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Development of Controller Program for Administering Triaxial Test Phases by Computer Commands

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***Abstract* — The triaxial testing is one of the most common and theoretically sound methods to determine the stress-strain-strength characteristics of soils in the laboratory. The primary function of a triaxial testing system is to apply a three-dimensional axisymmetric state of stress in terms of imposed axial and radial stresses as well as longitudinal deformations on a cylindrical soil specimen through all-around chamber fluid pressure and axial load mechanism, respectively. As such, the determination of stress-strength-strain properties of soils through laboratory measurements requires conducting high quality triaxial tests. In this regard, a programming code with user-friendly interfaces for running sophisticated triaxial testing procedures including initial saturation, consolidation and shearing test phases was developed. The created controller software is capable of performing the necessary triaxial test phases including test apparatus set-up, saturation, consolidation and shear testing. As such, the software can consistently control the triaxial system applying either undrained or drained linear stress paths as well as performing isotropically or anisotropically or alternatively one-dimensionally consolidated triaxial tests on soil specimens.**

***Keywords*— Triaxial Testing Procedures, Controller Software, Triaxial Test Phases, Computer Control Programming Code, User-friendly Interface**

I. Introduction *and Background*

The simplest form of triaxial tests is when the vertical stress is increased while keeping the horizontal stress constant. In order to more closely imitate the stress conditions in the ground during the construction and design life of the adjacent or overlying structure, more complex states of stress are required to be applied on the tested soil specimen during various stages of triaxial testing.

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The determination of the stress-strength-strain behavior of soft soils (i.e. clays) requires advanced computer controlled soil testing equipments which have certain operational performance capabilities in terms of running sophisticated and research oriented long-duration stress-path tests. Since these performance tests take long time duration as well as the entire testing process consists of different test phases. In the past, some researchers developed automated triaxial testing systems specialized for their research purpose to obtain accurate and robust test data to be used in their research studies including [1-4]. However, their efforts were mostly on the development of computer-automation hardware for triaxial test systems. On the other hand, the development of user friendly controller programs incorporating user interfaces and designed menu options have received little attention in order to run triaxial testing procedures by proceeding through different test stages starting from initial saturation phase, then processing through consolidation phase and ending with shearing test stage for attaining reliable test results and accurate characteristic curves in terms of stress-strength-strain behavior of the soil specimens tested. To this end, the development of up-to-date controller software with user interface for controlling the triaxial testing equipment and for administrating all the different triaxial test phases (i.e. saturation, consolidation, shearing) during the course of overall triaxial testing progress on soils will accompany with those previous efforts that were primarily on the design of testing equipment components and on the development of supplementary hardware for the automation of triaxial test systems.

II. Controller Software

A. *Introduction*

The software is capable of performing the primary triaxial test phases including: a) test apparatus set-up, b) saturation, c) isotropic and/or anisotropic consolidation, and d) shear testing. Additionally, the software enables the user to access measurement instrumentation readings as well as determine the specimen's current stress-strain state (Figure 1).

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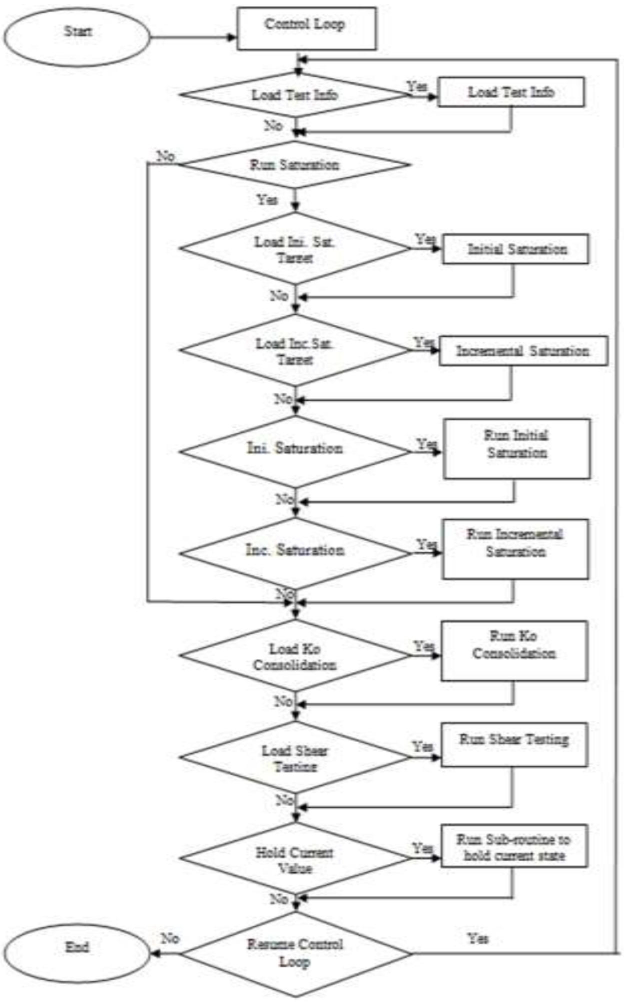

Figure 1. Flowchart of The Controller Software

B. *Current Test State Control and Continuation*

The triaxial specimen stress-strain state is measured by the instrumentation, and the instrumentation signals are read into the PC using an analog-to-digital (A/D) converter, and these signals are converted to engineering units. This current actual stress-strain-time state is compared with pre-scheduled values. If a difference occurs between these two at a given time, the control algorithm computes and actuates the stepper motors via the digital-to-analog (D/A) device to minimize or eliminate any differences that exist. This feedback control loop establishing the controlling functions of the testing software is shown in Figure 2.

Figure 2. Closed Feedback Control Loop Processed during the Execution of The Controller Software

After the readings of the measurement instruments are taken through the A/D card, the software converts these signals into engineering quantities, as given in Equation 1, to find the differences between target values and the true state of the specimen. Based on these differences, the software computes the number of steps required for each of the three motors to minimize the error.

$$\text{Output-Engineering-Unit}=\{[(\text{Output-Voltage-Reading}) - (\text{Transducer-Zero})]/V_{in}\}*C.F \qquad (1)$$

where *C.F.* is the conversion factor for that instrumentation device and V_{in} is the input excitation voltage (i.e. 5.5 VDC). Transducer zeros are obtained after system preparation and set-up for the triaxial test and prior to initiation of testing progress.

C. *Program Sub-Module for Conversion of Voltage Readings into Engineering Units*

The specimen's current stress-strain states are shown on the user interface as the triaxial test continues. A class module called *"Calibration"* controls this procedure for the conversion of voltage readings into engineering units and storage of test data. It was given in Equation 1 how this conversion process of transducers' voltage readings into engineering quantities is conducted. Furthermore, a clock sub-module within Calibration was written for time-based computations (e.g., computation of motor steps during K_o consolidation and shearing). The important pre-test parameters such as motor gain values, and instrumentation conversion factors are all input on the test information form. This class module reads these parameters to perform necessary operations and computations with the module. The calibration class module is truly the backbone of the entire control software.

D. *Saturation Phase Process Control*

The specimen is initially saturated prior to K_o consolidation and this is the first control program in the software structure. The specimen's initial effective stress (σ'_o) is first obtained in the saturation phase by applying a certain hydrostatic cell pressure (undrained) to the specimen to observe pore water pressure changes. This σ'_o value is that used throughout saturation as the difference between cell pressure and back pressure. The increments of cell and back pressure and the time over which they are to be applied are defined prior to starting incremental saturation. There are ten increments on the interface of this stage, which is typically enough for testing purposes. In order to minimize errors during incremental saturation, a modified feedback control loop is used. The error in both cell and back pressure is divided into ten to define the number of corresponding motor steps. Then, the difference between the prescheduled value and current state in the cell will be compensated with sub-increments. For example, if back pressure deviates from its pre-scheduled value during incremental saturation, this discrepancy is eliminated through modified feedback control loop using the following given in Equation 2:

*Required-Steps = (Back-Pressure-Error ÷ 10) * (Back-Pressure-Gain)* (2a)

Back-Pressure-Error = (Current-Back-Pressure) – (Pre-Scheduled-Back-Pressure) (2b)

where *Back-Pressure-Gain*, that is the number of stepper motor steps per 1 kPa change in back pressure, is determined empirically during calibrating the system for the step motor controlling back pressure. It is input into the program through the user interface when test process information is entered into the controller software at the beginning, prior to initiating triaxial testing progress.

A constant effective stress on the specimen equal to σ'_o measured during initial saturation is maintained throughout incremental saturation, and the goal at the end of this process is 100% saturation, as determined by the B-parameter. Further, it is important to note that the axial load is targeted to be maintained at zero throughout the saturation phase by adjusting the load frame motor using the current state load measurements acquired through axial force transducer.

Moreover, in order to apply "*anisotropic consolidation*" to the specimen, certain applied axial loads can be pre-determined for increment steps during this incremental saturation stage. In other words, after the hydrostatic saturation process, the saturation module is repeated, but this time with axial loads corresponding to the anisotropic stress increments desired, usually with a constant back pressure (the same value as at the end of the initial saturation).

E. *K_o – Consolidation Phase Process Control*

The K_o testing module controls constant strain rate K_o consolidation during which back pressure is kept constant. In addition, this software allows the user to apply either compression loading or swelling unloading to desired overconsolidation ratios (OCR). At the beginning of test phase, the user inputs strain rate, maximum strain, upper and lower vertical effective stresses limits, the comparison time, data storage interval, cell pressure increment or decrement and sample height. As with all axial displacement-based algorithms used in the research, the axial displacement is fundamentally an open-loop control using a deterministic conversion factor to achieve the desired strain rate. The specimen is deformed axially during compression at constant rate, and the cell pressure is adjusted to keep axial and volumetric strains equal, thus approximating a no lateral strain condition in the specimen. During swelling unloading, cell pressure is also adjusted to make the strains equal to each other. In both cases the algorithm of this procedure is as given in Equation 3:

COMPARE ➔ (Volumetric-Change) vs. {(Axial-Displacement)(Specimen-Area)}* (3a)

WHEN ➔ (Volumetric-Change) > {(Axial-Displacement)(Specimen-Area)}* (3b)

DECREASE ➔ (Cell-Pressure) (3c)

WHEN ➔ (Volumetric-Change) < {(Axial-Displacement)(Specimen-Area)}* (3d)

INCREASE ➔ (Cell-Pressure) (3e)

The variable, *Volumetric-Change*, refers to pore water volume change of the specimen between axial and volumetric strain comparison time intervals during the K_o consolidation process. One-dimensional conditions are allowed to be maintained using the area-volume technique during K_o consolidation of specimens. In this perspective, throughout K_o consolidation, the most important parameters to be obtained and compared for the progress of consolidation testing are pore water volume change and differential axial displacement. Those are compared at certain time intervals pre-determined by the user.

During K_o consolidation of specimens, the K_o value varies with σ'_v when loading. The K_o value starts to drop from unity to a certain value in the recompression stress range (i.e., $\sigma'_v < \sigma'_p$), then remains at around the true field K_o value of the soil specimen until the end of loading. For validation of the developed Visual Basic code in terms of K_o Consolidation of the specimens as well as to provide further observations pertaining to code design and process execution criteria during K_o Consolidation phase and the relevance of the operation in the triaxial cell to the in-situ conditions in terms of consolidation of soils in the field, clay specimens were K_o-consolidated in the triaxial system. The testing progress was administered by the developed controller software.

There are two possible limiting parameters to end K_o testing, maximum axial strain and maximum vertical effective stress (σ'_{vm}). When either of these limits is reached, the K_o process finishes and the current specimen stress-strain state is maintained to allow secondary compression of the soil. Swelling of the specimen is performed in exactly the same way as compression except the specimen is unloaded axially until the desired final vertical effective stress (σ'_{vc}) is reached. Again, for those tests involving an unloading phase, the current specimen stress-strain state at σ'_{vc} is maintained to allow secondary compression of the soil before shearing.

F. *Shearing Phase Process Control*

Constant rate of strain shear testing can be performed either drained or undrained by opening or closing, respectively, the back pressure valves. The main difference in the code for these two options is that in the undrained case, one essential disables the back pressure PVCC (pressure-volume-control-cylinder) stepper motor by setting its step count to zero; for the drained case, back pressure is maintained constant by adjusting the number and the direction of motor steps using the standard control loop for the back pressure PVCC. For either type of shear testing, the cell pressure remains constant; strain rate is determined by the user at the start, as is the maximum axial strain level to be allowed. It is also possible with shearing software to interrupt the test prior to reaching maximum strain limit for specific purposes.

Axial displacement is actuated using the open loop control. As per computation method of constant strain rate in the code, the number of axial load motor steps is computed based on specimen height, strain rate, axial displacement gain value, and the total elapsed time since the beginning of test (Equation 4), which is then, used to mobilize and impose constant-strain-rate per time on the soil specimens tested.

Required-Axial-Motor-Steps = (Current-Total-Steps) – (Previous-Total-Steps) (4a)

*Total-Steps ={(Axial-Strain-Gain) * (Strain-Rate) * (Sample-Height) * (Elapsed-Time)}* (4b)

The total number of axial load motor steps from the start of shearing is computed at every loop in the software. *Total-Steps* are the number of elapsed steps that have been applied up to the current loop; *Previous-Total-Steps* are the overall steps processed until the current loop for the variable of *Current-Total-Steps*. Required number of motor steps is found from the difference of these two variables. The gain value of axial strain is pre-designated by the user from calibration of loading motor.

III. Concluding Remarks

The design and development of a programming code with user-friendly interfaces for running sophisticated triaxial testing procedures as well as for administering different test phases including initial saturation, consolidation and shearing test stages were presented. The created controller software is capable of consistently controlling the triaxial system applying either undrained or drained linear stress paths as well as performing isotropically or anisotropically or alternatively one-dimensionally consolidated triaxial tests on soil specimens. Per the overall performance stability and the functionality of the controller software achieved, the sub-module programs developed for saturation, consolidation as well as shearing test phases facilitates consistent stress-path triaxial testing of soils with accurate test-duration readings obtained through robust transducers' measurements for on-time determining current state of testing progress regarding stress-strength-strain behavior of the soil specimen tested. The sub-module programs of the controller software and their primary operational functions are as summarized in Table 1.

TABLE I. THE TESTING CONTROLLER SOFTWARE PROGRAM MODULES AND THEIR PRIMARY FUNCTIONS

Program Module	Functions
Saturation	• Back-pressure saturates specimen to fully fill soil voids with water • Hydrostatically consolidates specimen • Acquires initial specimen effective stress • Holds final cell and back pressures and axial load
Ko Consolidation	• Ko consolidates specimen by comparing axial and volumetric strain • Either compresses or swells specimen during process • Hold final stresses to enable secondary compression
Shearing	• Performs either drained or undrained compression or extension tests at constant strain rate • Keeps back and cell pressure constant
A/D Converter	• Converts analog measurement instrumentation readings into digital form by using DLL functions provided by the card manufacturer
D/A Converter	• Makes the conversion of digital representations of computer commands into analog form to actuate and drive stepper motors
Calibration	• Converts voltage readings of transducers and LVDTs into engineering quantity for controller software enabling comparison of current state with pre-scheduled values • Stores test data in PC • Initiates and executes a program clock for the controlling software • Obtains test parameters from user interfaces to process triaxial testing

In conclusion, the developed controller software is particularly well-suited for long-duration tests with consistent procedures assessing strength-deformation properties of soil specimens. As such, the testing system is fully computer automated and test procedures are quite uniform resulting in obtaining repeatable, reliable and accurate test data through the performed triaxial tests as well as facilitating long-duration tests on the soil specimens.

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