Microcomputer-based laboratory apparatus for soil testing

Un appareillage d'essais de sol en laboratoire basé sur le micro-ordinateur

C.K.SHEN, Department of Civil Engineering, University of California, Davis, California, USA
X.S.LI, Department of Civil Engineering, University of California, Davis, California, USA
C.K.CHAN, Department of Civil Engineering, University of California, Berkeley, California, USA
Z.WANG, Department of Civil Engineering, University of California, Davis, California, USA

SYNOPSIS: This paper describes the 3 parts of a laboratory testing facility, namely: the testing apparatus, the load/control, and the data acquisition systems. The use of a microcomputer-based laboratory testing system can greatly improve the operation, it is capable of performing decision making, real time sampling, signal generation, control, etc. Also described in the paper is the use of the basic microcomputer-controlled triaxial system to perform on-line seismic response analysis of soil deposits. Brief illustrations of various applications are given and their respective advantages are discussed.

1 INTRODUCTION

Soil, as a construction material and/or the support for either deep and shallow foundations, requires the careful study of its mechanical and hydraulic properties. Often, the behavior of soil can best be learned through laboratory testing. Generally speaking, a complete testing facility consists of three major parts. The testing apparatus such as the triaxial cell is one of these parts. The other two parts are the load/control and the data acquisition systems. When electrical sensors are used in data acquisition, simple operations of amplification, summing, filtering etc. are performed on a limited basis. A microcomputer-based digital instrumentation system, on the other hand, is capable of performing decision making, real time sampling and processing, complicated signal generation, control, nonlinear operation and more.

Fig. 1a shows the schematic diagram of a data acquisition system. Signals picked up by the signal conditioner can be treated and converted for further processing (normally as voltage output). These signals are channeled through a multiplexer to selected channels at a regulated sampling rate. Often the gains of the channels are adjusted while a test is in progress, therefore a programmable amplifer/attenuator is needed to adjust the level of output. An analog to digital converter (ADC) is used to digitize the adjusted analog signals to be stored and/or processed by the computer. In essence, this system samples a number of physical quantities (X_i) which are conditioned, processed and finally converted to numerical numbers (Y_i) such that $Y_i = f(X_i)$. The functional relationship between X_i and Y_i is built into the electrical circuit boards in accordance with the design of the system, and is controlled by computer programming.

The schematic diagram of a load/control system is shown in Fig. 1b. It can be adapted to control specified testing processes, such as undrained testing with pore water pressure measurements. The operation of this system follows essentially a reversed order of the data acquisition system. Digital signals, entering the system via control of the computer software, are converted to analog signals in order to control operations such as the opening of a valve. The buffer in the system can be a power amplifier or a voltage-current converter to modify or condition the analog signals prior to being received by the various actuators. Again the input (D_i) and the output (P_i) of the system follow a certain functional relationship $P_i = f(D_i)$ which is based upon the circuit design and the operation requirements of a given system. This relationship can be easily modified by programming while testing is in progress.

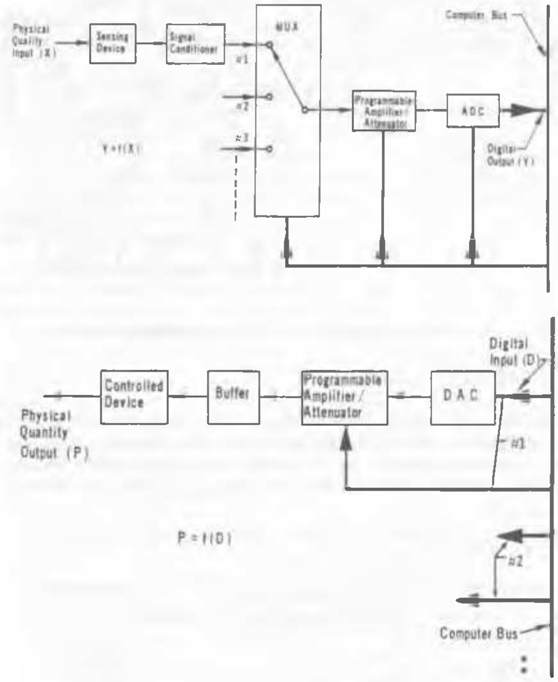

Figure 1. Schematic diagrams (a) data acquisition, (b) load/control

The use of computer-based control and data acquisition systems has the advantage of allowing closed-loop feedback to control certain governing parameters such as pressure, deformation, etc. in order to ensure accuracy and quality of laboratory testing. Since feedback loops can be simulated by mathematical models and incorporated into the software in most cases, no additional circuit design is needed. A considerable amount of effort has been devoted in recent years to upgrading laboratory testing techniques by integrating this modern microcomputer-controlled electronic technology into the load/control and the data acquisition systems. This paper summarizes some of the developments and applications in this area.

2 THE AUTOMATED TRIAXIAL SYSTEM

The triaxial testing apparatus is the most widely used testing device in geotechnical laboratories; the device, practical in design and versatile in control, is capable of performing tests with controlled stress or strain rate of loading, and for different types of prescribed stress paths under both drained and undrained conditions. In the automated triaxial testing system (Li, Chan and Shen, 1988), the computer programmed electronic signal for frequency and magnitude of loading is applied to an electro-pneumatic transducer which then controls pneumatic amplifiers for the application of loads. All modes of loading are controlled by closed-loop feedback schemes. The system is designed for performing both static and dynamic testing. A schematic diagram of the automated system is shown in Fig. 2. A brief description of some of the important elements of the system is given below.

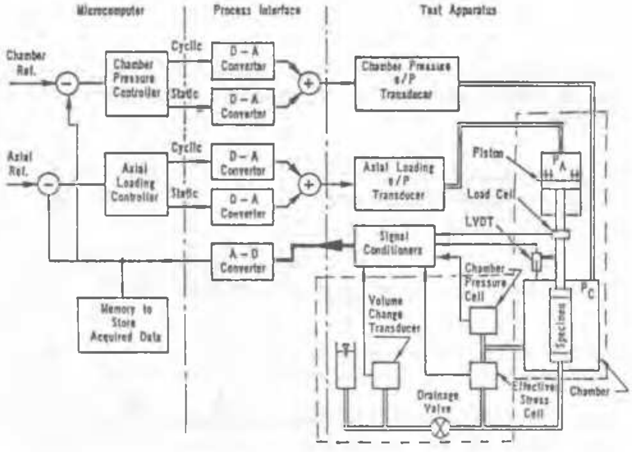

Figure 2. Schematic diagram of the automated system

2.1 Controller

The system uses two feedback control loops: one for the axial actuator and the other for the lateral actuator. Under software control, the two loops can work individually or synchronously. As an example, Fig. 3 shows the block diagram of the axial feedback loop. It has five major parts: computer, process interface, pneumatic loader, test apparatus with soil specimen, and sensors. The computer plays the role of loop control via software so that the loop behavior can be easily modified by changes in the program. From Fig. 3 it can be seen that four control parameters are needed to specify the operation of the loop. First, the Loop Switch turns on or off the feedback path. Second, the Loop Selector selects the mode of control (either load or displacement). Third, the Reference specifies the expected value of the selected mode; and fourth, the Optimizer adjusts the dynamic range of the ADC and correspondingly the coefficients of the discrete proportional-integral-differential (PID) controller. Proper selection of parameters for each control loop in testing provides considerable flexibility. For instance, an initially stress-controlled shear loading test can be easily converted to a strain-controlled test at a later stage.

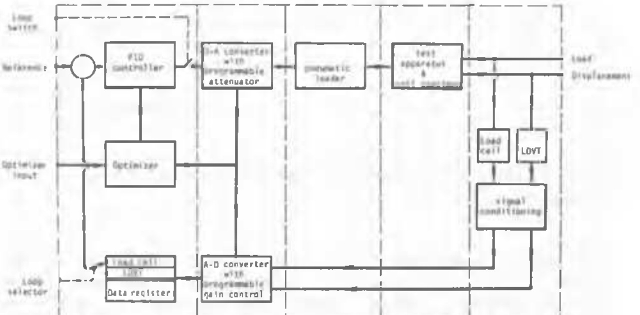

Figure 3. Block diagram of the axial feedback loop

2.2 Transducer and signal conditioner

A total of five sensors are used in the system: the 3000 lb. (13.3 kN) load cell is sized to the largest loading piston for the anticipated static load test. To measure the vertical displacement, a ± 1.5 in. (± 38 mm) LVDT with its small case size is selected to minimize the inertia loading on the sample, and to allow mounting close to the center of the specimen. Three pressure transducers are used to detect the chamber pressure, the effective pressure, and the volume change; the differential pressure transducer is a wet to wet type. The volume change device uses three different sizes of tubes with a valve mani-fold to select the range required for the particular test condition calculated in the software. The height of the water column under back pressure is measured by a sensitive differential pressure transducer.

The signal conditioning unit accommodates five channels for five sensors: the load cell, the three pressure transducers, and the LVDT. The output signals of these sensors are conditioned and then received by the process interface unit.

2.3 Interfacing unit

The process interface, as a peripheral device, forms the communication link between the computer and the loading/sensor system. It is a compact and powerful unit which can be used to interface with many different types of laboratory loading and measuring systems for material testing. The unit consists of a 16-channel, 12 bit, programmable-gain, high speed analog to digital converter (ADC), 8 channels of 12 bit, high speed digital to analog converters (DAC), and a 24-line digital input/output port. The DAC channels can also be configured as gain controllers to suit specific purposes of a designed system.

2.4 Software

The software is written in menu-form and is user friendly. All operation steps involved in tests are displayed on screen. The software written for this system includes back pressure saturation (B-value check); consolidation (isotropic, anisotropic, and K_0-confined state); monotonic loading (stress, strain, and stress/strain control; drained and undrained); arbitrary stress path loading; cyclic loading (up to 1 hz, stress or strain controlled); creep and relaxation; and a number of special loading programs.

This automated triaxial testing system has been used in laboratory research for the past 5 years. Recently, an extensive testing program was carried out on Leighton Buzzard 120/200 sand using this system (Yang, 1987). The Leighton Buzzard sand is a relatively uniform fine sand of sub-angular particles. Fig. 4 shows the undrained compression test results of a very loose and unstable speci-

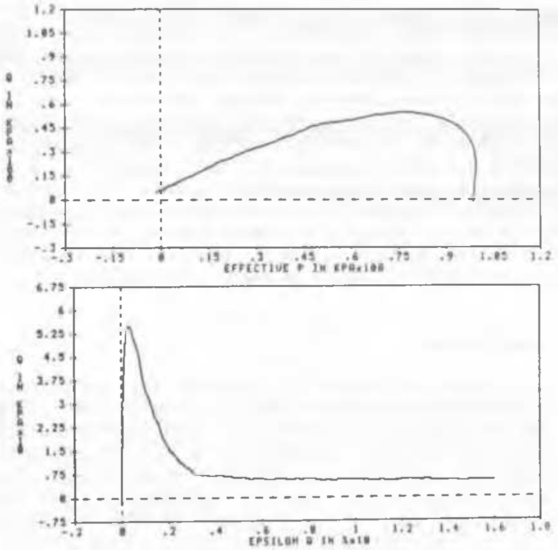

Figure 4. Undrained compression test - strain control D_r = 5%, σ_3 = 100 kpa

men (D_r=5%). Such information is best obtained by strain-controlled testing. The shear stress ($q=\sigma_1-\sigma_3$) - shear strain ($\epsilon_q=2/3(\epsilon_1-\epsilon_3)$) curve shows the peak shear resistance and the sudden drop of resistance (softening) as the unstable assembly of particles collapsed. The effective stress path in the p'-q space indicates a continuous decrease in shear resistance as a result of pore pressure buildup (or a reduction in effective confinement) in the specimen. At zero confinement, a small amount of shear resistance (approximately 7.5 kpa) is retained. It is worthy of note that the peak shear resistance for this specimen is associated with a small shear strain (less than 0.5%). It would be difficult to record the post peak response accurately if no feedback control and electronic data acquisition systems were used. Fig. 5 shows the results for a stress-controlled cyclic shear loading test on a loose specimen. The effective stress paths and the shear stress-shear strain loops are presented. Large shear strains are associated with stress paths approaching the phase transformation line under very small effective confinement. The shear strain buildup is slow and gradual before that. The results illustrated are typical of commonly prescribed triaxial tests. Other less traditional tests, such as the constant stress ratio (q/p') path test or more complex stress path tests can also be performed using the automated system. The following, however, is an example of special applications of the system.

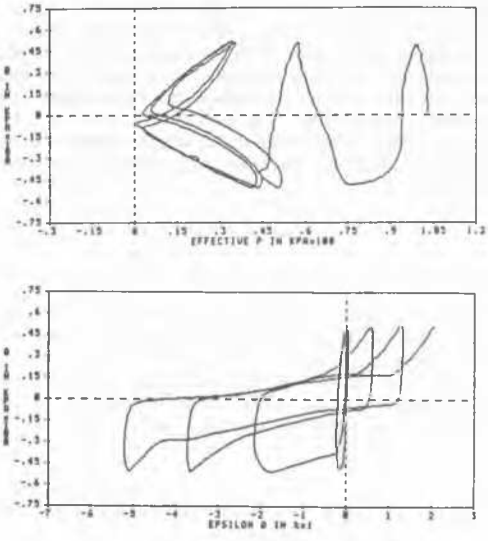

Figure 5. Undrained cyclic shear loading test - stress control D_r = 40%, σ = 100 kpa

3 THE ON-LINE TESTING SYSTEM FOR SEISMIC RESPONSE ANALYSIS OF SOIL DEPOSIT

Currently, for seismic response analyses of soils or soil/structure interaction, the soil behavior is determined in the laboratory under cyclic compressive (uni-amplitude) loadings of stress or strain. A variety of constitutive relationships have been suggested to model the soil behavior. The accuracy of the analysis is to a great extent dependent upon the versatility and reliability of the adopted mathematical model in describing the dynamic soil response.

Recently, both in Japan and in the United States, the use of a computer-controlled, on-line quasi-static test in dynamic structure analysis has been reported where the non-linear restoring forces of the structure elements are determined directly from the quasi-statically measured response. The basic concept of this method is to solve the governing equations of motion by means of a step-by-step numerical integration scheme that incorporates the measured force-deformation response in the numerical analysis; i.e. instead of using an idealized mathematical model of the structure components to describe the linear or non-linear force-deformation relationship (stiffness) of a structure, it uses the direct experimental feedback to determine the material behavior in computation.

Katado, et al. in 1984 adopted this approach to perform a soil response analysis under cyclic loading. In their illustration, the soil deposit was represented by a single-degree-of-freedom system. Unfortunately, a typical soil deposit cannot be simulated in the analysis by a single-degree-of-freedom system. A multi-degree-of-freedom system should therefore be considered if the computer-based on-line testing method is to be of any practical use in geotechnical investigations.

The use of the equipment for a multi-degree-of-freedom system (Wang, Shen, Li and Yang, 1986), is shown schematically in Fig. 6. On the left side is a layered deposit which is subjected to a base motion as shown. In this instance, it is assumed that layer "3" is a potentially troublesome layer and that its response to seismic loading contributes significantly to the overall site response. Instead of assigning the seismic response parameters as normally done in dynamic analysis, the dynamic response of layer "3" is obtained directly from the specimen tested in the automated triaxial testing system shown on the right side in Fig. 6. The seismic response of the specimen is measured and fed into the analysis, thus linking the on-line testing to the computational process. The computer with its associated equipment in the middle

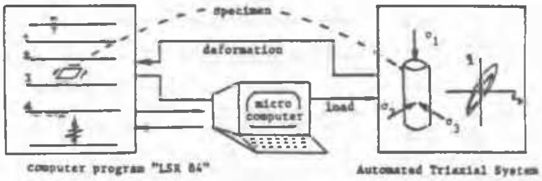

Figure 6. Computer on-line triaxial testing system

controls the entire operation to insure a proper interfacing of the major elements in a hybrid system of testing and computation.

For the on-line testing and analysis, for any time increment Δt the corresponding induced shear stress increment in layer "3" can be calculated from the equations of motion. The calculated stress increment is then taken as the load increment applied to the soil specimen. This is done internally via the software programming and microcomputer control of the testing system. The measured strain and the applied stress in the previous time step are converted to the corresponding tangential shear modulus. Thus the shear wave velocity for that layer can be calculated. Since it is related to both shear strain level and history, the output of the soil specimen in this time step will influence the response of the upper and lower layers in the next time step. The process is carried on step by step; in each step, the tangential shear modulus of the liquefiable layer is determined from the response of the on-line specimen in the preceding load increment. For layers not represented by the specimen, the plastic wave velocities are evaluated from the soil model incorporated in the computer program LSR84 by (Wang et al. 1980).

Assuming frequency independence of the hysteretic behavior of soil, the test is performed in a pseudo-dynamic manner (not in "real time"). The inertia effects and the viscous resistance of the potentially liquefiable layer are calculated by the computer program LSR84. Only the inelastic stress-strain relations are of concern in testing.

To illustrate this system both the on-line testing analysis and the conventional analysis were carried out on a sand deposit 29.5 m thick under undrained conditions. In the analysis, the sand deposit was divided into 4 layers. The on-line specimen was assumed to represent the #3 layer. A sinusoidal rock acceleration having an amplitude of 1.5 m/sec^2 and a period of 1.0 sec was assigned. Fig. 7 shows both the on-line and the conventional analysis results obtained using a visco-elastoplastic soil model. When comparisons are made between the on-line and the conventional approaches, the overall assessment of the results seem to lend credence to the use of the online system in seismic response analyses of soils. While this use of the triaxial testing device may not be the most suitable choice for current practice, the comparison does show that the on-line approach can adequately capture the essential features of the response of a liqueliquefiable soil during a seismic event. The results seem to indicate, however, that a torsional shear testing device which can apply pure shear loading to the specimen would provide a more suitable link with the equations of motion formulation based on shear wave propagation.

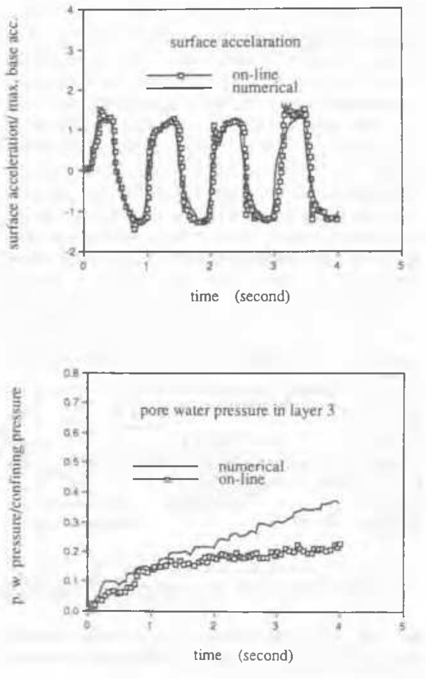

Figure 7. Site response comparison

4 CONCLUSION

A key element in developing automated testing systems for soil in the laboratory is the adoption of microcomputer based instrumentation and control that can facilitate the performing of soil testing at a level substantially superior to and more versatile than conventional practice in terms of accuracy, speed of application, and savings in time and labor. In this paper a general discussion of the major components of such a testing facility is presented. This is then followed by a description of several recently developed pieces of laboratory testing apparatus for soil, including the automated triaxial system to measure the response of soil under both monotonic and cylic loadings in the p-q stress space; and the on-line testing system for seismic response analysis of soil deposits. Some test results are presented for each of the systems described and discussions concerning the efficiency and advantages of the systems are summarized. It is concluded that the adoption of microcomputer-based technology in geotechnial laboratory testing offers significant advantages over the use of conventional test procedures.

REFERENCES

Li, X.S., C.K. Chan, and C.K. Shen, 1988. "An Automated Triaxial System." Advanced Triaxial Testing of Soil and Rock. ASTM, STP 977.

Wang, Z., Q. Han, and G. Zhou, 1980. "Wave Propagation Method of Site Seismic Response by Visco-Elastoplastic Model," Proceedings of the 7th WCEE, Vol. 2.

Wang, Z., C.K. Shen, X.S. Li and H.W. Yang, 1986. "Seismic Response Analysis of Soil Deposits by Computer On-Line Testing System - A Hybrid System." Proceedings on Third U.S. National Conference on Earthquake Engineering. EERI, Charleston, SC.

Yang, H.W. 1986. "Deformation of Fine Sand." M.S. Thesis, Department of Civil Engineering, University of California, Davis.