Using Device-Specific Data Acquisition for Automated Laboratory Testing

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Computer-based data acquisition systems are becoming common equipment in the geotechnical laboratory. Although centralized, laboratory-wide systems offer increased data accountability, flexibility, and access control, their high costs can be justified only in large laboratories and they are not suited for use in feedback control of computer-automated equipment. A device-specific data acquisition system is dedicated to a single testing apparatus and thus allows smaller laboratories to incorporate a data acquisition capability one device at a time. From a comparison of the two system types, it is concluded that only the device-specific approach is appropriate for use in computer-automated, feedback-based servo control of testing devices. Additional requirements for device servo control are described, including servo control algorithms (proportional and proportional plus integral plus derivative) and other software requirements for control based on device-specific data acquisition systems. Experiences in applying these basic principles to the computer automation of a number of different geotechnical laboratory devices are described. Data from various tests are provided to illustrate the automated test control quality. Improved technology and lower costs for data acquisition hardware and computers have made device-specific systems an economical solution for obtaining high-quality test data.

Although computer-automated geotechnical laboratory testing was a research topic 10 years ago, today the equipment for such testing is common in many research laboratories and in some commercial laboratories. Significant advances in and the reduced costs of personal computer (PC)-based technologies are in part responsible for this rapid development and practical implementation. The other driving force behind computer-automated testing equipment is the desire to improve laboratory productivity and data quality. Although the technology is widely available, there is an ongoing need for information about the many hardware and software choices.

This paper describes the use of data acquisition systems for computer-automated geotechnical testing. Two general approaches to data acquisition, centralized and device specific, are described, and the advantages and disadvantages of each approach are given, including their suitabilities for computer-automated test control. Other requirements for device servo (or feedback) control are described, particularly software features that the authors have successfully incorporated in developing automated equipment. The paper also describes the authors' experiences with automating various testing equipment, and data that illustrate the quality of test control are presented.

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APPROACHES TO DATA ACQUISITION

There are two basic approaches to computer-based data acquisition systems: centralized and device specific. Sheahan et al. (*1*) have presented a detailed guide for selecting and implementing a system, including the two predominant methods for analog-to-digital (A/D) conversion, successive approximation and integration. They concluded that although successive approximation is the more common and cheaper of the two methods, integration is the preferred method since successive approximation is more likely to sample a signal aberration. In either case, higher conversion resolution allows a larger range of output signals to be converted without hardware reconfiguration.

A brief overview of the two data acquisition approaches is presented here as background. Table 1 summarizes the advantages and disadvantages of both centralized and device-specific systems.

Centralized System

A centralized data acquisition system consists of a single computer controlling a data acquisition control unit that receives analog signals (from measurement instrumentation and excitation voltage) from a number of laboratory stations. The system will have multiple users and will simultaneously monitor a number of laboratory test devices, and it may have multiple user interface stations. A fixed terminal box at each laboratory station is connected to the central system through shielded cable. The box provides a point for connecting instrumentation and power supplies into the system while also serving as a power distribution and shielding panel. The computer controls system operation and user interactions and may have a number of peripheral devices connected to it. The system software can be highly complex and costly since it performs multiple tasks, includes a number of reliability and data integrity safeguards, and may have other special features. At present, the addition of software and hardware for centralized feedback control of multiple automated testing devices would be extraordinarily burdensome and expensive. However, the feasibility of such a scheme can be envisioned, and some laboratories may have a small-scale version of centralized feedback control.

The principal advantage of a centralized system is that it maximizes flexibility, data accountability, and quality control in the

TABLE 1 Advantages and Disadvantages of Centralized and Device-Specific Data Acquisition Systems (*1*)

SYSTEM	ADVANTAGES	DISADVANTAGES
Centralized	• Increased accountability • Better quality control of test results • More flexibility to add features and expand capabilities • Improved lab productivity • More advanced features • Only one A/D conversion unit to calibrate	• System is critical since so many users, single system • Laboratory personnel must share equipment • Need large lab to be economical • Software needs to be more general • Software can't be written by an "amateur" • High speed logging may crash system • Higher costs
Device Specific	• Smaller scale, good for small labs • Lower costs to bring on line • Can have system redundancy within lab • Only alternative for device automation • Can easily customize software	• Data accountability is reduced • Not as many special features in software or hardware • Becomes less economical as lab size increases • Each unit must be calibrated

laboratory. In addition, only one device needs to be calibrated and tracking of system error is easier. Such systems are economical only for relatively large laboratories, however, and at present cannot easily be adapted for centralized automated test control.

Device-Specific Systems

A device-specific data acquisition system monitors and logs data for a single laboratory device with a limited number of measurement devices. There is only one system user and one task running at a time. The same terminal boxes and shielding scheme used for the centralized system can be used for the device-specific system. The system's data acquisition module (purchased separately) may be inside the system's platform computer or it may be an external unit.

The device-specific system provides an affordable means for the small-scale laboratory to bring computer-based data acquisition on-line. In most cases, computer speed is not an issue, and good use can be made of older computers that might otherwise be obsolete. A major advantage of the device-specific approach is the simplicity of the required software. It can usually be written in-house and can easily be adapted to different applications. When the system is to be part of computer-automated equipment, control based on measurement instrumentation feedback is straightforward since the system is controlling only a single test process. In fact, the device-specific approach is the only one of the two approaches (centralized and device specific) that is easily adaptable for automated testing equipment.

Despite these advantages, the device-specific approach has two notable drawbacks: data accountability is reduced and each data acquisition unit must be calibrated. The effects of these drawbacks must be evaluated as part of the automated system's error analysis, as discussed in the following section.

EVALUATION OF THE DEVICE-SPECIFIC SYSTEM

Table 2 lists the sources of error, in order of relative magnitude, that should be evaluated before using a device-specific data acquisition system. Also listed are corresponding reasons for the error and check tests that can be performed to identify and quantify it. If the system is to be used for commercial testing, it should periodically be calibrated by a certified technician. The following paragraphs provide additional details on the items in Table 2.

Noise

Electronic noise is one reason for a loss of precision in the converted measurement signal, that is, the digital version of the true analog signal (the other reason is robustness, which is discussed in the next paragraph). Connection wires in the system act as antennas that pick up external electromagnetic interference, which can add high-frequency voltage to the analog signal being converted. This effect can be minimized by employing proper system shielding and grounding techniques [described by Sheahan et al. (*1*)] and by using an integrating A/D converter.

Robustness

The data acquisition system can be sensitive to the type of transducer being monitored and the circuit being used. The sensitivity of the system's precision to these influences is known as the robustness; the more robust the system, the less sensitive it is to these effects. For example, the system's precision may drop when a linear voltage displacement transducer (LVDT) is connected to it; the system may not be sufficiently robust to fully resist the effects of alternating current in the LVDT.

TABLE 2 Error Evaluation Summary for Device-Specific Data Acquisition Systems

ERROR SOURCE	CAUSES	CHECK TEST
Noise	• Electromagnetic interference • Improper grounding	• Shunt circuit and monitor output
Robustness	• Sensitivity of system to type of transducer and wiring	• Verify system performance with each transducer type
Voltage Offset	• Variations in analog circuits for different transducers	• Adjust device while monitoring stable signal
Imprecise Amplification	• Variations in semiconductors • Circuit losses • Improperly set devices	• Check for increasing difference between measured and input signal as input increases
Drift	• Ambient temperature changes • Circuit temperature changes • Poor quality circuit	• Converted signal vs. temperature curve • Usually random occurrence
Computer Clock Inaccuracy	• Poor quality computer clock • Circuit delays	• Verify with lab timer

Voltage Offset (Bias)

Voltage offset is the difference between the input signal and the converted, digital representation of that signal. This offset remains constant over the operating range of the transducer and is due to variations in the analog circuit that carries the transducer signal to the A/D module. Most systems do not have the advanced features necessary to automatically eliminate the bias. Thus, each time that a new transducer is connected to a channel, it may be necessary to eliminate the offset manually. Sheahan and Germaine (2) describe an integrating A/D conversion board in which zero offsets are corrected manually by using onboard trimming potentiometers.

Imprecise Amplification

Variations in circuits, voltage losses in the analog path, and improperly set amplification devices can cause signal amplification errors. The result is increasing differences between analog input and converted signal values over the transducer's operating range. Proper system calibration and diagnostic checks can prevent these types of errors.

Drift

Drift is the difference between analog input and converted signal values because of temperature changes, heating of the circuit, and poor-quality circuit components or circuit design. The first two causes are grouped under the category of thermal drift. Thermal drift is somewhat systematic in nature, but it is transient and cannot be corrected for; it is better avoided through the use of laboratory temperature control and good circuit design and hardware. Other types of drift are random and also cannot be corrected for.

Timer Inaccuracy

Most systems must rely on the host computer clock for determining when readings are taken and for computing the elapsed time that should be marked in the data file. These computer clocks can be inaccurate, and their accuracies should be verified against a reliable reference.

SERVO CONTROL ALGORITHMS

As previously noted, in many computer-automated equipment applications, the control software needs to be written in-house. Creating the structure and shell for this software is tedious, but it is not difficult. However, the control software's real essence, the feedback or servo control algorithm, requires an understanding of the system dynamics and knowledge of available options. As Figure 1 shows, the steps in the control algorithm are collection of

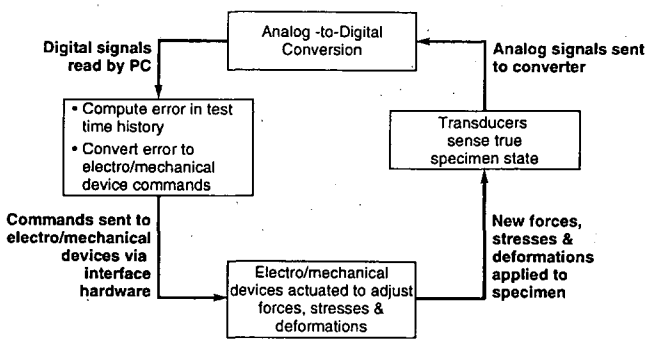

FIGURE 1 Control feedback loop used in computer-automated testing.

a set of measurements, comparison of the existing state of the test specimen with a preprogrammed state-versus-time schedule, determination of what actions are necessary to close the gap between actual and scheduled states, and sending out the commands to implement the action. Like any well-organized computer program, a successful servo control algorithm has many subroutines driven from a main program sequence.

Instrumentation Scan and Calculation of Current State

The system must quickly scan all instrumentation channels needed for servo control to capture the state of the specimen at a point in time. There should not be a large time gap between measurements that will be used in the same control cycle or stored together as simultaneous readings (e.g., specimen deformation and applied load). To convert a particular analog input signal, most device-specific data acquisition systems require either a prewritten subprogram to be called from within the main control program or some set of command lines to be executed in the main program. To prevent a false reading (i.e., one due to system error) from being used as the basis for feedback control, two sets of readings can be taken and compared. If the two sets of readings have a difference exceeding some tolerance level, another set of readings is taken until the tolerance criterion is met. Further error trapping may be necessary when corrective action is implemented.

To expedite the measurement instrumentation scan, the excitation voltage needs to be read only every 20 to 50 scans, provided that a high-quality power supply is being used. Scanning frequency can be reduced for other measurements that are not expected to vary at a high rate.

A check needs to be made at the end of every scan to see if the current set of readings is to be stored. If so, the current voltage readings should be written to disk immediately as raw data, without manipulation. This will ease error tracking.

At this point in the measurement scan section, transducer voltage readings should be converted into the engineering units required for feedback. Current readings can be displayed on-screen; however, such displays should be minimized because of the relatively long time needed to access output devices.

Determining Corrective Actions

The control algorithm is intended to quickly and smoothly close the gap between the present state of the test process and that scheduled in the programmed time history. Like numerical analysis, control algorithms rely on disequilibrium to function, with the goal being to minimize that disequilibrium. The error between the actual and target states is used to determine the mechanical process necessary at the test device to close the gap and achieve equilibrium. The mechanical process is actuated by output signals from the computer to an electromechanical interface.

There are three components of control: proportional control relies on the current difference between the actual and the target states, integration uses the sum of differences between the two states during previous control cycles, and derivative depends on the rate of change of the difference during previous cycles. The choice of which components to use in the control algorithm depends on the system's response to adjustments in pressure- and load-controlling devices like flow pumps, regulating valves, and mechanical load frames and on the soil's response to stress and deformation changes. Two common types of control algorithms, proportional and proportional plus integral plus derivative (PID), will be discussed. Either type of control algorithm usually requires trial-and-error selection of algorithm parameters, although some manufacturers of controlling devices include built-in control algorithms or automatic parameter determinations.

Proportional Control

The proportional control algorithm assumes that the error at any time, $e(t)$, between the present and targeted test process states is proportional to some "stiffness" of the control system. The output from the computer at time t, $u(t)$, used to correct the error is directly related to $e(t)$. This output may be a signal to control a direct current (dc) servomotor or some number of motor steps of a stepper motor. The governing equation for linear proportional control is

$$u(t) = K_p e(t) \tag{1}$$

where K_p is the proportional control constant or gain. This implies that the ratio of the change in pressure or load to some amount of pump, valve, or load frame movement is a constant. The actual stiffness or gain of the system must match that estimated in the control algorithm (the virtual stiffness). Sheahan and Germaine (*2*) illustrated the effects of mismatching the actual and virtual stiffness. When the virtual stiffness is too high (system is less stiff than estimated), the system behaves sluggishly; when the virtual stiffness is too low, the system responds more than estimated and can become unstable. The authors' experience with proportional control is with flow pumps and worm-gear mechanisms used in quasistatic tests that are driven by stepper motors or dc servomotors. Such tests permit sluggish control behavior without the loss of test control quality.

PID Control

The PID control algorithm is fundamentally different from a proportional control algorithm because it makes use of the system's recent performance history. For many applications, PID algorithms can achieve both a high degree of steady-state accuracy and a reasonable transient response (*3*). Two terms are added to the proportional control equation (Equation 1) to incorporate system performance history (or memory): an integral term and a derivative term, leading to the following equation:

$$u(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \left[\frac{de(t)}{dt} \right] \tag{2}$$

where

$u(t)$ = process output (i.e., control signal or number of motor steps sent to correct the error);
$e(t)$ = error term, which is the difference between the target value of the control feedback measurement, $r(t)$, and its current value, $y(t)$; and
K_p, K_i, K_d = proportional, integral, and derivative gain factors, respectively.

Equation 2 is a continuous analog controller that is converted to a digital controller (in which readings are taken at discrete times) by a difference equation. For digital control applications, this type of equation is solved by using a z-transformation, which is similar in principle to the solution of differential equations by using the Laplace transform. For a PID controller, each computation of the digital form of Equation 2 typically incorporates the current and the two most recent values of $r(t)$ and $y(t)$ and the two most recent values of the process output, $u(t)$. The PID algorithm gain factors are normally evaluated by a trial-and-error procedure that balances the controller's response time with its stability. A PID control algorithm should also include program statements specifying controller output limits. These limits, which account for spurious values computed by the controller because of noise, electrical surges, and so on, are used whenever the corresponding algorithm outputs exceed the limits. DeGroot et al. (*4*) provide other details on PID controller implementation for geotechnical laboratory testing.

Sending Commands To Implement Action

Any number of methods are available for actuating pumps, valves, or mechanical load frames. Two popular types are stepper motors, which rotate in small, discrete increments, and dc servomotors, which rotate smoothly at a velocity proportional to an input voltage. Both types of motors are available with sophisticated control hardware and preprogrammed software routines; many motors are more rudimentary and require that relatively simple software be written for their use.

Additional algorithms for error trapping can occur during this phase. Limits can be placed on the amount of corrective action to be carried out by the motors to reduce the impact of an erroneous measurement scan.

OTHER SOFTWARE REQUIREMENTS

In addition to the control algorithm and related software, the use of device-specific data acquisition for automated testing requires other software considerations.

Systems can include a provision for restarting the test after the software has crashed or a power outage has occurred. At the least, the system should be designed so that motors will not be left running uncontrolled after a crash has occurred. If possible, physical cutoff switches should be added to prevent damage to the system.

With each instrumentation scan, the program should check whether that set of readings should be saved; if not, they are used for that control cycle and effectively discarded. The interval for data logging can be based on the elapsed time between readings or on tests of data significance. In the simplest time-based scheme, the user enters a data logging increment, Δt_{log}, and an initial set of readings is stored at time t_{store}. After each instrumentation scan at time t, the program compares $t - t_{store}$ to Δt_{log}. If $t - t_{store} \geq \Delta t_{log}$, then the current measurements are immediately written to disk and t_{store} is reset to the current time t. Note that readings should not be saved in a volatile memory buffer and then written to disk later on; writing to disk at the time of the readings prevents inadvertent data loss. An interrupt needs to be incorporated in the program to change the logging increment, Δt_{log}. Data logging can also be programmed to occur according to more specialized time sequences, for example, schedules based on linear or logarithmic functions of time.

Logging increments based on tests of data significance are more sophisticated and more specific to a particular test type. A check is made to see how much a particular measured parameter has changed since the last stored value. When the change meets some significance level, a new reading is stored.

Another feature that can be incorporated is selective logging. At any time during the test, the user can tell the computer to take a reading at that point. Pressing a function key on the compute triggers a flag in the control loop, which causes a set of readings to be taken and written to disk; the flag is then reset.

EXAMPLES OF AUTOMATED LABORATORY TESTING

Direct Simple Shear Testing

The Geonor direct simple shear (DSS) devices (*5*) at the Massachusetts Institute of Technology (MIT) and the University of Massachusetts at Amherst (UMass-Amherst) use a 35-cm^2 circular specimen trimmed into a wire-reinforced rubber membrane to an approximate height of 2.3 cm. The membrane laterally confines the specimen, providing one-dimensional [coefficient of earth pressure at rest (K_0)] consolidation conditions with dead weights applied to a lever arm system. The device and the membrane lead to an applied simple shear strain deformation mode during drained or undrained shear. The shearing phase of the test is typically conducted at a constant rate of strain. Undrained soil behavior is studied with this device by conducting drained, constant-volume tests. Since the membrane prevents lateral soil deformation, constant volume conditions can be achieved when a constant specimen height is maintained; this is done by varying the applied vertical force (and hence stress) during shear. The changes in vertical stress required to keep the height constant are assumed to be equal to the pore pressure that would develop if the test was truly undrained (i.e., sealed) with pore pressure measurement taken. Dyvik et al. (*6*) showed the validity of this assumption for normally consolidated clay.

Three generations of closed-loop feedback servo control systems have been used at MIT for automated DSS testing with the Geonor device. The first system consists of a dc analog motor, an LVDT (or a proximity sensor), and a control box (Figure 2). The

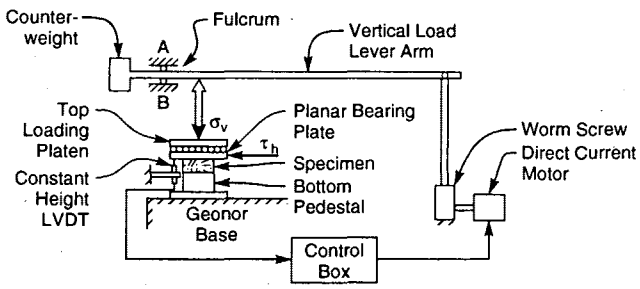

FIGURE 2 Constant-height servo control system for Geonor DSS (*4*).

LVDT monitors movements in the top loading platen, which is connected to the specimen top cap. The control box sends the difference (i.e., voltage error) between the LVDT reading and a reference voltage through an amplifier to drive the worm-gear motor at a rate proportional to the error. The worm-gear mechanism moves a lever arm, which applies the vertical force to the specimen. This closed-loop analog feedback system cannot correct for the apparatus compressibility during shear. Data readings during the test's shearing phase are taken by a centralized data acquisition system.

The second-generation system, which was first described by Malek (*7*), is similar to the system shown in Figure 2. The consolidation phase is still performed by using manual, incremental loadings. However, the control box was replaced with a computer, an A/D card, and a digital-to-analog (D/A) card, which are used to read the constant-height LVDT voltage and send command signals to the dc motor driver during undrained shear. The advantages of this system are that the control algorithm, which is software rather than hardware driven (as in the first-generation system), can correct for apparatus compliance during shear and data readings can be logged by the device-specific system, eliminating the need for a centralized data acquisition system.

In these two systems, only the shear phase of the test is automated, and the shear phase of the test consists of a proportional control algorithm for servo control. In the third-generation system, a PID control algorithm was used to automate both the consolidation and the undrained shear phases of the DSS test. The consolidation phase was converted to a constant rate of strain (CRS) load application. The resulting system provides more precise and detailed data during consolidation and dramatically reduces the elapsed time and the amount of labor required to perform a test. The PID algorithm also overcomes an inherent problem with the use of proportional control in the DSS.

The Geonor DSS uses a lever arm with a double fulcrum system to transfer the vertical load to a specimen (Figure 2). For forces of less than 525 N, the lever arm uses only a lower fulcrum for support; for forces of greater than 525 N, it also uses an upper fulcrum. When the vertical force approaches 525 N, the lever arm displaces on the two fulcrums without causing any change in force; this transition point is known as the dead zone. For normal incremental loadings this does not present any particular difficulties because the system is force controlled. It is problematic when conducting CRS consolidation with a proportional control algorithm because the system is inherently displacement controlled. When approaching the dead zone during a test, Walbaum (*8*) found it necessary to interrupt the computer program and manually control the servomotor until the dead zone had been passed.

By switching to a PID control algorithm, Ortega (*9*) dramatically reduced the dead zone control problem and obtained excellent results. Figure 3 shows a typical stress-strain curve obtained during CRS consolidation in the Geonor DSS on resedimented Boston blue clay (BBC). Figure 3 reveals only a slight discontinuity at approximately 150 kPa (i.e., 525 N acting on a 35-cm^2 specimen), which corresponds to the dead zone. Except during the early stages of the test, the cumulative strain rate achieved was close to the target value of 1 percent/hr during consolidation; however, the incremental strain rate was not as stable. Within approximately 40 min the PID control algorithm maintained a constant cumulative rate of strain within ±0.01 percent of the target value.

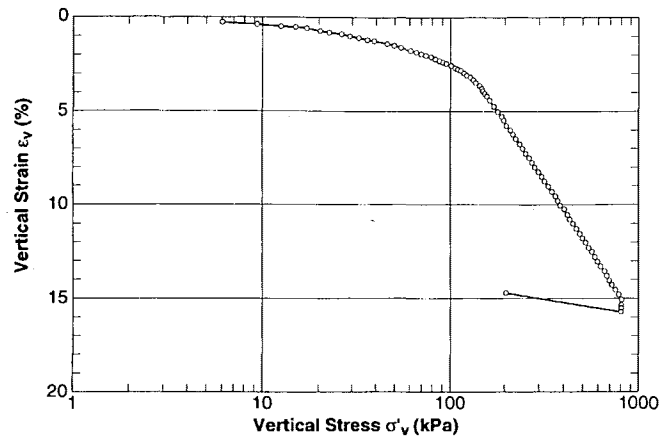

FIGURE 3 Compression curve from CRS consolidation in DSS apparatus (*9*).

Computer-Automated Triaxial Apparatus

A computer-automated triaxial apparatus was developed at MIT by the first author to perform an extensive series of K_0 consolidated-undrained shear tests (*10*). Its capabilities have since been expanded at Northeastern University (NU) to perform K_0 consolidated-drained linear stress path tests. In addition, the improved system at NU performs its own device-specific data acquisition and logging, rather than relying on a centralized system, as it did at MIT. The system consists of the triaxial cell, a load frame, two pressure-volume controllers [PVCs, which are based on the flow pump design (*11*)], electromechanical interface equipment, instrumentation, and the computer with the data acquisition card (Figure 4). The load frame and PVCs are actuated by using stepper motors; software commands are used to move each of the three motors a specific number of steps during each feedback control cycle. Only proportional control (Equation 1) has been used in this apparatus, and this has been sufficient to achieve the desired control quality in the quasistatic

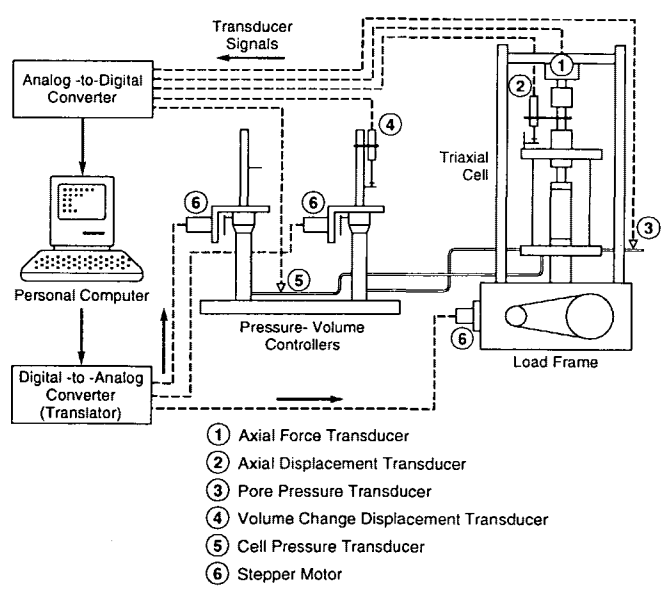

FIGURE 4 Computer-automated triaxial system.

tests performed with the apparatus. Although all measurement devices are read so that readings can be stored, the measurements used for feedback control depend on the test type.

Four types of control have been required in the testing programs that have used the automated triaxial cell.

Pressure Control

During virtually all test phases, hydraulic pressures (cell and back pressures) must be controlled. The computer takes readings from the cell and back pressure transducers (and their excitation voltages) and converts these readings into engineering units. In the software, the errors are computed between measured pressures and their respective target values. Each PVC (cell and back pressure) has its own predetermined gain value that converts the error for that pressure into the number of motor steps that must be actuated at each PVC to correct the error. Thus, Equation 1 becomes

$$\begin{aligned} \text{CELLSTEPS} &= \text{CELLGAIN*CELLERROR} \\ \text{BACKSTEPS} &= \text{BACKGAIN*BACKERROR} \end{aligned} \tag{3}$$

where CELLGAIN and BACKGAIN are the respective gain values in the cell pressure and back pressure PVCs, and CELLERROR and BACKERROR are the respective errors between the measured and targeted pressures.

Because the tests are quasistatic, gain values can be set intentionally low, causing the system to be slightly sluggish and requiring two to three control cycles to reach targeted values.

In both long-term and short-term tests, the cell pressure remains constant to ±0.3 to 0.4 kPa [standard deviation (*SD*)]. This type of precise control has permitted successful implementation of K_0 consolidated-drained linear stress path testing at NU.

Axial Load Control

For tests requiring axial stress control, the system must be able to control the axial force applied to the specimen accurately. The computer obtains the force transducer reading and computes the net axial load on the specimen (after applying corrections). After determining the error between this and the targeted net axial load, the number of steps is computed for the load frame motor to move by using an expression similar to that given in Equation 3. Sheahan and Germaine (*2*) showed the results from K_0 consolidated-undrained creep tests in which specified shear stress levels (q), where $q = \frac{1}{2}(\sigma_1 - \sigma_3)$ (σ_1 and σ_3 are major and minor principal stresses, respectively), were maintained to ±0.1 to 0.3 kPa (*SD*). The ability of the system to accurately control axial load and cell and back pressures allows high-quality stress-controlled tests to be performed.

Axial Strain Rate Control

Since the automated triaxial apparatus was originally used to study strain rate effects on soil behavior, the system needs to apply a variety of strain rates, each remaining constant during a test. The system's strain rate control is open loop, that is, it does not rely on feedback measurements. Calibration of the stepper motor-actuated load frame provided a consistent, linear relation between motor steps and axial deformation of the specimen. This calibration is used with the computer's clock to determine the number of load frame motor steps needed per cycle for a particular strain rate. Figure 5(*a*) and (*b*) shows how the incremental axial strain rate, $\Delta\epsilon_a/\Delta t$, varies during tests performed at different specified strain rates. The instability early in the various tests results from two different phenomena. In the fast-rate tests [Figure 5(*a*)] the instability is due to initial loading system compressibility; in the slow tests it is due to the algorithm used, which produces a more accurate strain rate with time.

Axial Strain Control

In relaxation tests, it is necessary to control the axial strain level being imposed on the specimen. This was perhaps one of the easiest control problems to solve for this apparatus since the number of load frame motor steps is directly proportional to the error in axial deformation (obtained from the same calibration used for

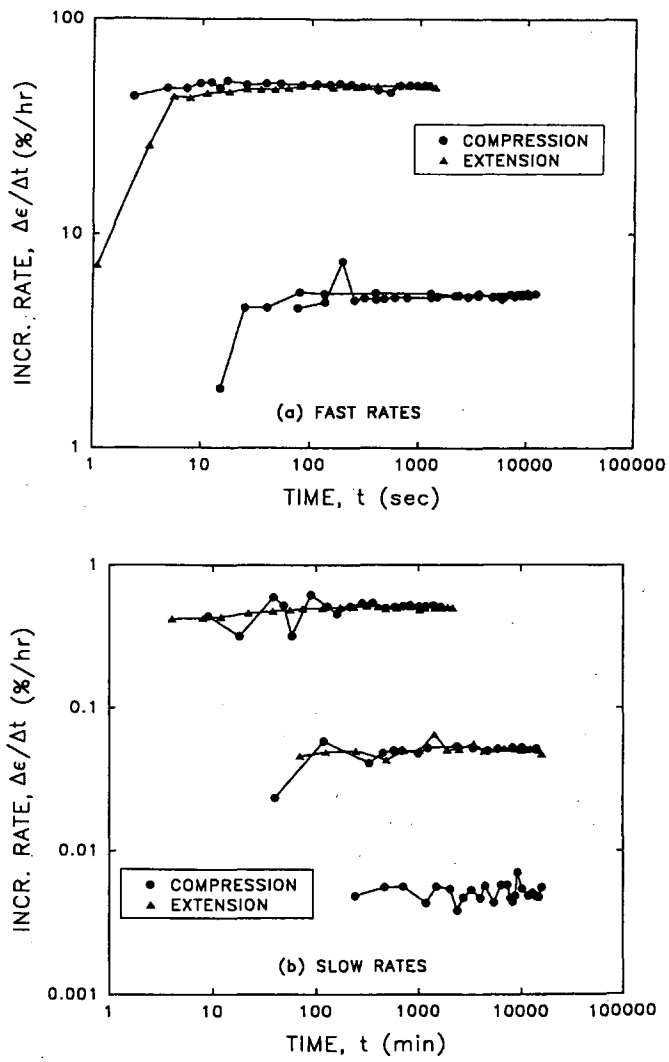

FIGURE 5 Incremental strain rate stability with time during conventional K_0 consolidated-undrained tests using the computer-automated triaxial system: (*a*) fast rates; (*b*) slow rates (*2*).

axial strain rate control). The results presented by Sheahan and Germaine (*2*) from two relaxation phases of a test showed that strain levels can be maintained to ±0.005 percent axial strain.

Multidirectional Direct Simple Shear Apparatus

DeGroot et al. (*12*) describe the multidirectional direct simple shear (MDSS) apparatus that was developed to experimentally simulate, at the element level, the stress conditions within the foundation soil of an offshore Arctic gravity structure. The MDSS uses a specimen of the same size and the Geonor wire-reinforced rubber membrane used by MIT and UMass-Amherst in the Geonor DSS apparatus. The MDSS is capable of applying a vertical stress and two independent horizontal shear stresses to a circular soil specimen. The vertical stress (σ_v) and first horizontal shear stress (τ_1) represent the stresses owing to the initial set down of an Arctic structure and are applied by using pneumatic cylinders. The second horizontal shear stress (τ_2) represents the horizontal ice loading on the structure and is applied by a variable-speed gear drive system at a constant rate of strain. The MDSS tests soil specimens under simple shear strain conditions and is capable of applying τ_1 at an angle relative to τ_2 ranging from 0 to 150 degrees. For a conventional K_0 consolidated-undrained test, the specimen is simply consolidated under the vertical stress and is then sheared undrained by application of the second shear.

Data acquisition and servo control in the MDSS is performed by using a device-specific system based on an International Business Machines–compatible PC and software written in BASIC. Pneumatic cylinders, controlled by voltage outputs to electro-pneumatic (E/P) regulators, apply σ_v and τ_1 to the specimen. The E/P regulator maintains air pressure proportional to an electrical signal generated by a D/A card onboard the computer. Application of σ_v and τ_1 to the specimen is automated by using a stress-controlled closed-loop system with a proportional control algorithm. Estimates of the target σ_v and τ_1 are applied to the specimen. The computer then collects consolidation data readings (i.e., values of the vertical and shear strains) and also monitors σ_v and τ_1 via the vertical load cell and a pressure transducer, respectively. Errors are corrected by using a proportional control algorithm that adjusts the signals being sent to the regulators. This algorithm maintains the stresses acting on the specimen to within 1 kPa of the required level (*4*).

As in the Geonor DSS, undrained shear in the MDSS is achieved by maintaining a constant specimen height during shear. A PID control algorithm monitors the specimen height with an LVDT; a specimen height change causes the computer to actuate the pressure regulator that controls σ_v. Proportional control maintained the height of the specimen during constant-volume shear, but not without significant instability in σ_v. Figure 6 shows the variation in σ_v (normalized by the preshear consolidation stress σ'_{vc}) versus shear strain during shear in two tests on the same soil specimen. In the first test (filled symbols), proportional control was used and the oscillation about the mean is apparent. The results of the second test (open symbols) show the improvement in control quality when the PID control algorithm was used.

Figure 7 plots the constant-height LVDT signal error versus shear strain during a typical conventional K_0 undrained test run in the MDSS. The signal error, $e(t)$, is computed as the difference between the feedback signal, $y(t)$, and the reference value, $r(t)$,

$$e(t) = y(t) - r(t) \tag{4}$$

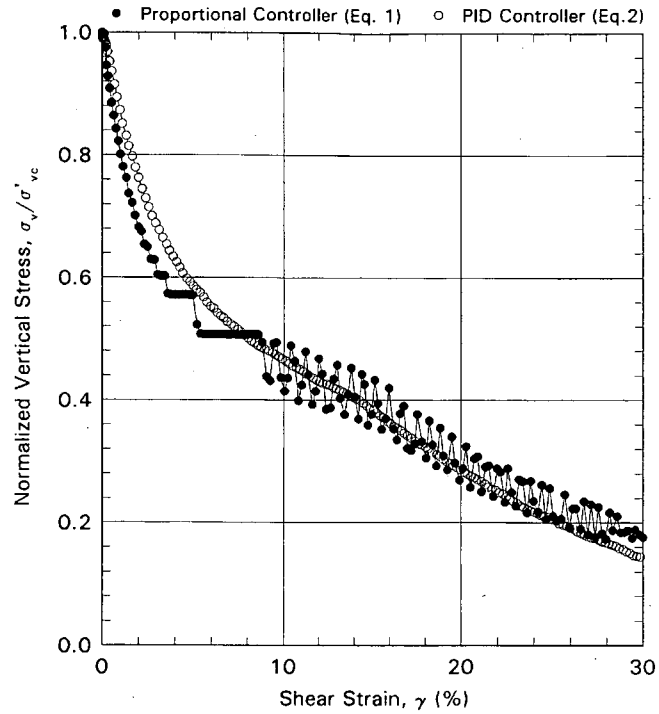

FIGURE 6 Normalized vertical stress (σ_v/σ'_{vc}) versus shear strain from undrained DSS tests on normally consolidated BBC using proportional and PID controller (*4*).

If $e(t)$ is positive, then the specimen is being compressed; the reverse holds if $e(t)$ is negative. Figure 7 shows that the maximum error in specimen height during shear was less than 0.7 μm, or 0.004 percent of the specimen height. The average error during a test was typically much less, ±0.1 μm, or ±0.0005 percent of the specimen height. The maximum deviation of the constant-height LVDT's position from its target value always occurs at the start

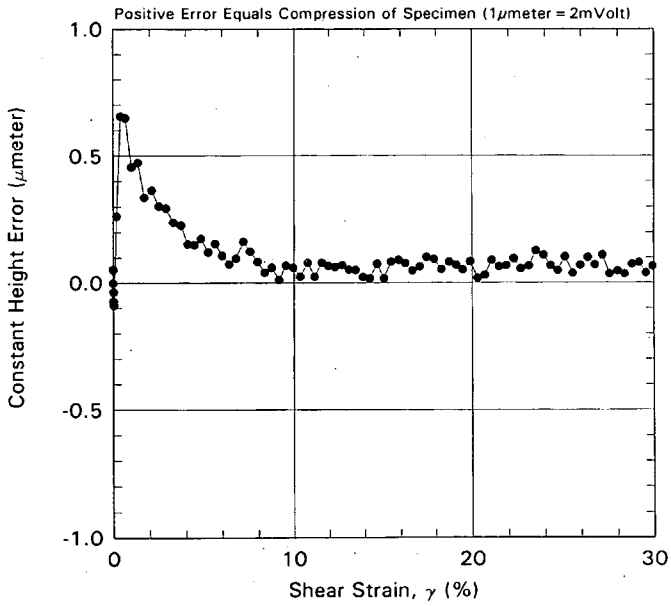

FIGURE 7 Constant-height LVDT error during undrained DSS test on normally consolidated BBC specimen using PID controller (*4*).

of the test's undrained shear phase. When undrained shear is initiated, the system must quickly adjust the vertical stress because of the high rate of pore pressure change or else lag behind in its response. As pore pressure changes become more gradual, the control system can easily keep up. A faster control cycle would alleviate the early control problems.

SUMMARY AND CONCLUSIONS

The use of device-specific data acquisition systems for computer-automated geotechnical laboratory testing was described. Details on evaluating errors in the device-specific system were given. Control algorithms were explained, including detailed descriptions of two specific algorithms, proportional and PID. Some other software requirements for automated control were given. Examples of automated laboratory testing were presented to show the control quality achieved by using various hardware and control algorithms.

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