Instrumentation for Measuring Earth Pressures due to Compaction

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The Instrumented Retaining Wall Facility at Virginia Polytechnic Institute and State University (Virginia Tech), developed to study the factors that control the magnitudes of earth pressures induced by compaction of soil, is described. Previous investigations of earth pressures induced by compaction have shown that measuring earth pressures due to 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 accurately determined; (3) the large inherent variability in earth pressures results in possible erroneous evaluations if too few measurements are made; and (4) 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 electronic instruments and the data acquisition system in the facility make it possible to perform efficient and accurate studies of earth pressures during and at the end of backfilling and their variation with time after backfilling. This facility offers promise for investigating aspects of the horizontal and vertical earth loads on retaining walls that are not reflected in conventional earth pressure theories but have significant effects on the stability and performance of retaining walls.

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 of earth pressures induced by compaction have shown that measuring earth pressures due to compaction is difficult because:

- Earth pressure cells sometimes give erroneous readings, depending on their stiffness and how they are installed;
- Compaction-induced earth pressures vary rapidly with depth, resulting in misinterpretation if fill elevations are not measured with sufficient accuracy;
- There appears to be large inherent variability in earth pressures, resulting in possible erroneous evaluations if too few measurements are made; and
- Small wall movements can change earth pressures very significantly, requiring walls to 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.

DESIGN FEATURES

The instrumented retaining wall is 7 ft high and 10 ft long. Figure 1 shows the principal features of the wall, and Figure 2 shows the wall before and after backfilling. The bottom of the wall is 3 ft below floor level, 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 Figure 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 in. above the bottom, and one located 60 in. 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 Figure 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 Figure 3. These pressure cells are all quite stiff, and are mounted flush with the faces of the wall panels. They are located at 6.0 in. vertical spacings in four vertical strips on the two wall panels. They thus provide closely spaced points for determining variations of earth presssure with depth, as well as 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 the horizontal position over the fill. The frame is shown in Figure 1 and is visible in Figure 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.

Movements of the wall panels are measured by 8 linear variable differential transformers (LVDTs), one near the top

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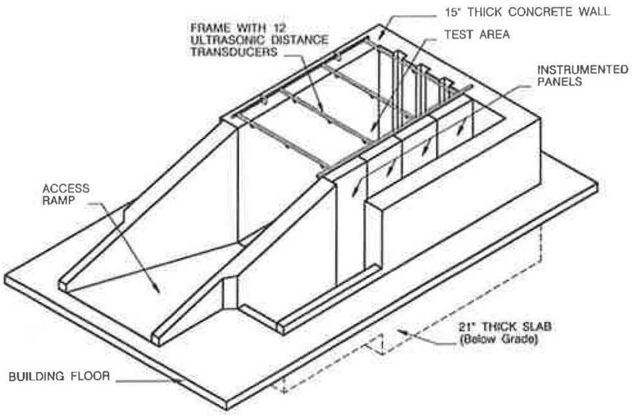


FIGURE 1 The Instrumented Retaining Wall Facility.

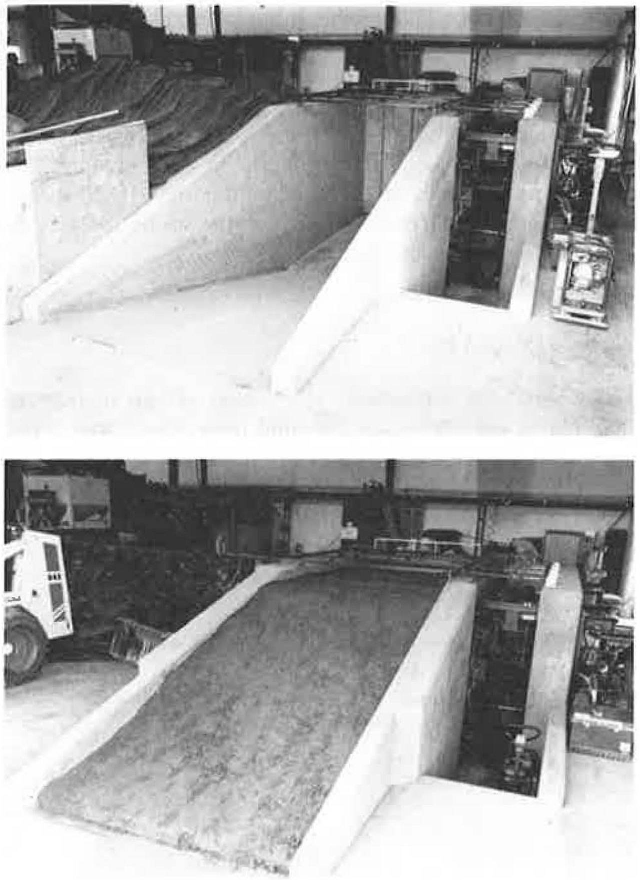


FIGURE 2 Facility before and after backfilling.

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, in order to determine possible temperature effects on the readings.

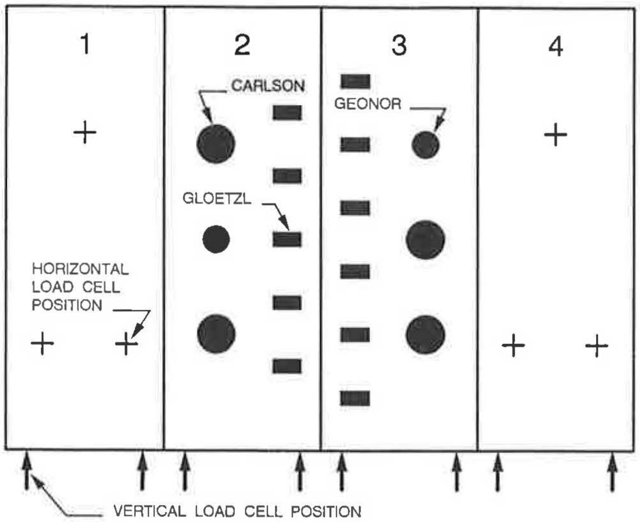


FIGURE 3 The four panels of the instrumented wall.

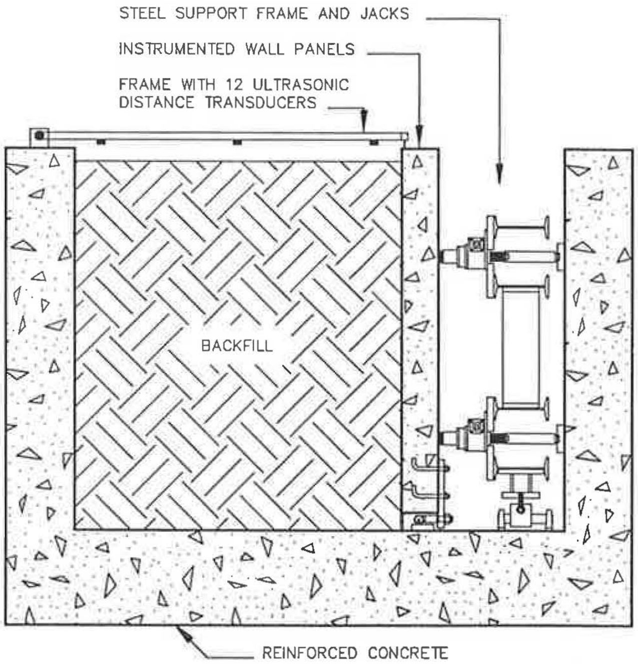


FIGURE 4 Cross-section through the instrumented wall.

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 measurements provide the information needed to adjust the Gloetzl cell readings for temperature-induced zero shift.

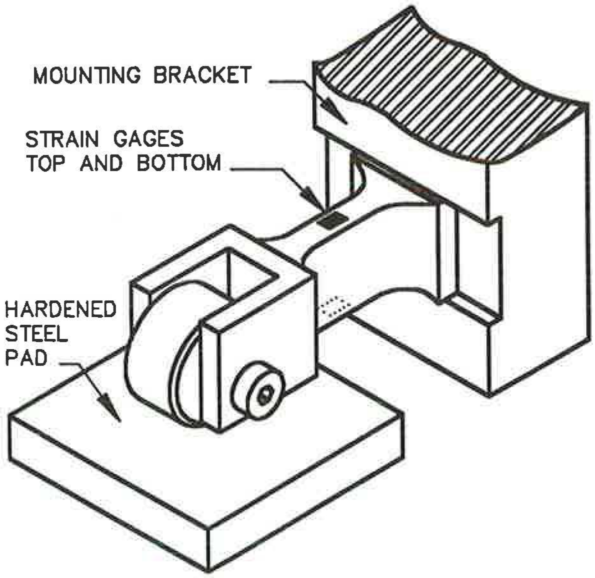
All of the instruments are monitored by a computer-controlled data acquisition system. Measurements are made after each lift has been placed loose and again after it has been compacted. Two independent sets of readings are made each time and stored in different data files. This provides security in case one set of readings should be destroyed accidentally, as well as 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.

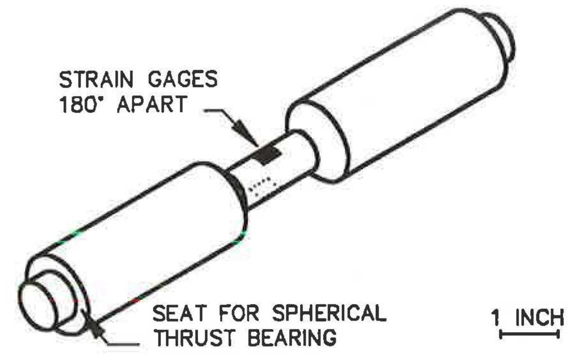
TECHNICAL CHARACTERISTICS OF THE INSTRUMENTATION SYSTEM

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 Figure 5, these load cells are 4 in. 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 gauges attached to the cantilever beams. The accuracy of the load cells is about 15 lb, or about 30 lb per panel.



VERTICAL LOAD CELL



HORIZONTAL LOAD CELL

FIGURE 5 Vertical and horizontal load cells.

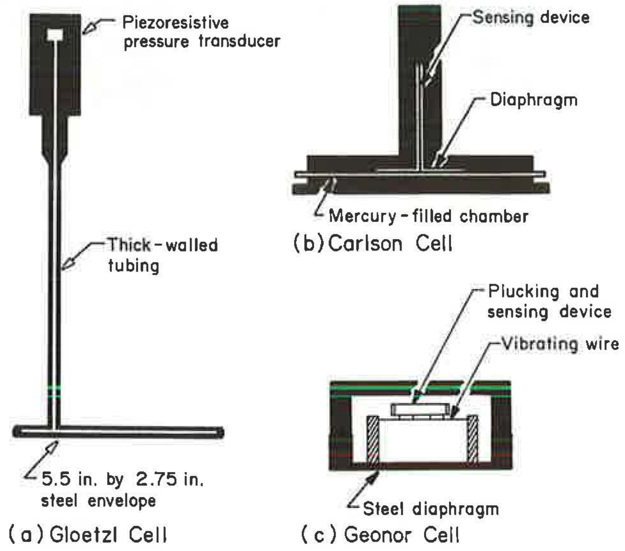
Horizontal Load Cells

The horizontal reaction forces on the wall panels are measured using column load cells with bonded strain gauges. As shown in Figure 5, the ends of the columns are seated in spherical bearings to minimize bending moments. The accuracy of the load cells is about 50 lb, resulting in overall accuracy of about 150 lb 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. Comparing these to the same quantities determined from the earth pressure cell readings provides an independent check on accuracy.

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 of 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 these springs that there is no appreciable change in the spring force 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 Figure 6(a). They are 5.5 in. long, 2.75 in. wide, and 0.18 in. thick. The front face is flat. The oil pressure is transmitted to a pressure transducer by means of a heavy gauge steel tube that extends from the back of the cell. The cells used in this were fitted with electrical pressure transducers so that they could be read using the data



(a) Gloetzl Cell (b) Carlson Cell (c) Geonor Cell

FIGURE 6 Earth pressure cells.

acquisition system. The transducers were purchased in the United States and were attached to the pressure cells at the Gloetzl factory in Germany.

The Carlson earth pressure cells are 7.4 in. in diameter and about 1 in. thick, as shown in Figure 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 pressure readings are sensitive to the temperature of the cell, and the temperature is measured each time a pressure reading is made.

The Geonor earth pressure cells are 6.5 in. in diameter and 1.8 in. thick. As shown in Figure 6(c), the face of the gauge is a stiff metal diaphragm. The diameter of the active portion of this diaphragm is 2.95 in. Attached to the back of the diaphragm is a taut wire that is caused to vibrate at its natural frequency by an electrical magnet, which 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 and transmitted as an electrical signal to the data acquisition system. The frequency of vibration is determined by counting the number of signal pulses for a set period, like one second.

Ultrasonic Distance Measuring Devices (UDMDs)

As illustrated in Figure 7, the UDMDs send out a burst of ultrasound at a signal frequency and measure the length of time for the first reflected wave to reach the instrument. This interval of time, divided by the speed of sound, is twice the distance from the instrument to the surface causing the reflection. 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, resulting in accuracy of about 0.1 in. in the measured values of fill depth. The maximum range of the UDMDs is about 30 ft, which is considerably longer than required for this application.

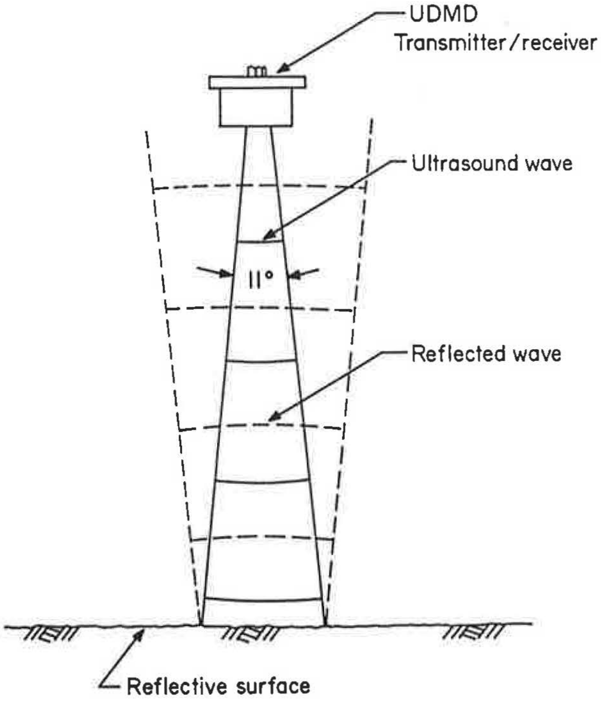


FIGURE 7 Ultrasonic distance measuring device (UDMD).

Linear Variable Differential Transformers (LVDTs)

The LVDTs are powered by direct current. Their range of measurement is 1.0 in. By accounting for output nonlinearity, accuracies on the order of 0.0005 in. are achievable.

Thermocouples

The thermocouples are conventional copper-constantan devices capable of measuring temperature with an accuracy of 0.5 degree Fahrenheit.

DATA ACQUISITION SYSTEM

Computer

The data acquisition system is controlled by the IBM XT microcomputer shown in Figure 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 Figure 8 contains the multiplexing cards that are connected to each of the instruments. The data acquisition cards in the computer select the channel to be read and read the signals from the instruments.

Power Supply

The power supply for the instruments is located in the cabinet with the multiplexing cards. It is connected to a digital voltmeter that is used to regulate its output with an accuracy of 0.02 percent before each set of readings.

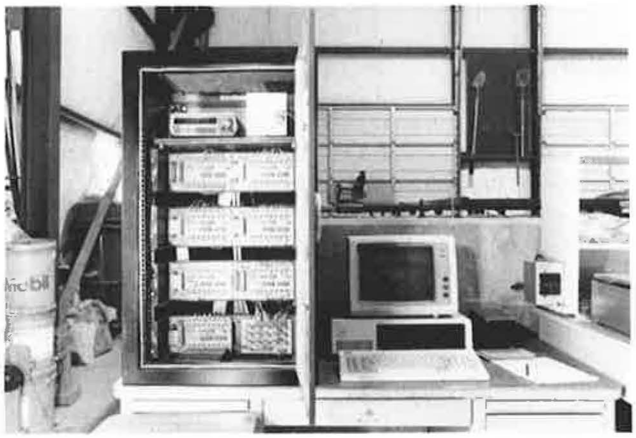


FIGURE 8 The computer and the cabinet containing the multiplexing cards.

Voltage Measurements

The reading of instruments that produce 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 produce voltage signals that are transmitted through the multiplexing cards connected to the DAS-8 controller card. Under software control, the DAS-8 selects each channel in turn, converts the analog signal to digital form, and transmits it to computer memory. The 12 bit analog to digital conversion is capable of dividing a signal into as many as 4,096 parts.

Frequency Measurements

The Geonor earth pressure cells produce 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. Each Geonor cell is connected to a separate channel on the CTM-05 controller card. The Geonor cells have their own control circuits, which are connected to the power supply and produce 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 to a UDM-MUX multiplexer card in an external cabinet by a 14 conductor cable. Each of the UDMDs is connected to a separate channel on the multiplexing card. 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.

Software Control

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 provide logical procedures for eliminating erroneous readings. They also store the data acquired in files on hard and floppy disks and add identifying labels specified by the user.

Each of the voltage measurements is repeated 20 times, and the average of these 20 readings is calculated. 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, and the result is stored. 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 average frequency is multiplied by a constant to convert it to pressure, and the value is stored in the data file.

The logic governing the reading of the UDMDs is the most complex of any of the instruments. This is necessary because sometimes a reflected signal is not detected. The software addresses each of the instruments 10 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 10 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 reduce the measured time intervals to distance values. These are stored in the data file together with the number of successful attempts to read the instrument. With this procedure for data acquisition, the system performs well.

Operation

Two routines are used to make readings. The first is used when a loose lift of backfill has been placed behind the wall, before it has been compacted. This routine does not include UDMD measurements, because they are not effective in measuring the elevation of the nonreflective loose earth. It does include readings of all the other instruments. Making two sets of readings with this routine takes about 3 minutes.

The second routine is used after a lift has been compacted. It includes readings of the UDMDs as well as the other instruments. Making two sets of readings with this routine takes about 5 minutes.

System Development

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 the first author 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 the first author.

CALIBRATIONS AND ACCURACY OF INSTRUMENTS

Calibrations

The load cells were calibrated twice, once in a universal testing machine in the geotechnical engineering laboratory, and once

TABLE 1 SUPPLIERS 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, Inc. 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 Stamford, CT 06907
Data Acquisition Hardware Models: DASH-8, EXP-16, CTM-05	MetraByte Corporation 440 Myles Standish Blvd. Taunton, MA 02780

in place after installation in the experimental 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 calibrating 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 takes into account the use of multiple readings to improve the resolution of each set of readings.

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 similar facility 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 elab-

TABLE 2 ESTIMATED INSTRUMENT ACCURACIES

Instrument	Estimated Accuracy[a]
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° F

[a] 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.

TABLE 3 APPROXIMATE COST OF INSTRUMENTED RETAINING WALL FACILITY

Item	Cost
Reinforced Concrete Sidewalls, Floor, and Ramp	$15,500
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
LVDTs (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

orate 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 handling, automatic data acquisition reduces the time for collecting data, and computer programs reduce the time required for processing and plotting the information.

MEASURED EARTH PRESSURES AND SHEAR LOADS

The first experiments in the Instrumented Retaining Wall facility were performed using a silty sand from the foundation of Yatesville Dam in Kentucky. About 45 percent of this material passes the #200 sieve, and the fines are nonplastic. It has a Standard AASHTO maximum dry density of 120 lb/ft^3, and an optimum water content of 12.5 percent.

In the first tests the backfill was placed behind the wall at a water content of about 14.5 percent, and compacted with a Wacker BPU 2440A vibratory plate compactor. The lifts were 4 in. thick after compaction. The compacted density was 120 lb/ft^3. The water content was approximately 2.0 percent wet of the line of optimums, and a small amount of water drained from the fill during a 2 day period after placement. Although the fill was compacted to 100 percent of the Standard AASHTO maximum dry density, it remained sufficiently deformable after compaction that the vibrating plate compactor left a track about 0.5 in. deep on the final pass, and the Bobcat tractor loader left tire prints about 1.0 in. deep on the compacted fill.

Earth pressures measured after compaction are shown in Figure 9. Integration of the measured pressure distribution indicates that the horizontal resultant force is about 5600 to 5800 lb, depending on how the pressures are assumed to vary above the top and below the bottom pressure cells. The sum of the horizontal force transducers for panel 3 indicates a horizontal resultant force of 5400 lb, about 4 percent to 7 percent less than indicated by integration of the pressure diagram. The resultant force acts at 0.38(H) based on the force transducer data and at 0.34(H) based on the pressure cell data.

Figure 9 includes a theoretical earth pressure variation that was calculated using the method of Duncan and Seed (*2*) and the computer program NCOMP, developed by Seed and Duncan (*3*). The measured and calculated values agree well on average. The measured values are smaller than the calculated values near the top of the fill, however, and larger than the calculated values near the bottom.

The differences between the measured and the calculated values can be attributed to two factors:

1. It seems likely that the dynamic force applied by the vibrating compactor is smaller than the manufacturer's rated force of 5400 lb, perhaps because the moist silty sand is not very firm even after compaction to 100 percent of the Standard AASHTO maximum dry density. This would explain the fact that the measured values are smaller than the calculated values in the upper 3 ft.
2. The measured total stress coefficient of earth pressure at rest for the moist silty sand is about 0.8, rather than the expected value of 0.5 used in calculating the theoretical variation shown in Figure 9. This high value of K_0 may be related to pore pressure effects within the backfill during compaction. A small amount of water drained from the fill after compaction, and the pressure decreased about 35 percent within a 5 day period after compaction, bringing the value of K_0 down to about 0.5.

It is planned to study these effects further through experiments to measure the dynamic forces applied by vibratory compactors and laboratory tests to study the factors that influence the value of K_0 for compacted fill.

Vertical shear loads measured during backfilling and for a period of about 5 days after compaction are shown in Figure

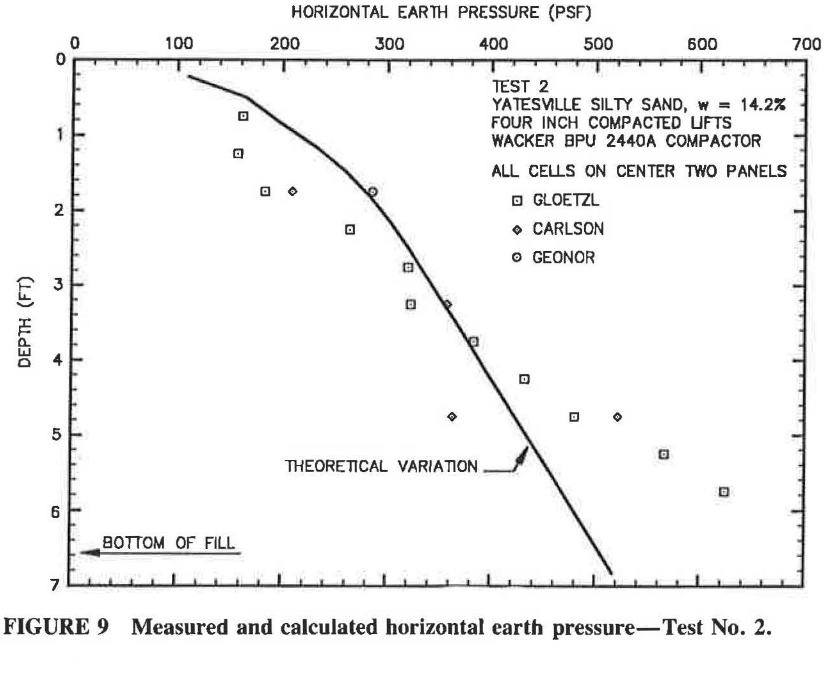


FIGURE 9 Measured and calculated horizontal earth pressure—Test No. 2.

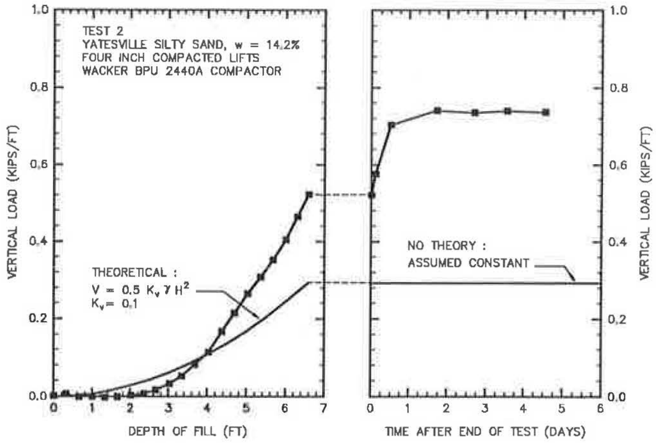


FIGURE 10 Measured and calculated vertical shear loads—Test No. 2.

10. The "theory" used to calculate the theoretical values shown in Figure 10 is quite rudimentary. The theoretical variation shown in the figure is based on the results of finite element analyses of a number of 40 ft high walls. These analyses indicated that the value of the vertical shear coefficient (K_v) is not less than about 0.1 for a wide range of conditions of wall geometry and backfill properties.

It can be seen that the equation shown in the left side of Figure 10 underestimates the vertical shear load for fill depths greater than about 4 ft. Since the shear load results from settlement of the backfill relative to the wall, and since the amount of settlement increases with increasing fill depth, it seems probable that the shear load (V) should be proportional to fill depth (H) raised to a power larger than two. More experimental and theoretical work is needed to develop improved means for estimating shear loads on walls.

As shown at the right side of Figure 10, the measured shear load increased by about 40 percent over a period of about 5 days after backfilling. This increase in shear load is believed to result from settlement of the fill over this period, although no measurements of the settlement were made in Test No. 2. Settlements as small as 0.1 in. would be sufficient to mobilize significant shear loads on the wall. Further study is planned to investigate the factors causing changes in shear loads with time after compaction.

CONCLUSION

The Instrumented Retaining Wall Facility at Virginia Tech has been developed to study the factors that influence normal and shear loads on retaining walls. The electronic instruments and the data acquisition system in the facility make it possible to perform efficient and accurate studies of earth pressures during and at the end of backfilling and their variation with time after backfilling. This facility offers promise for investigating aspects of the horizontal and vertical earth loads on retaining walls that are not reflected in conventional earth pressure theories, but which have significant effects on the stability and performance of retaining walls.

ACKNOWLEDGMENTS

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