Data Acquisition System and Computer Control of Calibration Chamber Tests on Sand

M. A. GABR AND R. H. BORDEN

A data acquisition system is used to control the coefficient of earth pressure at rest (K_0) consolidation of dry sand calibration chamber (CC) specimens and subsequently apply lateral compression loading. Instrumentation included inductance coils for measuring vertical and lateral displacements and voltage/pressure transmitters for the application and control of vertical and lateral confining pressures. The objective of the research was to perform Marchetti dilatometer tests on a series of CC specimens subjected to prescribed stress paths. The K_0 consolidation process is simulated by subjecting the specimens to vertical stress increments while restricting the lateral strain. Restriction of the lateral strain is accomplished by applying appropriate lateral pressure increments on the basis of feedback deformation data. In general, during this process, a radial strain magnitude of 0.001 was considered acceptable for the simulation of the K_0 condition. The test instrumentation provided for lateral displacement measurement with adequate accuracy. Noise effects were accounted for by scanning each collecting port 100 times/sec. The 100 readings were then averaged to produce one reading per second. The inductance coils, generally found to be insensitive to soil composition and moisture content, provided adequate means of measuring displacement given the chamber dimensions and constraints related to sample access. Minor leaks were detected when the chamber pressure was increased to a value equal to or greater than 138 kPa (20 psi). Leak compensation is provided by the closed loop-computer control system through the automatic increase in the air supply volume on the basis of the pressure magnitude inside the chamber.

This paper presents the description and performance of a digital/analog-analog/digital (D/A-A/D) computer-controlled data acquisition system that was used for the collection and control of pressure-deformation data during calibration chamber (CC) tests. The calibration chamber system, shown in Figure 1, consists of a fiberglass chamber wall, fiberglass strand-reinforced concrete top and bottom caps, four steel tie rods, a sand-raining device for specimen preparation, a hydraulic oil pump, and a hydraulic cylinder attached to a quadripod frame for the insertion of penetration devices. The chamber cell is made from fiberglass, a nonferrous material, to accommodate the lateral displacement measuring system, which operates by sensing electromagnetic fields. This displacement measuring system requires no holes in the chamber wall, which is desirable from a safety perspective.

The diameter of the chamber cell is 1.07 m (42 in.), with a 12.7-mm (0.5-in) wall thickness. O-rings are used at the top and the bottom caps to ensure air tightness. In comparison with similar facilities described by Laier et al. (*1*), Holden (*2*), Parkin and Lunne (*3*), Bellotti et al. (*4*), Mitchell and Villet (*5*), Sweeney (*6*), and Lima (*7*), the North Carolina State University (NCSU) chamber is slightly smaller than several of the facilities and has a lower maximum allowable pressure. On the other hand, the NCSU chamber has the capability of independently applying vertical and lateral pressures and measuring the actual radial displacement at the midheight of the specimen. Detailed descriptions of the chamber construction and performance testing are presented elsewhere (*8*,*9*).

The maximum design pressure that can be applied to a soil specimen inside the chamber is 276 kPa (40 psi). This pressure can be independently applied in the vertical and lateral directions. The chamber is capable of accommodating a soil specimen that is 0.69 m (37 in.) in diameter and 0.69 m (37 in.) in height. The chamber walls and the top cap constitute the boundaries that limit the maximum displacement of the soil specimen to 76.2 mm (3 in.) in the vertical direction and 50.8 mm (2 in.) in the outward radial direction. Vertical stresses are applied to the specimen via the chamber piston (diameter = 0.69 m), which is raised by pressurized air. The lateral pressure is also applied by means of the air pressure surrounding the specimen membrane.

Specimens are enclosed within a rubber membrane that is clamped both to the bottom piston and to a top platen that forms the top boundary of the specimen. The thrust of the chamber piston is transferred from the bottom piston through the sand to the top platen and into the concrete top cap, which is anchored with four steel tie rods that are screwed into the concrete base. These four steel rods were calculated to have an elastic deformation of 0.002 mm/1 kPa of applied piston pressure, thus allowing vertical displacement of the specimen to be obtained by directly measuring the vertical movement of the piston. A hydraulic cylinder with a maximum thrust of 53.4 kN (6 tons) and a maximum traveling displacement of 457 mm (18 in.) is used to insert penetration devices into the soil. This cylinder was driven by using a pressurized hydraulic pump. The system used both reversible and pressure-compensating flow control valves that allowed the penetration speed to vary from 0 to 50.8 mm/sec.

INSTRUMENTATION

The computer control system consists of a Zenith 150 microcomputer outfitted with a high-performance analog and digital input/output data translation board (DT-2801). The clock speed of the system is 12 MHz. The D/A-A/D board has 8 differential or 16 single-ended analog input ports and two channels for D/A transmission. The D/A converter has a 12-bit register that specifies

M. A. Gabr, Department of Civil Engineering, West Virginia University, Morgantown, W.Va. 26505-6101. R. H. Borden, Department of Civil Engineering, North Carolina State University, Raleigh, N.C. 27695-7908.

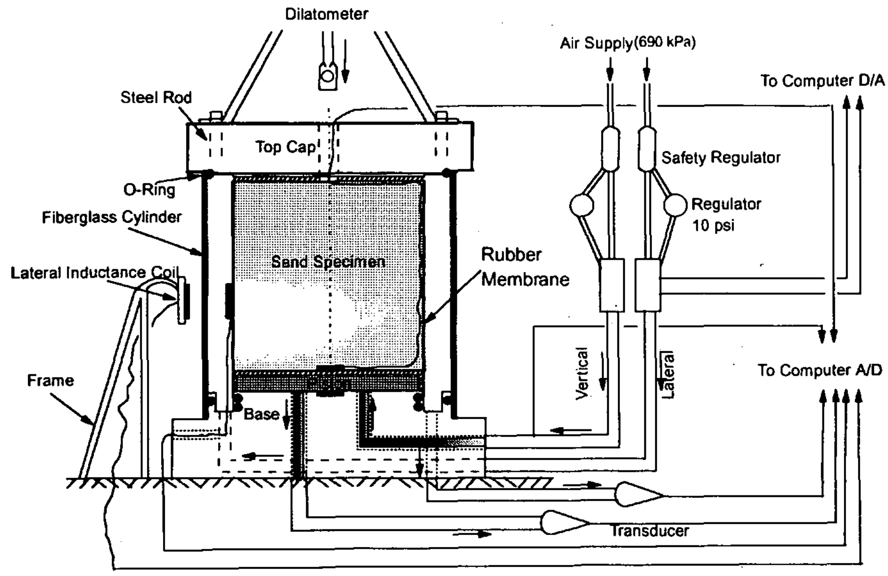


FIGURE 1 Calibration chamber details.

voltage in the range of 0 to 10 V with a resolution of 10 × 2^{-12} V, such that 000000000000 = 0 V and 111111111111 = $10(1.0 - 2^{-12}) = 9.9976$ V.

Vertical and lateral deformations are monitored through bipolar A/D channels. Vertical and horizontal pressures are supplied and controlled by using Fairchild voltage-to-pressure (V/P) regulators, which are operated by using D/A output channels with pulse-width modulation. Signal conditioning with a gain of up to 8 is used to improve the resolution of the readings.

Pressure System

The main objective of the pressure control system shown in Figure 2 is to provide and accurately monitor the air pressure supply to the chamber in both the vertical and the horizontal directions. The vertical pressure is supplied via a V/P regulator to the bottom piston. The confining pressure is similarly supplied through a pipe configuration to the space between the soil specimen and the outer fiberglass cell.

The pressure control system consists of two regulators that reduce the laboratory line air pressure from 690 kPa (100 psi) to 276 kPa (40 psi) to ensure that the chamber is never subjected to a pressure in excess of the design pressure. The 276-kPa (40 psi) pressure is fed into two regulators that supply a constant air pressure to two Fairchild no. 10 V/P transducers. Voltage signals are transmitted to the V/P transducers from the two D/A channels. By using bias and multiplier adjustments, a correlation between the input voltage and the output pressure is established. In this particular testing program, a 10-V input signal produced a 276-kPa (40 psi) output pressure.

A major difficulty in designing the pressure control system was to overcome the influence of potential leaks and maintain the desired pressure within acceptable limits. In addition, it was essential to measure the actual pressure buildup inside the chamber instead of the specified pressure. Therefore, independent pressure output ports were installed away from the pressure input ports to check the actual pressure values inside the chamber. These pressure output ports are connected to high-resolution (0.2 percent) 0- to 345-kPa (0- to 50 psi) T-Hydraulics pressure transmitters that are capable of producing amplified 0- to 10-V signals. These output voltage signals are collected by using differential A/D ports. Figure 3(*a*) shows the pressure regulators and control system. Pressure compensation to account for leaks is implemented through a closed-loop monitoring system. If the actual pressure inside the chamber is less than the specified pressure, and appropriate signal is transmitted to increase the pressure magnitude.

During the application of the vertical pressure and while the bottom piston was lifted up, specimens were observed to tilt. This tilting action was undesirable because of the possibility of damaging the O-ring seals within the piston. Also, a tilt would cause loss of vacuum and specimen collapse. To overcome this tilting problem, eight pieces of Styrofoam were attached to the circumference of the rubber membrane in a 45-degree arrangement. The Styrofoam pieces would act as spacers to prevent the initiation of tilting of the specimen. Care was taken to ensure that the Styrofoam pieces would not initially touch the fiberglass outer cylinder wall, hence minimizing the potential for the development of friction forces. However, the magnitude of any friction forces caused by the use of this tilt-control measure was taken into account through the calibration procedure described here.

To ensure that the actual vertical pressure applied to the specimen was known, the influence of all potential friction forces was investigated. By applying 27.6 kPa (4 psi) of vertical pressure to the piston, a typical 0.69-m (37-in.)-high specimen was lifted up until its top was flush with the top concrete cap. The vertical pressure was then reduced, using the computer control, in 0.7-kPa (0.1 psi) increments to determine the pressure at which the specimen started to move. It was found that when the vertical pressure was reduced to the range of 13.1 to 13.8 kPa (1.9 to 2.0 psi) the specimen began to move down. The 13.8-kPa (2 psi) pressure was close to the pressure exerted on the piston as a result of the specimen's own weight. Therefore, the friction force was determined to be approximately equal to 45.3 kg (100 lb), or 0.7 kPa (0.1 psi) pressure equivalent, for the 0.69-m (37 in.)-diameter piston.

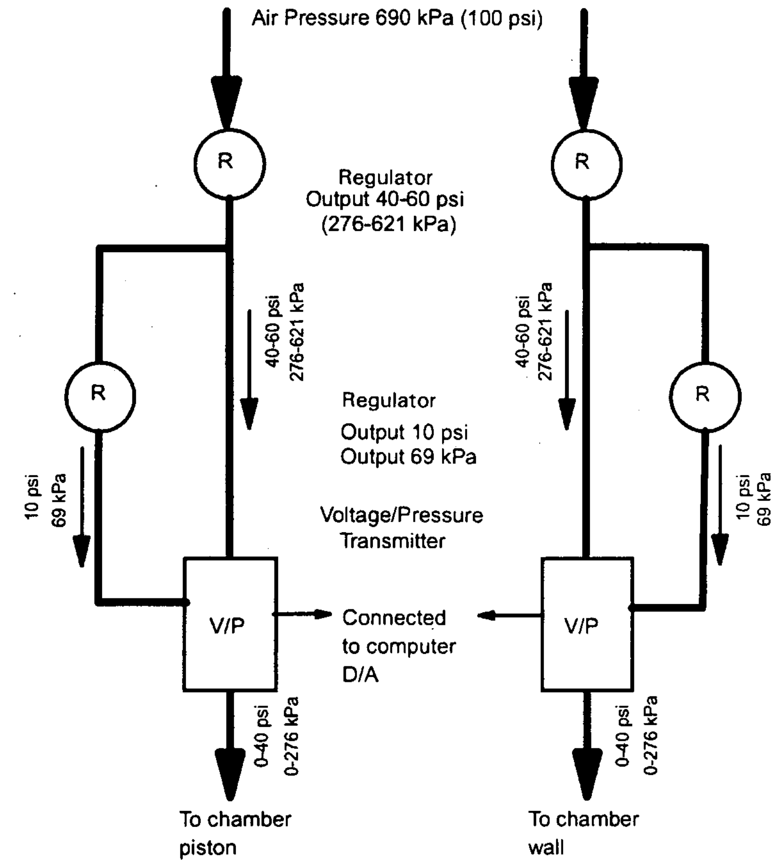


FIGURE 2 Configuration of vertical and confining pressure application system.

Displacement-Measuring System

The inductance coils developed by Selig and colleagues (*10–12*) provided the best option for displacement measurements given the chamber material, dimensions, and functioning capabilities. Previous work (*13*) supported the use of inductance coils as displacement-measuring devices. Four pairs of inductance coils are used in the displacement-measuring system. Three pairs, each consisting of an excitation coil and a receiving coil, are used to measure radial or lateral displacement at the midheight of the specimen and one pair, located on the center of the bottom piston, is used to measure the vertical displacement at the bottom of the specimen. Although several arrangements of coils have been reported in the literature (such as coaxial, coplanar, and orthogonal configurations), only the coaxial arrangement is used because this particular configuration produces the largest signal and therefore the best resolution. Figure 3(*b* and *c*) shows the locations of the vertical and radial inductance coils.

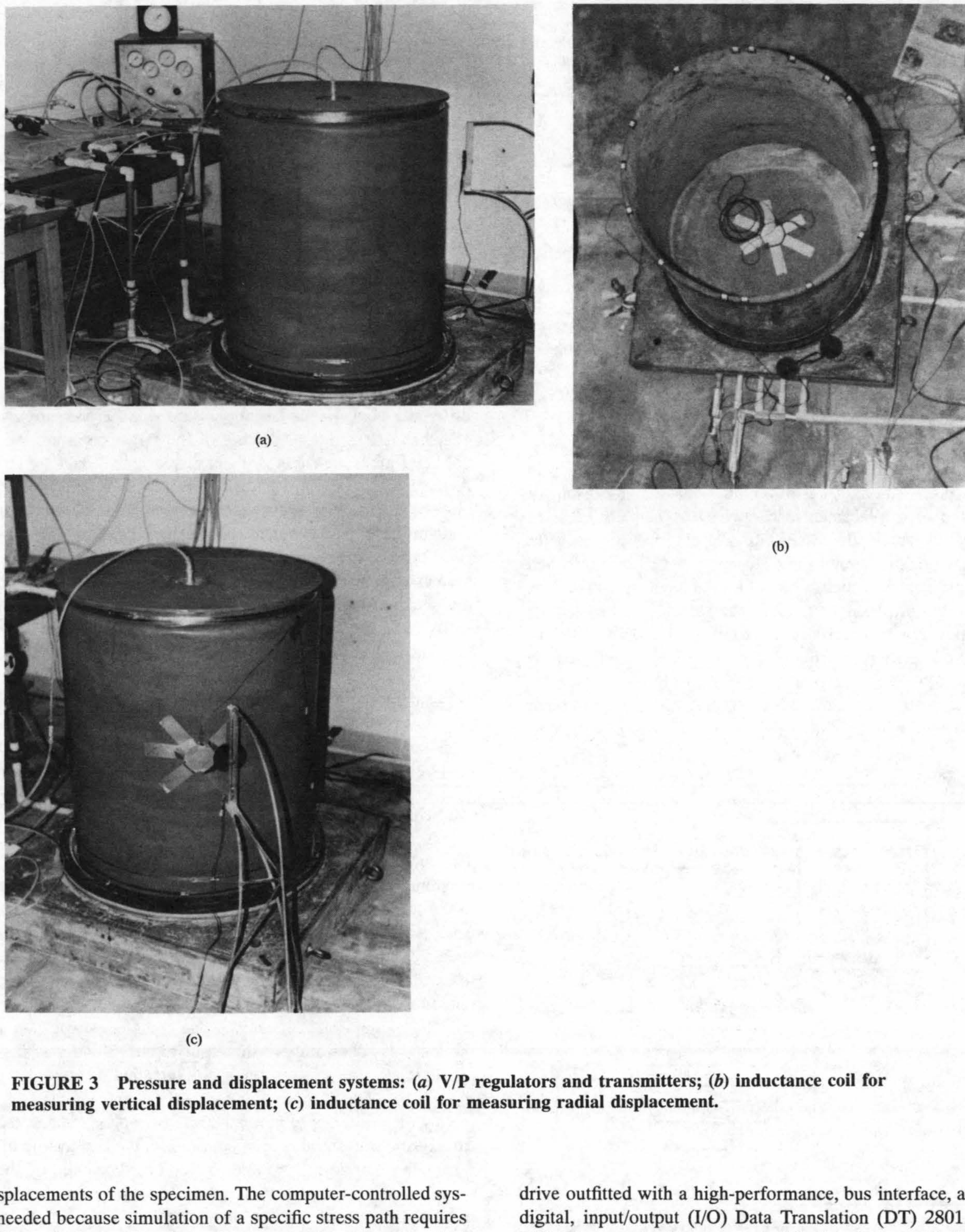
For the three lateral displacement measurement coil pairs, one coil of each pair is mounted on the rubber membrane containing the soil specimen, whereas the other coil is attached to an aluminum frame. The frames are portable and have a sliding track to allow for vertical adjustment of the coil position. This adjustment is needed to ensure the generation of signals with the largest possible amplitude. Before the outer fiberglass chamber is assembled, the three pairs of coils are carefully adjusted to be parallel to each other. They are positioned at 120 degrees, with respect to each other, around the circumference of the specimen membrane. After the initial vertical pressure is applied, the specimen is lifted up and the coils become misaligned. Therefore, the outer coils are readjusted by moving them upward until the maximum voltage signal is reached, indicating the best alignment.

The vertical displacement measurement coil is set up by using a different arrangement. The excitation coil is placed on the top surface of the base piston, with the electrical cord taped along the inside wall of the rubber membrane and stretched up to the surface of the sand specimen. The receiving coil is embedded in the top of the concrete pedestal, below the piston. After the specimen is lifted up and contact between the specimen top and the top cap is achieved, the confining pressure is applied and the vacuum pressure is released. Calibration of the inductance coils is performed before every test.

Figure 4 shows a typical calibration curve for one pair of coils along with the best-fit function that was implemented in the computer control software. The calibration curves are established in a temperature and humidity environment similar to that in which the coil will function during a given test. Electromagnetic radiation sources such as the computer screen and nearby motors are adequately separated from the coils to avoid adverse effects on the measured readings.

COMPUTER CONTROL SYSTEM

The main function of the computer control system is to manipulate and monitor the applied pressures and collect the radial and ver-



(a)

(b)

(c)

FIGURE 3 Pressure and displacement systems: (*a*) V/P regulators and transmitters; (*b*) inductance coil for measuring vertical displacement; (*c*) inductance coil for measuring radial displacement.

tical displacements of the specimen. The computer-controlled system is needed because simulation of a specific stress path requires the ability to apply small and simultaneous horizontal and vertical pressure increments. In addition, the computerized system saves the labor resources that are needed to record the large volume of data collected at a high sampling frequency from the four displacement measuring devices and the two pressure transducers. Moreover, the computer system is relatively operator independent, and therefore, it is more feasible to reproduce the experiments.

The closed-loop control logic of the computerized system is shown in Figure 5. The Zenith 150 microcomputer has a hard drive outfitted with a high-performance, bus interface, analog and digital, input/output (I/O) Data Translation (DT) 2801 board. A DT 707 connector board was used for interfacing with the pressure transducers and the inductance coils. All functions on the board are controlled by writing and reading commands, command parameters, and data to a 12-bit register installed on the board. The 12-bit register has a resolution of 1 in 4,096 parts.

A computer program, CONTROL, supported by the DT real-time PCLAB macroroutine libraries, was developed for the tests. In addition to applying and monitoring the pressures, the computer program is used for the collection of displacement data after each

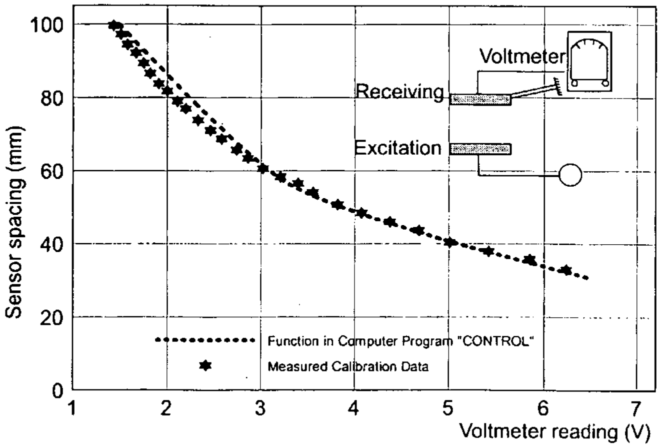


FIGURE 4 Variation of sensor spacing as a function of generated signal: measured and modeled functions.

target pressure increment is achieved. Eight channels are used in the control process. Four A/D differential channels are used for the collection of displacement data, two D/A channels are used for the pressure application, and two A/D channels are used for the feedback pressure monitoring. To account for the noise and avoid aliasing effects (which appear if the sampled signal contains frequencies that are higher than half the sampling period), each collecting port is scanned 100 times each second. The 100 readings are then averaged to produce 1 reading per second. A flow chart of the CONTROL program is shown in Figure 6.

The computer program proceeds by prompting the user to input the target vertical and confining pressures. The digital data, corresponding to the applied pressures, are converted to analog values

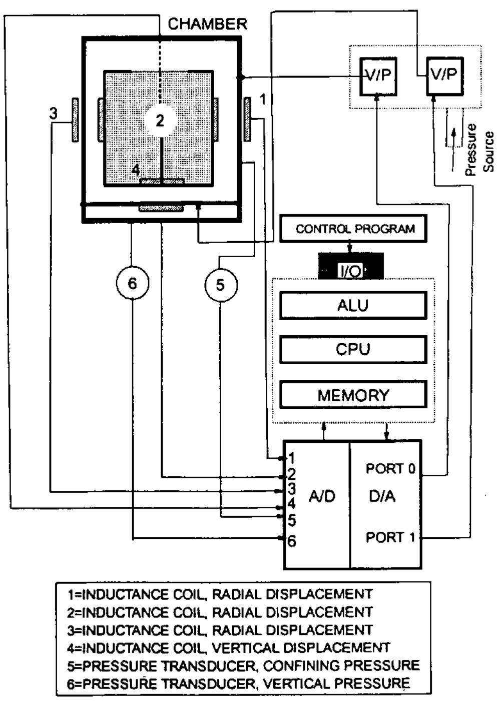


FIGURE 5 Closed-loop computer control system (ALU = arithmetic logic unit, CPU = central processing unit).

and then transmitted as voltage signals to the D/A ports. The voltage signals are received by the V/P regulators and cause the air pressure valves to release vertical and confining pressures. After the pressures corresponding to the received signals are applied to the chamber, they are continuously monitored by reading the output pressure signals coming from the pressure transmitters connected to the inside of the chamber. On the basis of the difference between the target pressures and the horizontal and vertical pressures inside the chamber that are fed back, incremental voltage signals are generated. These signals are then transmitted via the D/A port to the V/P regulators to either increase or decrease the applied pressures. This closed-loop application and monitoring process, schematically shown in Figure 5, is repeated at a time interval of approximately 4 sec.

The magnitude of a pressure increment, or decrement, is chosen in proportion to the value of the target pressures. The higher the target pressure value, the higher the increment value. When the difference between the target pressure and the pressure inside the chamber is less than 2 percent of the target pressure, the output voltage signals are stabilized and displacement data are collected. A mechanical pressure gauge is mounted on the outlet of the chamber pressure system as a backup gauge. It has been observed that the difference between the pressure readings taken visually from the pressure gauge and those obtained by using the control system were in the range of 1 percent of the desired chamber pressure.

To avoid the overshooting of the required pressure value, thus causing undesirable overconsolidation effects, the required pressure is applied by using a stepwise pressure process. In one case, for example, a target pressure of 34.5 kPa (5 psi) was attained in 10 steps of 3.45 kPa (0.5 psi) each. This procedure ensures the simultaneous application of the vertical and confining pressures, thus achieving the prescribed stress path.

CONSOLIDATION AND TESTING

The automation system allows for the independent control of the magnitude of the vertical and lateral confining pressures applied to the soil specimen. This feature permits consolidation of a specimen according to a prescribed stress path. For a series of CC specimens into which the dilatometer test apparatus was to be inserted, coefficient of earth pressure at rest (K_0) consolidation was chosen to model the in situ press path to which the soil was subjected during normal deposition. The complete stress path used in the study is schematically shown in Figure 7 and was chosen to approximate the stresses on a soil element next to a laterally loaded pile. The K_0 consolidation process was simulated by subjecting the specimen to vertical stress increments and at the same time restricting lateral movement through the application of a corresponding horizontal pressure increment. The ratio of the horizontal pressure to the vertical pressure to maintain the condition of zero lateral strain was assumed to be K_0 during the test. In general, during this process, the magnitude of the radial strain that was considered acceptable for the simulation of the K_0 condition was approximately equal to or less than 0.1 percent. The process of applying the initial stress conditions to the soil specimen is described in the following steps:

Step 1: Apply 13.8 kPa (2.0 psi) of vacuum pressure to the specimen to hold the specimen before removing the plastic former (membrane stretcher).

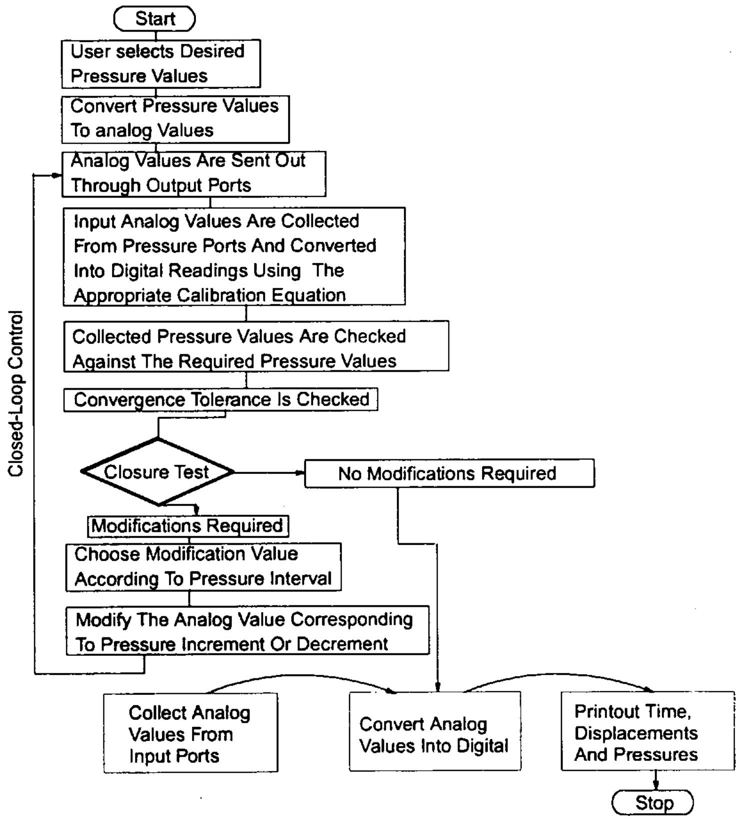


FIGURE 6 Flow chart of computer program CONTROL.

Step 2: Apply 20.7 kPa (3.0 psi) of vertical pressure to the bottom of the specimen to lift it up until the specimen top is flush with the top concrete cap, thus creating a good seal between the rubber gasket at the specimen top and the concrete cap.

Step 3: Release vertical pressure to 15.2 kPa (2.2 psi). This pressure value was applied to overcome the weight of the specimen. Set up inductance coils and take initial displacement readings, which were assumed to be the zero lateral displacement readings.

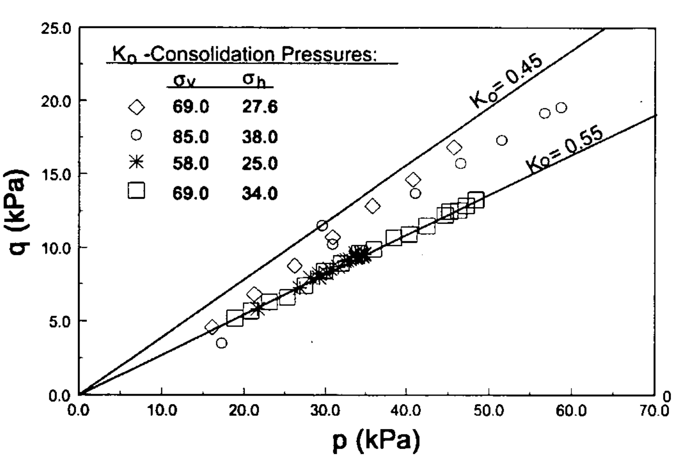


FIGURE 7 Measured K_0 values from CC test [σ_v = vertical consolidation stress, σ_h = horizontal consolidation stress, $q = (\sigma_v - \sigma_h)/2$, and $p = (\sigma_v + \sigma_h)/2$].

Step 4: Apply 27.6 kPa (4.0 psi) of vertical pressure and 13.8 kPa (2.0 psi) of confining pressure to ensure good contact between the specimen and the top cap. The confining pressure is applied to hold the specimen.

Step 5: Release vacuum pressure.

Step 6: Apply the desired vertical pressure increment and, by using the control program, adjust the horizontal pressure to maintain lateral displacement corresponding to 0.1 percent strain or less. This procedure was repeated for the initial four tests performed on loose sand. However, it was found that the K_0 values obtained from each test were within the narrow range of 0.45 to 0.55, as shown in Figure 7. Therefore, given that the sand-raining process used to form the specimens produced repeatable uniformity, a less time-consuming procedure was adopted. This procedure was similar to the one described above except for the determination of K_0. The K_0 was assumed to be known, and the vertical and confining pressures were applied in increments that maintained the K_0 condition until the desired initial stress condition was achieved.

Once the initial stress condition was achieved, a stress path similar to that shown in Figure 8 was applied to the specimen in steps. During the application of this stepped-load stress path, displacement readings were recorded on the computer disk after the sample was allowed to stabilize. Stabilization was inferred from the monitored displacements, and the sample took approximately 10 to 15 sec to stabilize under the applied pressure increments.

Typical results of one of the tests performed on a loose sand specimen are shown in Figure 9(*a*) and (*b*). A summary of the 22

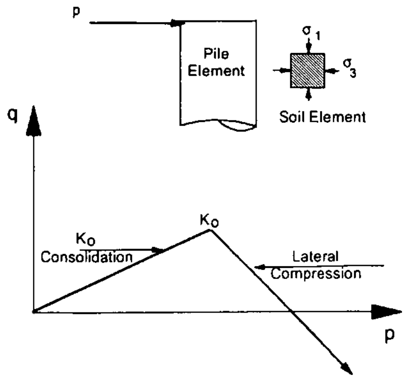


FIGURE 8 Stress path for the CC tests ($\sigma_1 = \sigma_v$ and $\sigma_3 = \sigma_h$).

tests performed during the course of this project has been presented previously (9). Thirteen tests were devoted entirely to the establishment of the system, development of the computer control program, and learning about the system's uncertainties.

As shown in Figure 9(*a*), the prescribed stress path was adequately followed by using the control system. The vertical and horizontal pressures were applied to achieve a K_0 of 0.4, and then the lateral compression pressure was increased while maintaining the vertical pressure constant at approximately 69 kPa (10 psi). During the application of the vertical and horizontal pressures, the radial strain was maintained at a value of less than 0.1 percent up to the point at which in situ stress conditions were simulated, as shown in Figure 9(*b*). After the K_0 condition was achieved, the displacement values were collected from the three inductance coil pairs as the horizontal pressure was increased. In conjunction with these tests, and outside the scope of this paper, the Marchetti dilatometer test was conducted at depth intervals of 100 mm (4 in.). The inductance coils proved capable of detecting small displacements (less than 1 mm) at the sample boundary. The boundary displacements were found to be a function of the specimen density, with low-density specimens showing essentially no boundary movement (*14*).

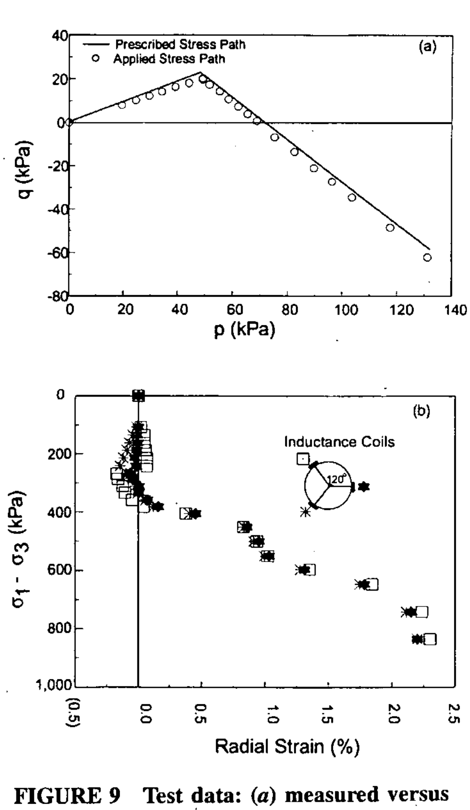


FIGURE 9 Test data: (*a*) measured versus specified target stress path; (*b*) measured radial displacements under the specified stress path.

SUMMARY AND CONCLUSIONS

A computer-controlled data acquisition system was used to conduct a series of CC tests on sand. The system consisted of a Zenith 150 microcomputer that was outfitted with a bus interface high-performance analog and digital I/O DT 2801 board with 12-bit register. The control and monitoring instrumentation consisted of two pressure regulators that supplied a constant air pressure to two Fairchild no. 10 V/P transducers and four pairs of inductance coils. In situ stress conditions were simulated by using the instrumentation system along prescribed stress paths. The test data that were monitored included three radial displacements, vertical displacement, and the vertical and confining pressures. Deformations were monitored and collected during the consolidation process to assess the accuracy of simulating the in situ K_0 conditions. Pressures were applied according to a prespecified stress path by using the developed system. A closed-loop algorithm was used to apply and monitor the prespecified stress path. On the basis of the results of the study described here, the following conclusions can be drawn:

1. Closed-loop algorithms provide an effective technique for the independent control of vertical and confining pressures and the simulation of K_0 conditions. By using a computer with a clock frequency of 12 MHz, the duration of the control cycle was 4 sec for each pressure increment. An additional 10 to 15 sec was needed for the pressure to stabilize.
2. The inductance coils proved to be effective for short-term deformation measurements during the tests. Calibration on a regular basis was needed to ensure that electromagnetic drifts did not affect the performance of the coils. The high-speed feedback of deformation readings allowed the adjustment of the applied pressures to achieve the K_0 condition.
3. The data acquisition system proved to be cost-effective and reliable. However, in most cases off-the-shelf products will not meet project-specific needs, as in the case of the study described here. The off-the-shelf software available for conventional triaxial testing was not suitable for the needed closed-loop and displacement control procedure to achieve the prespecified K_0 and the consequent stress path loading. In the case of the present study, extensive development and custom design were required to construct a system that provided the needed displacement and stress controls.
4. The initial cost of the data acquisition system was offset by the savings in personnel costs and the costs associated with systematic data recording and storage.

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