaches the yield surface "approx. at the point where the precons. pressure is reached" along the p'-axis, which is not always true. However, because this implementation of the MCC model required soils to be normally-consolidated to lightly overconsolidated ($p' \geq \frac{1}{2} p'_0$), it is true that the value of p′ would always be similar to p'_0 at the yielding in all tests simulated by the software. Improved constitutive modeling capabilities should be implemented in the program so that users could test an even wider variety of cases. However, all of the students demonstrated some level of accurate understanding of this topic and, as a group, performed much better than the initial evaluation group.

- *“Explain, to the best of your understanding, the meaning and importance of the third stress invariant, θ.”* Again, all participants in the second evaluation answered this question correctly. Some recognized that in conventional lab tests they had no control over this value (because the test specimen is cylindrical and thus radial stresses are required to be equal). A typical response was, “My basic understanding is simply that θ is a way of representing the deviation of the stress path from the principal stresses. But in lab tests, you can’t vary this → i.e. CU [consolidated undrained] or CD [consolidated drained] you merely have the σ_1 and σ_3 terms and both are principal stresses.” One student freely admitted that he did not fully understand the concept, but that he obtained his answer using the “Help” function (a resource option that did not occur to students participating in the initial evaluation).

V. Conclusions



○ Drained
● Undrained
p'o (kPa): 100.9
M 0.75
G 2.5e+04
N 3.4
κ 0.05
λ 0.25
e 0.7
σ_1 112
σ_2 80
σ_3 80
$\Delta\varepsilon_v^e$ -0.000758
$\Delta\varepsilon_q^e$ 0.0004258
$\Delta\varepsilon_v^p$ 0.000758
$\Delta\varepsilon_q^p$ 0.001409
Δu 13.35

Figure 6. Incremental Strains investigation module interactively demonstrates MCC computational processes.

The original version of Soil-MIST demonstrated significant potential as a tool for teaching advanced soil mechanics. Giving students wide control over their own actions and providing real-time graphical feedback in the form of stress path plots promotes intuitive understanding of soil mechanics. The three-dimensional plots of stress paths and yield surfaces represented a powerful new framework for considering true triaxial stress conditions. The 3D plotting application allowed students to rotate the viewing angle and view the surface in shaded or wireframe mode. Additionally, investigation modules were developed to permit the student to examine particular components of soil mechanics theory in depth. However, students who are accustomed to performing experiments only in controlled laboratory environments can become overwhelmed with suddenly being given such wide capabilities. Steps must be taken to ensure that the student is given proper guidance. Thus the software was reworked according to tenets of learner-centered design.

Post-test evaluation of learning goals demonstrated significant improvements in the Soil-MIST program after its scaffolded re-design. No new functionality was added between the first and second evaluations; instead, investigation modules that provide interaction with the underlying theoretical equations were moved from the optional lower level to become required tasks that the user must first complete in order to gain additional capability. In addition, warnings and guidance were provided to help the learner complete a task when he/she demonstrates misunderstanding or inability to complete the task without help. These supports fade away after the learner demonstrates proficiency in performing the task.

A benefit of supporting the beginning learner with software scaffolding is that it encourages learning by independent experimentation. It also overcomes the problems generally associated with independent experimentation; namely, that the learner does not have sufficient background to interpret the results of the experiment. With intrinsic scaffolding, the learner gains capability progressively after demonstrating that he/she is learning new material. Additionally, because intrinsic scaffolding requires that the task itself be changed as the learner gains capabilities, knowledge transfer is inherent in the design, and the knowledge learned is not limited to the context of laboratory testing.

Bibliography

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[1] Arduino, Pedro, Augusto Op den Bosch, and Emir Jose Macari, "Geotechnical triaxial soil testing within virtual environment," *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, v. 11, n. 1, January 1997.

[2] Whitaker, William, "Teaching soil mechanics laboratories with computer assistance," *Computing in Civil Engineering*, ASCE, Washington DC, 20-22 June 1994.

[3] Charney, D.H., L.M. Reder, and G.W. Kusbit, "Goal setting and procedure selection in acquiring computer skills: a comparison of tutorials, problem-solving, and learner exploration," *Cognition and Instruction*, v. 7, n. 4, 1990.

[4] Willam, K.J., and E.P. Warnke, "Constitutive model for triaxial behavior of concrete," *Colloquium on Concrete Structures Subjected to Triaxial Stresses*, ISMES, Bergamo, IABSE Report Vol. 19, 1974.

[5] Macari, Emir Jose, and Pedro Arduino, "Overview of state-of-the-practice modeling of overconsolidated soils," *Transportation Research Record 1479*, Transportation Research Board, Washington DC, 1996.

[6] Soloway, Elliott, Mark Guzdial, and Kenneth E. Hay, "Learner-centered design: the challenge for HCI in the 21st century," *Interactions*, April 1994.

[7] Jackson, Shari L., Joseph Krajcik, Elliot Soloway, "The design of guided learner-adaptable scaffolding in interactive learning environments," ACM Computer-Human Interactions Conference (CHI98), Los Angeles CA, April 1998.

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