Virginia Polytechnic Institute
and State University

Department of Civil Engineering

GEOTECHNICAL ENGINEERING

INSTRUMENTED RETAINING WALL FACILITY

VIRGINIA TECH
BLACKSBURG

PURPOSE OF FACILITY

The Instrumented Retaining Wall facility at Virginia Polytechnic Institute and State University (Virginia Tech) has been developed to study the factors that control the magnitudes of earth pressures induced by compaction of soil. Previous investigations have shown that measuring the earth pressures that result from compaction is difficult because:

(1) Earth pressure cells sometimes give erroneous readings, depending on their stiffness and how they are installed.

(2) Compaction-induced earth pressures vary rapidly with depth, resulting in misinterpretation if fill elevations are not measured with sufficient accuracy.

(3) There appears to be large inherent variability in earth pressures, resulting in possible erroneous evaluations if too few measurements are made.

(4) Small wall movements can change earth pressures very significantly; walls must be stiff and mounted on unyielding supports to measure earth pressures that are not influenced by wall movements.

The experimental facility at Virginia Tech has been designed to overcome these problems, and to achieve accurate measurements of compaction-induced earth pressures at a scale approaching field scale.

The facility also has other capabilities in addition to measurement of compaction - induced earth pressures. The instrumented wall panels can be moved toward or away from the backfill to measure the effects of wall movements on earth pressures, and the wall panels are instrumented so that shear loads as well as normal loads can be measured. The facility can be used to investigate earth pressures due to loads on the surface of the backfill, and to study how the results of in situ tests are affected by soil density and lateral earth pressures.

DESIGN FEATURES

The instrumented retaining wall is 7 ft high and 10 ft long. Fig. 1 shows the principal features of the wall, and Fig. 2 shows photos of the wall before and after backfilling. The bottom of the wall is 3 ft below floor level in the building, and the top is 4 ft above. The area in back of the wall, where the backfill is placed, is 6 ft wide. A 6 ft wide ramp leading into the area provides access for loading and compacting equipment.

The wall is divided into four panels, each 2.5 ft wide and 7 ft high, as shown in Fig. 3. Each of these panels is mounted on two vertical load cells that support the weight of the panels and measure the vertical shear loads exerted on them by the backfill. Each panel is supported horizontally by three load cells, two located 20 inches above the bottom, and one located 60 inches above the bottom. These load cells are used to measure the magnitude and position of the resultant horizontal force exerted on each panel by the backfill.

All four wall panels are attached, through the horizontal load cells, to a stiff steel frame, as shown in Fig. 4. The frame is supported vertically by bearings that can slide and rotate, and horizontally by jacks that can be used to induce translational or rotational movements. Because the frame is very stiff, the four wall panels always move together, remaining in the same plane.

A total of 17 earth pressure cells (11 Gloetzl cells, 4 Carlson cells, and 2 Geonor cells) are mounted on the center two wall panels, as shown in Fig. 3. These pressure cells are all quite stiff, and are mounted flush with the faces of the wall panels. They are located at six inch elevation increments in four vertical strips. They thus provide closely spaced points for determining variations of earth pressure with depth, and redundancy with respect to pressure cell elevation and pressure cell type.

The elevation of the surface of the fill is measured, after each lift is compacted, using an array of 12 Ultrasonic Distance Measuring Devices (UDMDs) mounted on a frame that rotates down into a horizontal position over the fill. The frame is shown in Fig. 1 and is visible in Fig. 2. The UDMDs can sense the position of the fill after compaction, but they cannot be used to measure the position of the loose fill, because the ultrasonic signals are scattered rather than reflected.

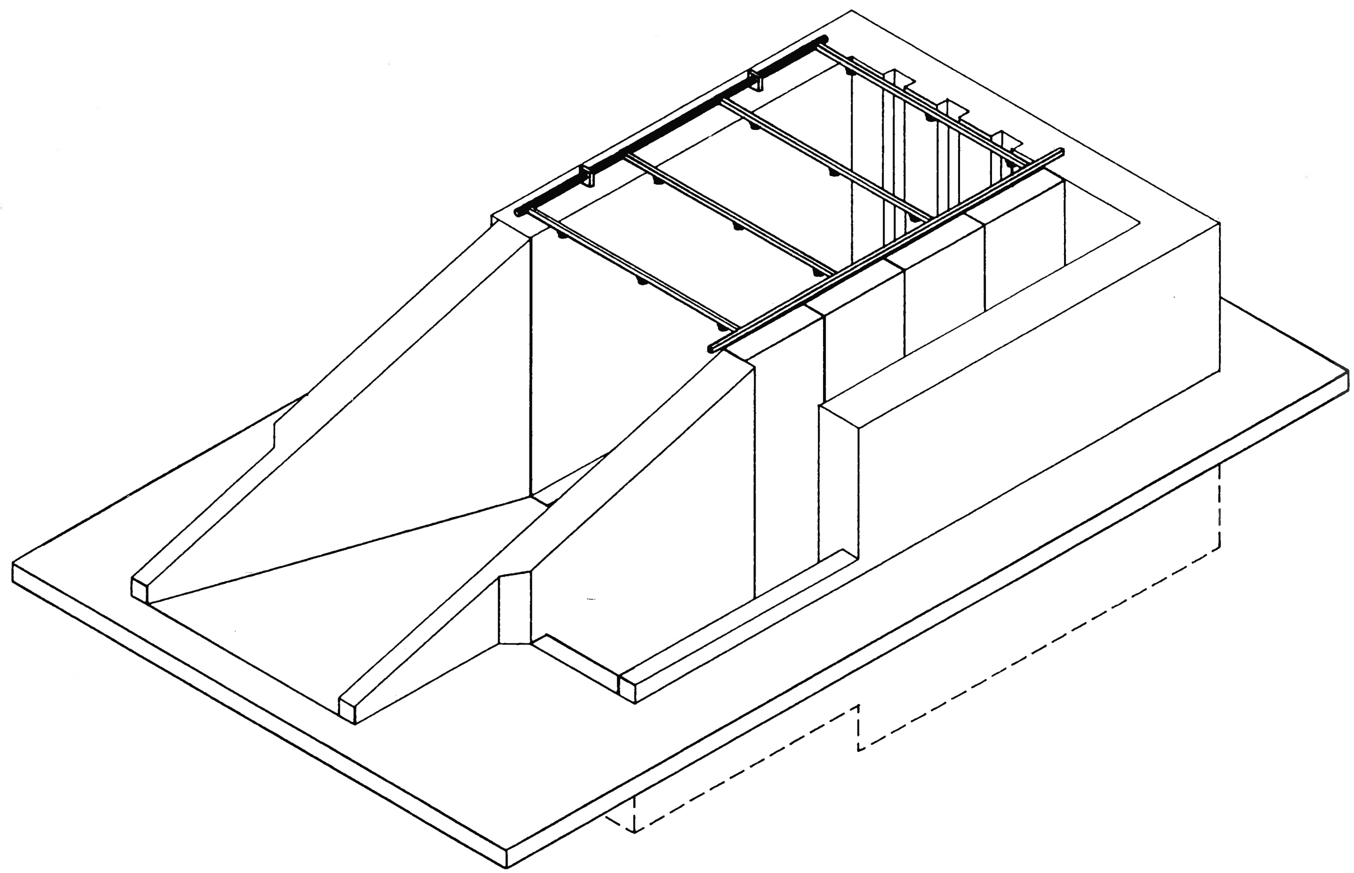

Fig. 1 - The Instrumented Retaining Wall Facility

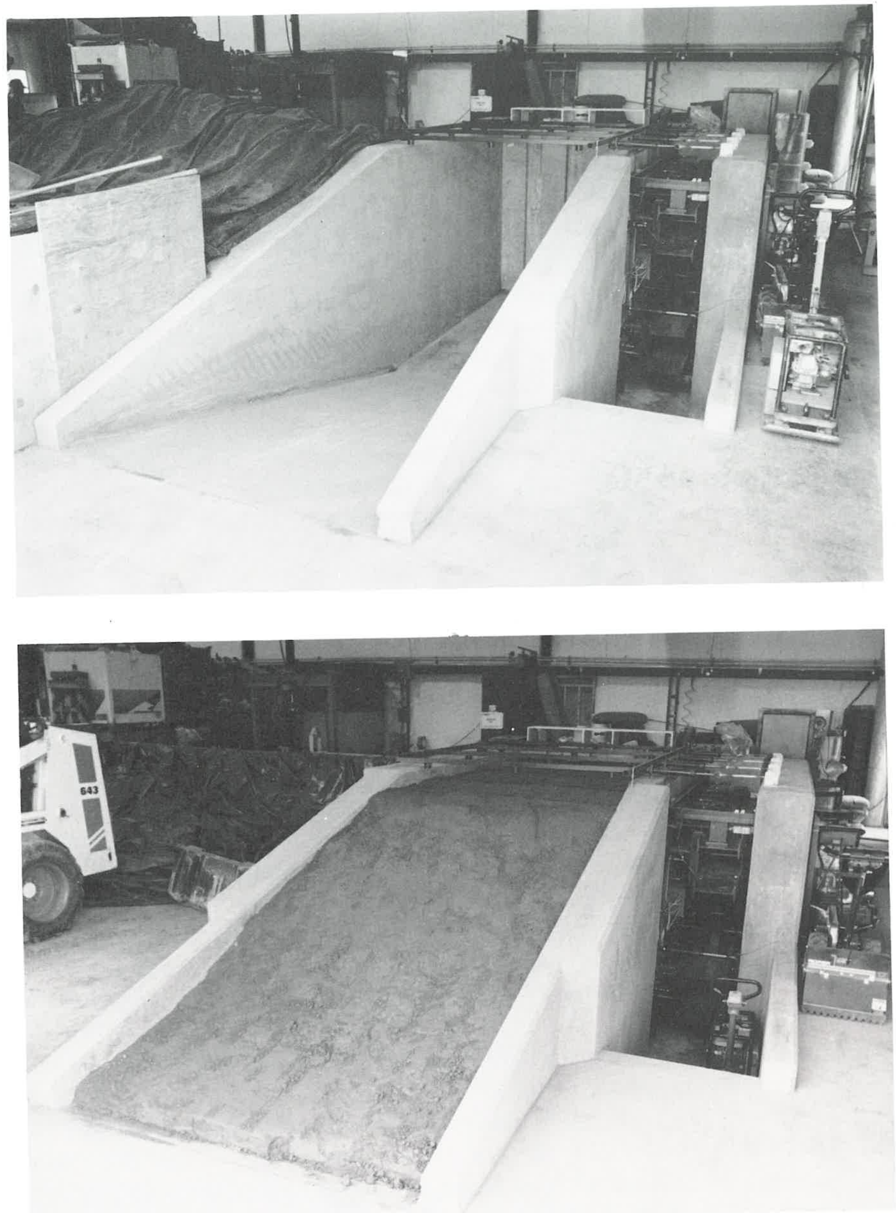

Fig. 2 - Photos of the Facility Before and After Backfilling

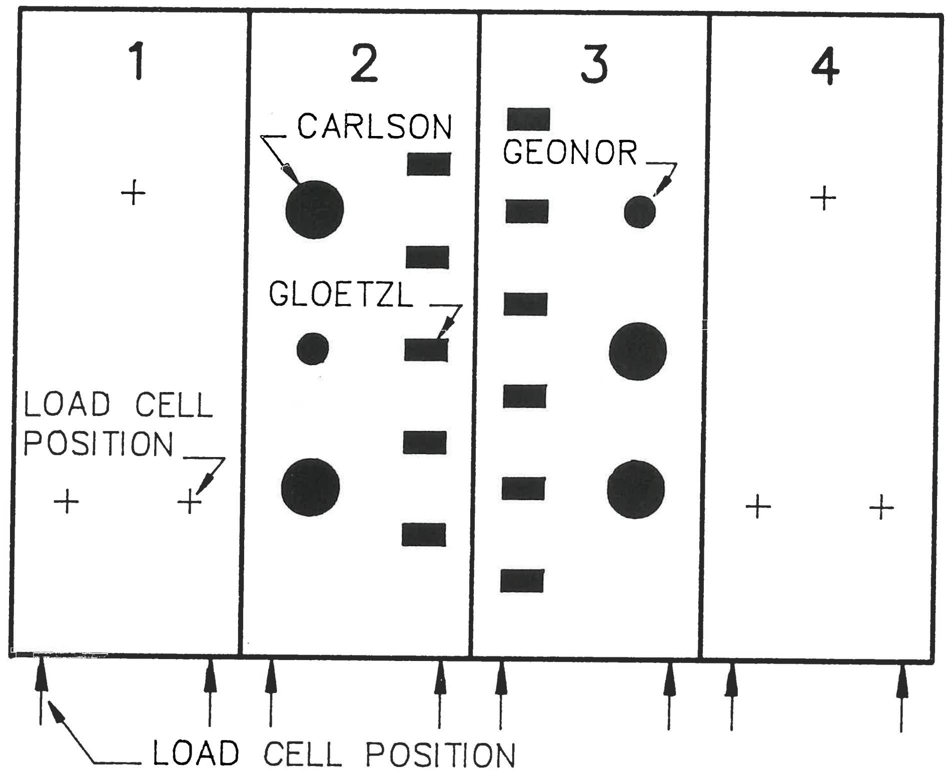

Fig. 3 - The Four Panels of the Instrumented Wall

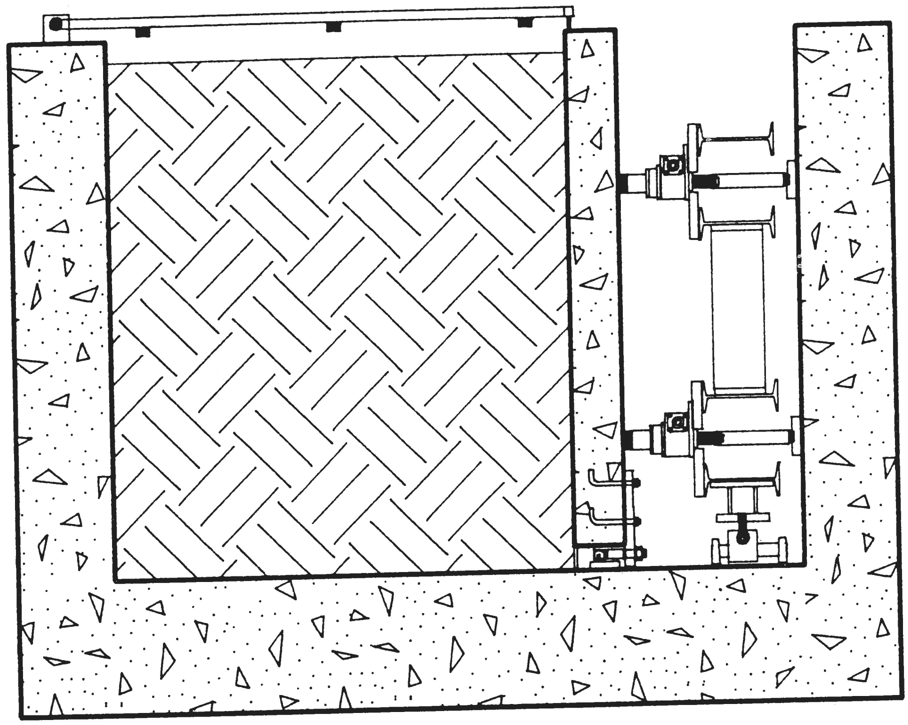

Fig. 4 - Cross-Section Through the Wall

DESIGN FEATURES (continued)

Movements of the wall panels are measured by 8 LVDTs, one near the top and one near the bottom of each wall panel. These are mounted on unstressed reference frames attached to the reinforced concrete wall that supports the steel frame. A ninth LVDT, mounted on the floor slab of the building, is used to measure possible movements of the reinforced concrete wall. The floor slab is isolated from the concrete wall by an expansion joint. Two thermocouples are used to measure the temperature of the LVDT support, to monitor possible temperature effects on the readings.

The temperature of the wall panels is measured at three locations, one near the bottom of the wall, one near the middle, and one near the top. These provide the information needed to adjust the Gloetzl cell readings for temperature-induced zero shift.

All of the instruments are monitored by a computer-controlled data acquisition system. Measurements are made after each lift has been placed loose, and again after it has been compacted. Two independent sets of readings are made each time, and stored in different data files. This provides security in case one set of readings should be destroyed accidentally, and redundancy in case some of the measured values appear questionable. Making two sets of readings takes about 5 minutes.

The process of placing fill behind the wall and compacting it is recorded on videotape to provide a detailed record of each test. The video camera operates for 3 seconds in each 30 second period. This provides a record of 15 hours of activity on a 90 minute tape. On fast forward, the record can be scanned in 9 minutes.

TECHNICAL CHARACTERISTICS OF THE INSTRUMENTATION SYSTEM

Vertical Load Cells. The vertical forces on the wall panels are measured by means of the load cells that support the panels. As shown in Fig. 5, these load cells are 4 inch long cantilever beams that are bolted to brackets at the bottoms of the panels. The free end of each beam has a roller bearing wheel that can move back and forth on a hardened steel pad epoxied to the concrete floor. This permits free lateral movement of the wall panels. The vertical forces are measured by means of bonded strain gages attached to the cantilever beams. The accuracy of the load cells is about 15 lbs, or about 30 lbs per panel.

Horizontal Load Cells. The horizontal reaction forces on the wall panels are measured using column load cells with bonded strain gages. As shown in Fig. 5, the ends of the columns are seated in spherical bearings to minimize bending moments. The accuracy of the load cells is about 50 lbs, resulting in overall accuracy of about 150 lbs for the horizontal force on a single wall panel. With two load cells at the bottom of each panel and one at the top, it is possible to determine both the magnitude and the position of the resultant force acting on each panel.

The horizontal load cells work only in compression. During the early stages of filling, when fill is being placed and compacted below the bottom load cells, the top load cells tend to go into tension, and become loose in their bearings. To prevent this, they are prestressed in compression by springs located at the top and 2 ft above the bottom of the wall panels. These springs hold the horizontal load cells in compression at all times. The load cells are so much stiffer than the springs that there is no appreciable change in the spring forces as the forces in the load cells change.

Earth pressure cells. The Gloetzl earth pressure cells consist of two rectangular steel plates, welded together around their edges, with a thin film of oil between them, as shown in Fig. 6(a). They are 14 cm long, 7 cm wide, and 0.45 cm thick. The front face is flat. The oil pressure is transmitted to a pressure transducer by means of a heavy gage steel tube that extends from the back of the cell. The cells used in the Retaining Wall Facility were fitted with electrical pressure transducers so that they could be read using the data acquisition system. The transducers were purchased in the United States, and were attached to the pressure cells at the Gloetzl factory in Germany.

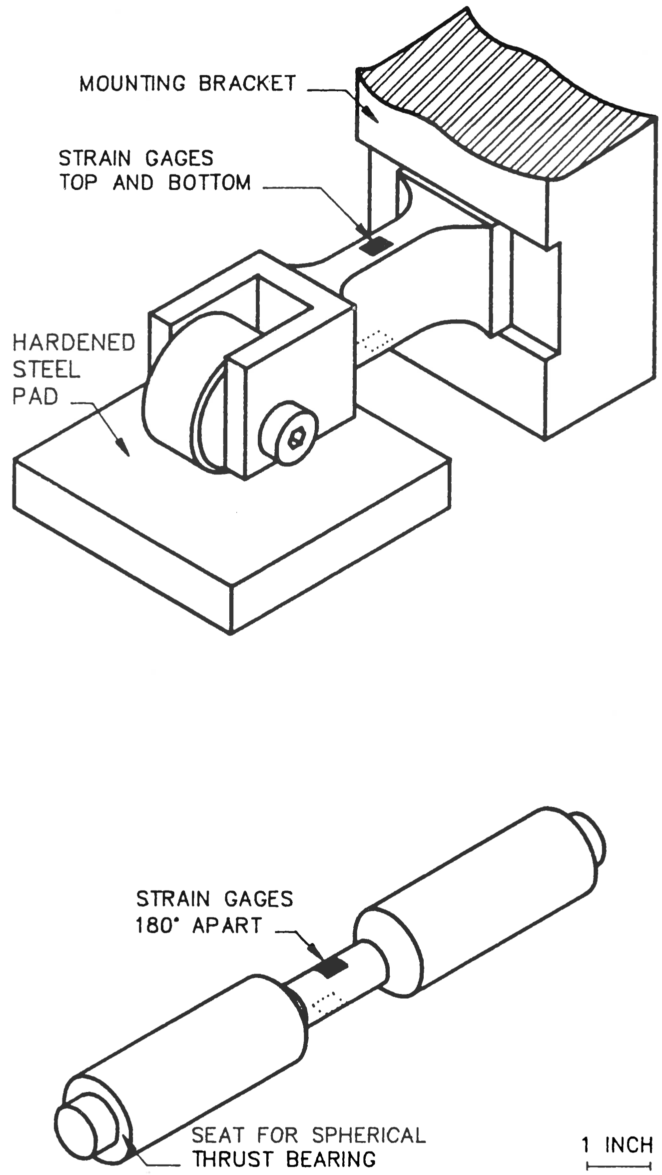

Fig. 5 - Vertical and Horizontal Load Cells

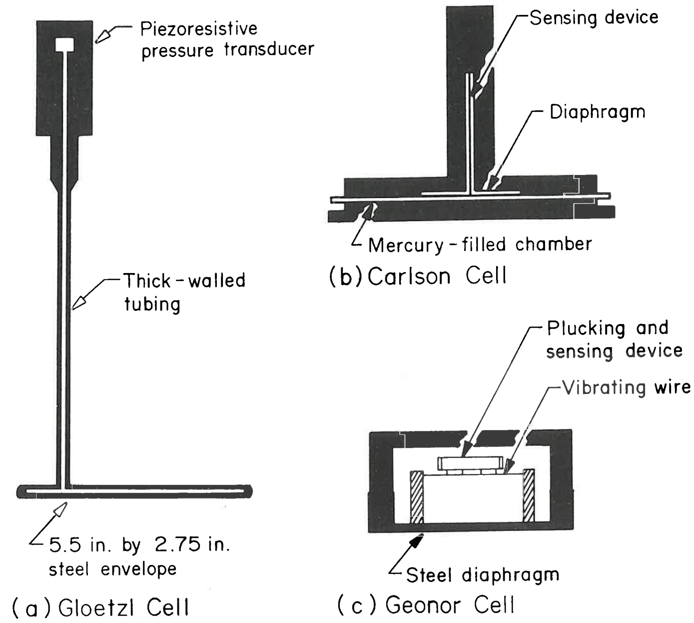

Fig. 6 - Earth Pressure Cells

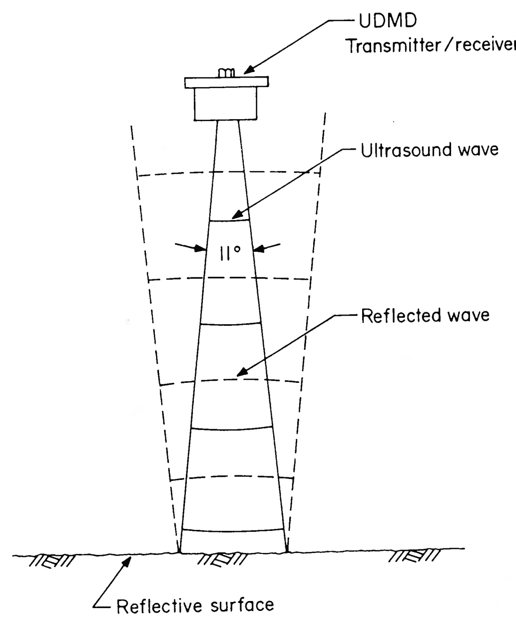

Fig. 7 - Ultrasonic Distance Measuring Device (UDMD)

TECHNICAL CHARACTERISTICS (continued)

The Carlson earth pressure cells are 7.4 inches in diameter and about 1 inch thick, as shown in Fig. 6(b). Behind a heavy metal faceplate they contain a thin film of mercury. The pressure in the mercury is measured using an extensometer contained in a cylindrical housing attached to the back of the cell.

The Geonor earth pressure cells are 16.5 cm in diameter and 4.6 cm thick. As shown in Fig. 6(c), the face of the gage is a stiff metal diaphragm. The diameter of the active portion of this diaphragm is 7.5 cm. Attached to the back of the diaphragm is a taut wire which is caused to vibrate in its natural frequency by an electrical magnet that is switched on and off at intervals. As the pressure on the face of the cell changes, the tension in the wire and the natural frequency of its vibration also change. The vibration of the wire is picked up by a small pickup device in the cell. The frequency of vibration is determined by counting the number of signal pulses for a set period, like one second.

<u>Ultrasonic Distance Measuring Devices (UDMDs)</u>. As illustrated in Fig. 7, the UDMDs send out a burst of ultrasound at a single frequency. The interval of time for the first wave to be reflected back to the instrument, divided by the speed of sound, is twice the distance from the instrument to the reflecting surface. The speed of sound in the atmosphere is affected by temperature and humidity. To correct for these effects another measurement is made with a UDMD aimed at a target located at a fixed distance from the device. This measurement provides a calibration reading each time a set of measurements is made, and results in accuracy of about 0.1 inches in the measured values of fill depth.

<u>Linear Variable Differential Transformers (LVDTs)</u>. The LVDTs are powered by direct current. Their range of measurement is 1.0 inch. By accounting for output nonlinearity, accuracies on the order of 0.0005 inches are achieved.

<u>Thermocouples</u>. The thermocouples are conventional copper-constantan devices capable of measuring temperature with an accuracy of 0.5 degree Fahrenheit.

DATA ACQUISITION HARDWARE

Computer. The data acquisition system is controlled by the IBM XT microcomputer shown in Fig. 8. Three data acquisition cards in expansion slots in the computer control the selection of the data channels and the reading of the instruments. The cabinet to the left of the computer in Fig. 8 contains the multiplexing cards that are connected to each of the instruments.

Power Supply. The power supply for the instruments is located in the cabinet with the multiplexing cards. It is regulated to an accuracy of 0.02 percent before each set of readings.

Voltage Measurements. The reading of instruments that output voltage signals is controlled by a MetraByte DAS-8 card in the computer. This card is connected to seven MetraByte EXP-16 multiplexing cards by a 37 - conductor ribbon cable. Cold junction compensation for thermocouples is provided by circuitry on the EXP-16 cards. The load cells, the Gloetzl cells, the Carlson cells, the LVDTs, and the thermocouples (a total of 51 instruments) all output voltage signals. Under software control, the DAS-8 selects each channel in turn, converts the analog signal to digital form, and transmits it to computer memory.

Frequency Measurements. The Geonor earth pressure cells output oscillating voltage signals, the frequency of which vary depending on the pressure. These instruments are read under the control of a MetraByte CTM-05 card in the computer. The Geonor cells have their own control circuits which are connected to the power supply, and output signals continually. Under software control, the CTM-05 card selects each channel in turn and measures the frequency by counting cycles for a fixed period of time, about one second.

UDMD Measurements. The basic measurement for the ultrasonic distance measuring devices is the interval of time required for a reflected ultrasound signal to return to the instrument. A UDM-PC controller card in the computer is connected by a 14 - conductor cable to a UDM-MUX multiplexer card in an external cabinet. Under software control, the UDM-PC card selects each channel in turn, causes the UDMD to transmit an ultrasound signal, and measures the length of time required to receive a return signal of the same frequency.

Fig. 8 - The Computer and the Cabinet Containing the Multiplexing Cards

SOFTWARE CONTROL

Program Logic. The data acquisition system is controlled by a computer program written in Microsoft QuickBASIC 4.5. The subroutines in this program address the data acquisition controller cards in the computer, and relay instructions for the sequence of reading the instruments, and the number of times each is to be read. In cases where instruments are read more than once, the subroutines average the readings and use logical procedures to eliminate erroneous readings. They also store the data acquired in files on hard and floppy disks.

Each of the voltage measurements is repeated 20 times. The voltage readings for the load cells, the Gloetzl cells, the LVDTs, and the thermocouples are multiplied by their calibration constants to convert the readings to engineering units. Four separate voltage readings are required for each Carlson cell. These are used in a series of equations that determine a raw pressure reading uncorrected for temperature, the temperature of the cell, the temperature correction, and finally the pressure corrected for temperature.

The frequency of the signal from each Geonor cell is monitored twice, for one second each time, and the two values are averaged.

The logic governing the reading of the UDMDs is the most complex of any of the instruments. The software addresses each of the instruments ten times. If a reflected sound wave is detected, the time interval for wave return is recorded. If a return wave is not detected any of the ten times the instrument is addressed, that is noted. After the tenth attempt, the average return time is calculated. A calibration factor is calculated based on the return time for the UDMD that is aimed at a fixed target. This calibration factor is used to convert the measured time intervals to distance values.

Operation. Two routines are used to make readings. The routine used when a loose lift of backfill has been placed behind the wall does not include UDMD measurements. Making two sets of readings with this routine takes about three minutes. The routine used after a lift has been compacted does include readings of the UDMDs. Making two sets of readings with this routine takes about five minutes.

SYSTEM COMPONENTS

The suppliers of the instruments and data acquisition hardware used in the Instrumented Retaining Wall Facility are listed in Table 1. The load cells for measuring horizontal and vertical forces were designed by Allen Sehn and were built in the Civil Engineering Department shops at Virginia Tech. The computer programs that control the operation of the data acquisition system were written by Allen Sehn.

Calibrations. The load cells were calibrated twice - once in a universal testing machine in the geotechnical engineering laboratory, and once in place after installation in the retaining wall facility. The two calibrations of the horizontal load cells differed by about 2.0 percent, due to the fact that larger voltage drops occurred at various locations after all of the instruments were installed in the instrumentation circuit. The two calibrations of the vertical load cells differed by about 6.0 percent for the same reason. The second set of calibrations, which were made using the same data acquisition system used in the tests, is used in reducing the data.

The earth pressure cells were calibrated after they were installed on the wall, by placing a pressure cylinder against the wall panel at the location of each earth pressure cell, and pressurizing a rubber membrane in contact with the face of the cell. During calibration it was found that the readings of the Carlson cells drifted with time, and this was traced to heating of the cell due to the electrical current flow during the measurements. To overcome this problem the applied voltage was reduced, and the length of time the voltage was applied was standardized.

The LVDTs were calibrated using a micrometer in a benchtop calibration frame. The readings of the thermocouples were checked against a thermometer and an ice bath. Finally, as mentioned previously, a calibration factor for the UDMDs is measured each time a new set of readings is made.

Accuracy of Instruments. The estimated accuracies of the instruments are listed in Table 2. These values reflect the influence of all of the factors that determine the repeatability of measurements over a period as long as the several days involved in a test, as well as the intrinsic accuracy of the instruments. It also takes into account the use of multiple readings to improve the resolution of each set of readings.

Table 1. Supplies of Instrumentation Hardware

Item	Manufacturer
Gloetzl Earth Pressure Cells Type: E 7/14 K3.5 Z4 Model: C, with adaptor for Omega pressure transducers, special order	Gloetzl Gesellschaft fur BaumeBtechnik GmbH 7512 Rheinstetten 4-Fo. WEST GERMANY US Representative: Geo Group, Inc. 2209 Georgian Way #12 Wheaton, MD 20902
Carlson Earth Pressure Cells Model: S-25	Carlson/RST Instruments 1190-C Dell Avenue Campbell, CA 95008
Geonor Earth Pressure Cells Model: P100 0-5 Bar	Geonor A/S P.O. Box 99 - ROA 0701 Oslo 7 NORWAY US Representative: Geonor, Incl 1454 Van Houten Ave. Clifton, NJ 07013
Ultrasonic Distance Measuring Devices and Interfacing Hardware	Contaq Technologies Corp 15 Main Street Bristol, VT 05443
LVDTs Models: 353-000 351-000	Trans-Tek, Inc. Route 83 P.O. Box 338 Ellington, CT 06029
Pressure Transducers (Used with Gloetzl cells) Model: PX236 Thermocouples type T	Omega Engineering, Inc. One Omega Drive Stanford, CT 06907
Date Acquisition Hardware Models: DASH-8, EXP-16, CTM-05	MetraByte Corporation 440 Myles Standish Blvd. Taunton, MA 02780

Table 2. Estimated Instrument Accuracies

Instrument	Estimated Accuracy*
Gloetzl Cells	± 0.25 psi
Carlson Cells	± 0.50 psi
Geonor Cells	± 0.25 psi
Horizontal Load Cells	± 50 lbs
Vertical Load Cells	± 15 lbs
Ultrasonic Distance Measuring Devices	± 0.10 in.
LVDTs	± 0.0005 in.
Thermocouples	± 0.5 Deg. F

* Estimate based on consideration of overall system performance as installed in the Instrumented Retaining Wall Facility at Virginia Tech. May not reflect the accuracy of the instrument alone or under different conditions.

COST OF THE FACILITY

Approximate costs for the components of the Instrumented Retaining Wall facility are listed in Table 3. The total is about $173,000. It is interesting to compare the cost of this facility with the cost of a facility of almost exactly the same size built by Terzaghi at MIT in about 1930. Terzaghi (1) stated that the total investment in the MIT facility was about $50,000. Using the change in the Engineering News Record Construction Cost Index as a guide, the comparable current cost would be about $1,200,000 in 1990. The difference in cost is largely attributable to the availability of smaller and less costly devices for measuring the forces on the wall. Terzaghi's facility had intricate and elaborate force measuring systems based on the principle of balance beam scales. Today these are replaced by more compact and less expensive electrical measuring devices.

The cost of operation of the new facility is probably also much lower, due to the fact that power equipment greatly reduces the amount of time required for material haondling, automatic data acquisition reduces the time for collecting data, and computer programs reduce the time required for processing and plotting the information.

ACKNOWLEDGMENT

Many people have assisted with the development of the Instrumented Retaining Wall Facility. Al Sehn, now Assistant Professor of Civil Engineering at the University of Akron, designed and supervised construction of the entire facility. George Filz, Professor Tom Brandon, Glen Thomas, Brett Farmer, Clark Brown, Eric Zeimer, Tony Brizendine, and David Wasiela of Virginia Polytechnic Institute and State University, Ed Brylawski of Geonor, Inc., and Brian Dawes of Geo Group, Inc. all made important contributions to its development. The facility was developed under the supervision of Professor J. Michael Duncan.

Development of the facility was sponsored by the National Science Foundation, the Nikken Sekkei Corporation of Japan, the U.S. Army Corps of Engineers, and Virginia Polytechnic Institute and State University. Reed Mosher of the U.S. Army Engineers Waterways Experiment Station, and Don Dresler and Lucian Guthry of the Office of the Chief of Engineers have assisted in setting the objectives for and sponsoring the research performed at the facility.

Table 3. Approximate Cost of Instrumented Retaining Wall Facility

Reinforced Concrete Sidewalls, Floor, and Ramp	$15,000
Gloetzl earth pressure cells + transducers (11)	5,300
Carlson earth pressure cells (4)	3,100
Geonor earth pressure cells (2)	1,500
Jacks to move walls (4)	2,500
Horizontal load cells (materials labor for (12)	8,400
Vertical load cells (materials + labor for 8)	8,000
Ultrasonic Distance Measuring Devices (16, not all deployed)	3,500
LVCTs (9)	4,100
Thermocouples (5)	200
Video camera, VCR, TV and controller	1,400
Analog to Digital card DASH-8 (1)	400
Frequency to Digital card CTM-05 (1)	300
Multiplexing cards EXP-16 (7)	2,600
Computer IBM XT (1)	1,500
Bobcat Loader	11,000
Wacker BPU 2440A Compactor	3,000
Santo SV-104 Compactor	1,400
Wacker BS 60Y Compactor	1,900
Rototiller	600
Soil delivery & conditioning	4,000
Building & crane (half of 2400 ft^2 bldg)	45,000
Miscellaneous materials	5,000
Design	25,000
Fabrication	6,000
Assembly	10,000
Calibration	2,000
Total:	$173,200

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