FIELD MEASUREMENTS OF LATERAL EARTH PRESSURES ON A CANTILEVER RETAINING WALL

H. M. Coyle, R. E. Bartoskewitz, and L. J. Milberger, Texas Transportation Institute, Texas A&M University; and
H. D. Butler, Texas Highway Department

This paper presents results from a research study on determination of lateral earth pressure for use in retaining wall design. The broad objective of the study is to develop improved design procedures for retaining walls. The limited objective of the phase of the study covered in this paper is to measure the pressure acting on a typical cantilever retaining wall and to compare the measured pressures with theoretical pressures determined by Rankine and Coulomb theories. Terra Tec pneumatic and Geonor vibrating wire pressure cells were used to measure lateral earth pressures. Procedures used to calibrate the pressure cells are presented. Measurements of the lateral movement of the wall were made during and after backfilling. Data covering a period of 14 months are presented. These data include graphs of earth pressure and wall movement versus time and graphs of pressure distribution versus depth. Engineering properties of the backfill materials are presented. Computed earth pressures based on the Rankine and Coulomb active case are compared with measured pressures. A significant finding is that the measured pressures near the base of the wall are higher than the active pressures. They are nearly equal to the at-rest pressures that are possible as a result of the small movements that occurred at the base of the wall.

•THE findings presented in this paper were obtained during the second year of a 5-year study on determining lateral earth pressure for use in retaining wall design. During the first year of this study an effort was made to evaluate commercially available earth pressure cells. Two promising earth pressure cells were selected for use during the second year. The two cells selected were the Terra Tec pneumatic cell and the Geonor vibrating wire cell. The main effort during the second year involved measurement of the distribution of pressure on a cantilever retaining wall and improvement of calibration procedures for the pressure cells.

The test site for this study is located along highway US-59 near the intersection with Interstate 45 in Houston. Seven cantilever retaining walls were constructed at this site. The Texas Highway Department designated these as retaining walls A through G. One panel in retaining wall G was selected for use during the second year of this study, and this panel is designated here as test wall G. Four Terra Tec and two Geonor cells were installed in test wall G in March 1972. Backfilling operations began in early April 1972, and periodic measurements of earth pressures have been made since that time. The data obtained during the period from April 1972 through May 1973 are presented in this paper. Additional measurements of earth pressures on test wall G are being made during the third year of this research program.

The ultimate objective of the 5-year research study is to develop a more economical design procedure for retaining walls. The specific objectives of the work initiated during the second year of the study were as follows:

1. To measure lateral earth pressures on a cantilever retaining wall using the Terra Tec pneumatic and Geonor vibrating wire pressure cells;

2. To improve the procedures used for calibrating these cells and investigate the effects of grouting, temperature, and drift or change in zero gauge reading on cell response;

3. To measure the lateral displacement of the retaining wall in conjunction with pressure measurements so that wall movements can be correlated with measured pressures;

4. To sample and test the soil used for backfill material; and

5. To compute lateral earth pressures using existing theories (Rankine and Coulomb) so that a comparison can be made between the theoretical pressures and the measured field pressures.

PRESSURE CELLS

The reasons for selecting the Terra Tec and Geonor cells for use in the second year of this research study have been presented in some detail elsewhere (1). The Terra Tec cell is relatively new and has not been proved reliable for long-term performance. However, the ability to backflush the Terra Tec cell and purge the system of entrapped moisture indicates that these cells can be kept operative for long periods of time if mechanical difficulties do not develop. The Geonor cell has been used successfully for long-term pressure measurements, particularly in Canada and Europe (3, 4). The principle of operation of the Terra Tec and Geonor cells is covered elsewhere (1) and will not be discussed in this paper. The Terra Tec cell with readout device is shown in Figure 1. The Geonor cell with readout device is shown in Figure 2.

Before the Terra Tec and Geonor pressure cells could be installed in test wall G it was necessary to conduct calibration tests to determine the response of the cells in terms of pressure sensitivity and temperature variations. Pressure sensitivity of the cells as used in this paper means the output of the pressure cell in response to an applied pressure, or change in pressure, as made manifest by the readout unit to which the cell is connected. In the case of the Terra Tec cells, this response is indicated by a pressure reading in pounds per square inch on the readout unit. The pressure sensitivity of the Terra Tec cell is therefore the pressure change required on the face of the cell to produce a change of 1 psi in the reading of the pressure gauge on the readout unit.

For the Geonor cell the situation is somewhat more complex. During a typical calibration test, known pressures are applied incrementally on the face of the cell. At each pressure increment the frequency of vibration in hertz of the wire inside the cell is displayed on the readout unit. The output of the vibrating wire cell is intrinsically nonlinear, and a graph of applied pressure versus frequency of vibration does not plot as a straight line. Based on the fundamental mathematical theory of the cell, the manufacturer suggests (2) that the data be transformed so that a linear plot will be obtained. If f_0 is the frequency at zero pressure and f is the frequency with a known pressure applied, the squared-frequency difference is then $\Delta f^2 = f^2 - f_0^2$. For example, the cells installed in test wall G have a nominal zero pressure frequency of f_0 = 1100 Hz. At 12 psi (83 kPa) applied pressure (the maximum pressure applied during calibration tests) the nominal frequency is f = 1385 Hz; Δf^2 is then $1385^2 - 1100^2$ or Δf^2 = 708 225 Hz. With frequency recorded to four significant figures, Δf^2 is divided by a scale factor of 1000 to obtain numbers that do not exceed the precision of the input data. A plot of applied pressure versus $\Delta f^2/1000$ will be linear, and the slope of the straight line is regarded as being the pressure sensitivity of the cell. Thus, the pressure sensitivity of the Geonor cell is defined as the pressure change per unit of squared-frequency difference Δf^2 divided by 1000.

Calibration was accomplished by placing a pressure cell inside a sealed chamber and then increasing the air pressure in the chamber. A typical calibration run consisted of applying 23 increments of pressure beginning with 0, increasing to 12 psi (83 kPa), and returning to 0. Each increment of pressure was nominally 1 psi (6.9 kPa). A typical calibration curve for the Terra Tec cells is shown in Figure 3. Figure 4 is a typical applied pressure versus frequency plot for the Geonor cells and illustrates the nonlinear response of the cell. Figure 5 shows the linear plot of pressure versus squared-frequency difference.

Figure 1. Terra Tec cell and readout device.

Figure 2. Geonor cell and readout device.

Figure 3. Typical calibration curve for Terra Tec cell (1 psi = 6.9 kPa).

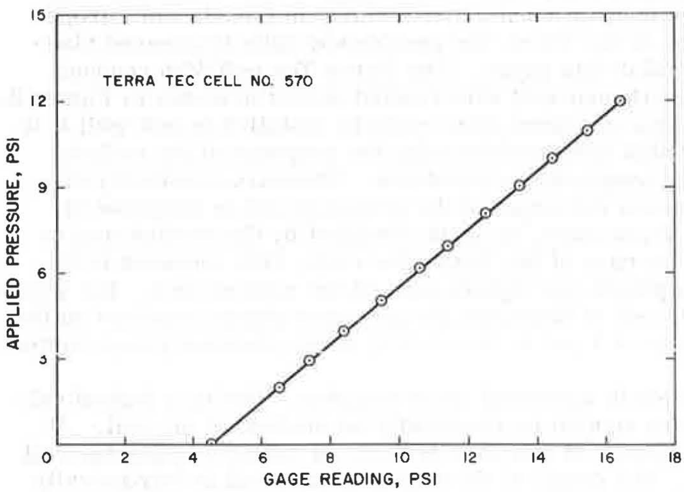
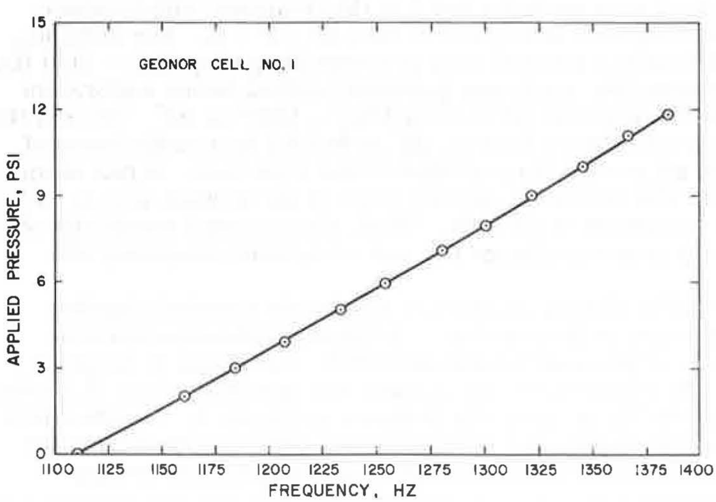


Figure 4. Typical pressure versus frequency curve for Geonor cell.



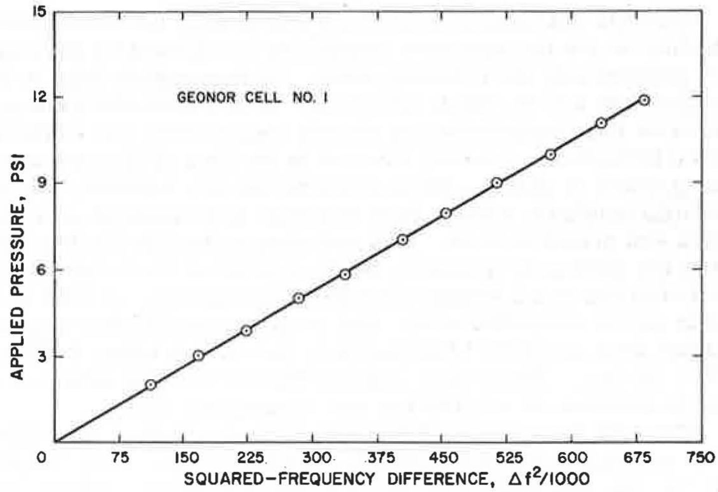


Figure 5. Typical calibration curve for Geonor cell.

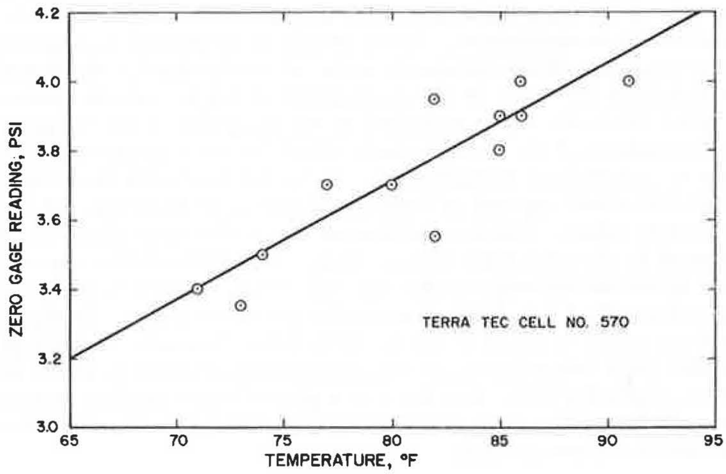


Figure 6. Typical field relationship between zero gauge reading and temperature.

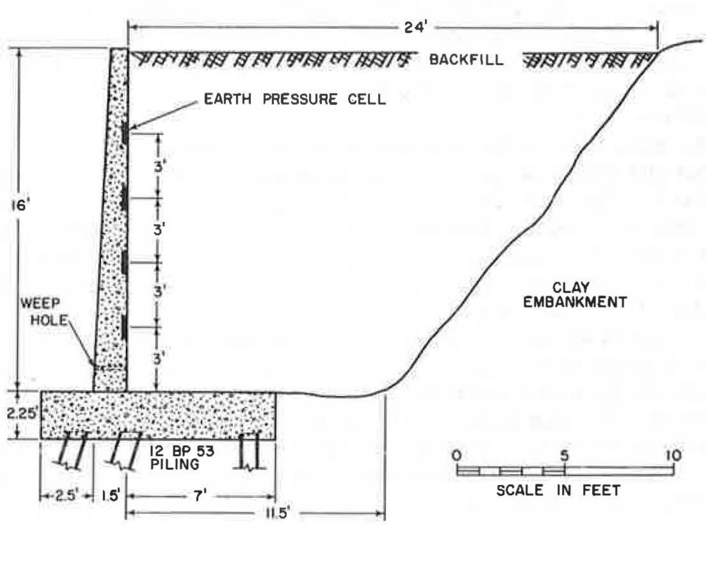


Figure 7. Cross section of test wall G (1 ft = 0.305 m).

After the calibration tests were completed, an investigation was made to determine whether or not the pressure sensitivity is affected or altered when the pressure cells are grouted into the retaining wall. To accomplish this, a Terra Tec cell was grouted into a 4-in.-thick (102-mm), 16-in.-diameter (406-mm) block of concrete. To simulate field installation as closely as possible, the concrete block was cast and allowed to harden. A cavity was cut in the face of the concrete and the pressure cell was grouted in place. Three coats of flexible weatherproof coating containing a high-strength synthetic rubber base material were applied over the entire surface of the block and pressure cell. This was done to isolate the back face of the pressure cell from the pneumatic pressure being applied on the front face. The cell was then calibrated in the exact manner described previously. A total of six calibration tests were made on the embedded cell. The pressure sensitivities computed from the test data ranged from 0.972 to 1.013 psi/psi, the median being 1.006 and the average being 1.001 psi/psi. These data indicate that there is no effect on pressure cell response due to installation or grouting into a retaining wall.

After the pneumatic calibrations were conducted, the effect of temperature on the zero reading was investigated in the laboratory. Five temperatures were used: 52, 62, 74, 84, and 104 F (11, 17, 23, 29, and 40 C). All the cells were placed inside a room where the temperature was maintained constant at one of the given test temperatures. A 24-hour waiting period was allowed for the cells to reach equilibrium with the ambient temperature. A second 24-hour period was allowed during which the zero gauge readings of the pressure cells were checked periodically. All cells were found to exhibit an increase in the zero gauge reading with an increase in temperature.

After the cells were installed in the retaining wall, additional data were obtained for evaluation of the temperature effect on zero reading. In this case it was impossible to control the temperature. In order to obtain the widest range of temperature within the short amount of time available to acquire the data, both day and night readings were taken. The temperatures recorded were those of the concrete immediately adjacent to the pressure cells. They were obtained by means of thermocouples that were mounted directly on the surface of the concrete, a thermocouple being mounted approximately 1 in. from each of the pressure cells. In this manner, a range of temperature from 71 to 91 F (22 to 33 C) was obtained. Readings were not begun until several days after the cells were installed in order to allow the epoxy grout sufficient time to fully harden. Figure 6 is a plot of zero reading versus temperature for Terra Tec cell No. 570. It is representative of the data obtained from the other three Terra Tec and two Geonor cells.

INSTALLATION OF CELLS

A typical cross section of the cantilever retaining wall (test wall G) is shown in Figure 7. It should be noted that the cantilever retaining wall is resting on H piles. The water table is located below the footing of the wall. Weep holes are provided to allow drainage and thus to try to prevent any hydrostatic pressure from building up behind the wall.

The back face of the retaining wall was instrumented with four Terra Tec and two Geonor pressure cells. The cell locations on the retaining wall panel are shown in Figure 8. The four Terra Tec cells were arranged in a vertical row so that measured pressure distribution behind the wall could be established. The upper and lower Geonor cells were located at the same depths as the top and bottom Terra Tec cells so that a check could be made of the magnitudes of the measured pressures at the 4-ft (1.2-m) and the 13-ft (4-m) depths. Also, the upper Terra Tec (No. 570) and upper Geonor (No. 1) could be uncovered at some time after backfilling to check the zero gauge readings for these two cells. A thermocouple was installed at each pressure cell location so that temperature could be determined at the time the pressure readings were taken.

Because the construction of test wall G was completed prior to the installation of the pressure cells, it was necessary to cut a cavity in the wall and grout the cells in place. After the cavities had been cut, the pressure cells were cemented in place with an epoxy grout known as "Patch All Special". The cells were installed so that the face of each cell was flush with the back of the wall. Care was taken to ensure that uniform and intimate contact with the seating surface was achieved. The installation procedure for a Terra Tec cell is shown in Figures 9, 10, and 11.

A thermocouple was installed at each pressure cell location. Each thermocouple was covered with a waterproofing compound. All connector cables and wires were secured to the retaining wall with a strip of raw tread rubber. The completed installation of the cells for test wall G is shown in Figure 12.

The backfill operation for test wall G took place over a period of 6 days. The backfill material was dumped and roughly spread by heavy scrapers. The completed spreading and compaction were done with a bulldozer. The backfill material was spread in approximately 8-in. (200-mm) lifts, and the bulldozer made approximately three passes on each lift. Care was taken to ensure that none of the instrumentation on the test wall panel was damaged by the earthmoving equipment. Earth pressure measurements were made during the backfilling operation.

Samples of the backfill material were taken during the backfilling operation in order to determine in-place moisture content and wet unit weight (density). The wet (total) unit weight next to the test panel averaged 91.6 pcf (1463 kg/m^3), and at the center of the backfill the wet unit weight averaged 101.3 pcf (1618 kg/m^3). The average moisture content was 20.4 percent, and the specific gravity of the soil was 2.68.

The observed unit weights may be somewhat lower than the unit weights achieved. This is due to the high placement moisture content of the backfill and the method of sampling. Unit weight determinations were made with a Soiltest balloon volumeter. The apparatus is used to determine the volume of soil removed from a test hole by measuring the amount of water required to completely fill the hole. Due to the high moisture content of the soil it is possible that the water balloon pressing against the side of the hole may have increased the volume of the hole. Using the larger volume to compute the unit weights would have the effect of giving lower unit weights than those actually achieved. Because of this problem, a wet unit weight of 110 pcf (1760 kg/m^3) was used in the theoretical computations presented in this paper. An average wet unit weight of 110 pcf was obtained in the backfill of the test panel during the first year of this research study using essentially the same backfill material.

The backfill material was a tan fine sand containing a small percentage of silt. The soil was classified as SP-SM according to the Unified Classification System. Undrained direct-shear tests were conducted on representative samples of the backfill material, and the angle of internal friction was determined to be 32 deg.

DATA COLLECTION

The lateral earth pressures measured on test wall G from April 1972 through May 1973 are given in Table 1. Also, the measured pressures are plotted versus time in Figures 13 through 15. In general, it may be stated that the performance of the pressure cells has been reasonably consistent. The plotted data in Figures 13 through 15 indicate either a simultaneous increase or decrease in pressure during a given period of time. Maximum pressures were achieved at the completion of the backfilling operation, and, except for minor variations, the pressures remained relatively constant until October 1972. The reason for the drop in measured pressures during the winter months is not known. It is possible that temperature corrections were not accurate because the temperature calibration curves were established for a range of 70 to 90 F (21 to 32 C) and the temperatures dropped to 40 to 50 F (4 to 10 C) during the winter months. Consequently, extrapolation was required in order to establish a temperature correction for these lower temperatures.

In October 1972 the upper pressure cells were uncovered (Terra Tec No. 570 and Geonor No. 1) by removing approximately 5 ft (1.5 m) of the backfill material. This was done to establish whether the zero pressure reading for each cell had changed during this 6-month period. As shown in Table 1, the zero pressure readings did not change significantly. However, after the backfill material was replaced, the pressure readings for these two cells never returned to the prior reading of approximately 2 psi (14 kPa). It should be noted that Geonor No. 2 became inoperative in February

Figure 8. Location of earth pressure cells, test wall G.

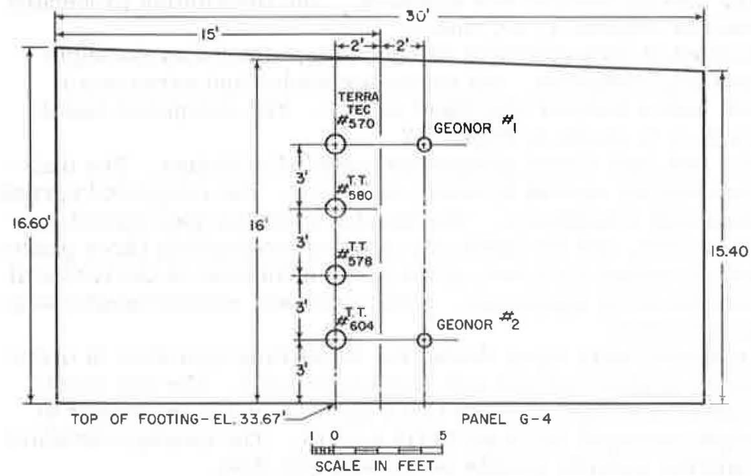


Figure 9. Cell cavity.

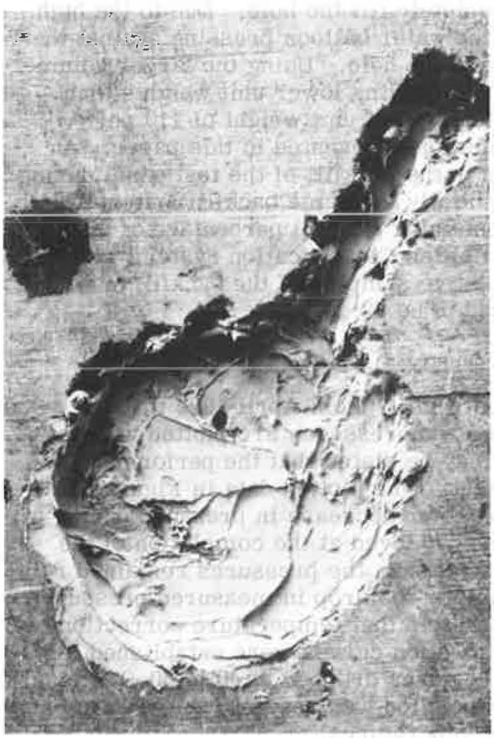
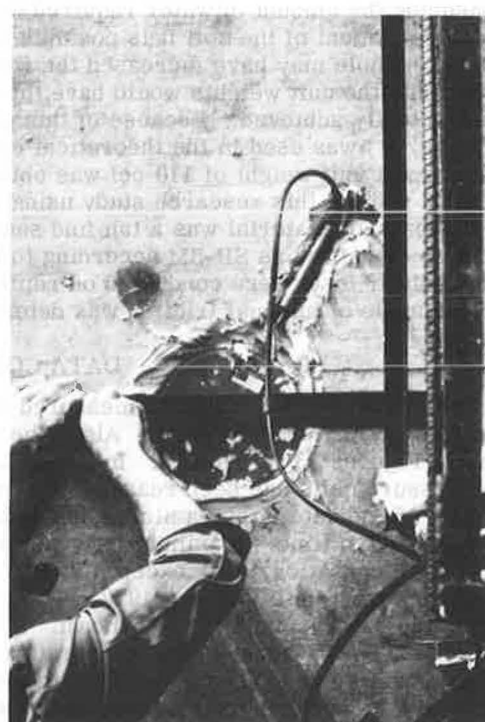


Figure 10. Installed cell.



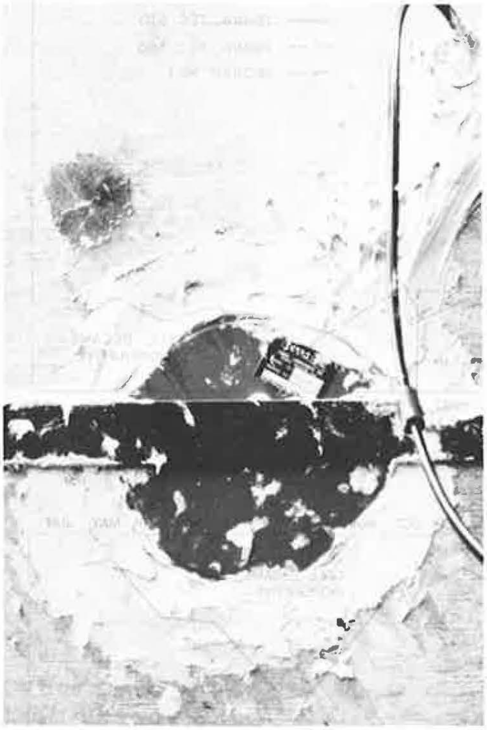


Figure 11. Final grouting.

Figure 12. Completed installation.

Table 1. Measured lateral earth pressures (in psi) for test wall G.

Date	Elasped Time in Days	Terra Tec 9 570	Terra Tec 9 580	Terra Tec 9 578	Terra Tec 9 604	Geonor 6 1	Geonor 6 2
12 April 1972	1	0	0	0	0.64	0	0.46
13 April 1972	2	0	0	0	1.97	0	1.79
14 April 1972	3	0	0	0	1.20	0	1.19
17 April 1972	6	0	1.65	4.00	4.55	0	4.23
18 April 1972	7	1.74	2.93	6.35	8.05	2.92	7.89
Backfilling operation completed							
20 April 1972	9	1.66	2.87	6.65	8.59	2.40	8.27
25 April 1972	14	1.10	2.48	6.20	8.49	1.80	8.64
2 May 1972	21	1.24	2.54	5.97	8.30	2.64	8.23
10 May 1972	29	1.70	2.98	6.78	8.97	2.89	8.71
17 May 1972	36	0.40	2.60	6.03	8.20	2.31	8.34
1 June 1972	51	1.08	2.27	6.27	8.40	2.40	8.35
15 June 1972	65	2.18	2.68	6.56	9.13	3.22	8.35
18 July 1972	98	1.42	2.24	6.00	8.35	2.40	8.07
6 Sept. 1972	148	2.16	2.51	6.43	9.24	2.30	8.52
10 Oct. 1972	182	1.70	1.76	6.06	8.60	2.38	8.45
5 ft of backfill removed							
10 Oct. 1972	182	0.05	1.96	5.86	8.40	-0.20	8.13
19 Oct. 1972	191	-0.07	2.56	6.52	9.05	-0.08	8.73
Backfill replaced							
19 Oct. 1972	191	0.33	2.46	6.42	8.95	0.31	8.69
19 Dec. 1972	252	-0.05	1.20	4.50	6.35	0.74	7.70
8 Jan. 1973	272	-0.65	0.40	4.30	6.20	0.63	8.12
26 Feb. 1973	321	-0.45	2.00	5.40	7.95	0.35	—[a]
5 April 1973	359	-0.15	1.65	5.10	8.05	0.43	—[a]
9 May 1973	393	-0.10	2.20	6.00	9.40	—[a]	—[a]
31 May 1973	415	0.35	1.75	5.80	9.30	—[a]	—[a]

Note: 1 psi = 6.9 kPa.

[a]Gauge inoperative.

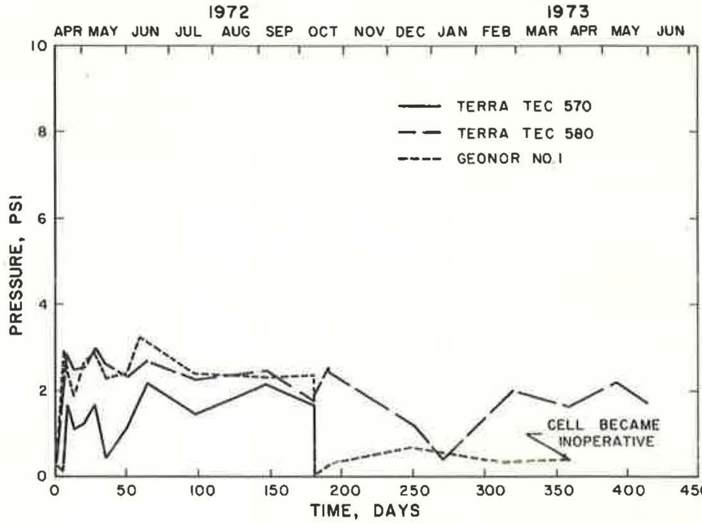


Figure 13. Measured pressure versus time, Terra Tec No. 570 and 580 and Geonor No. 1.

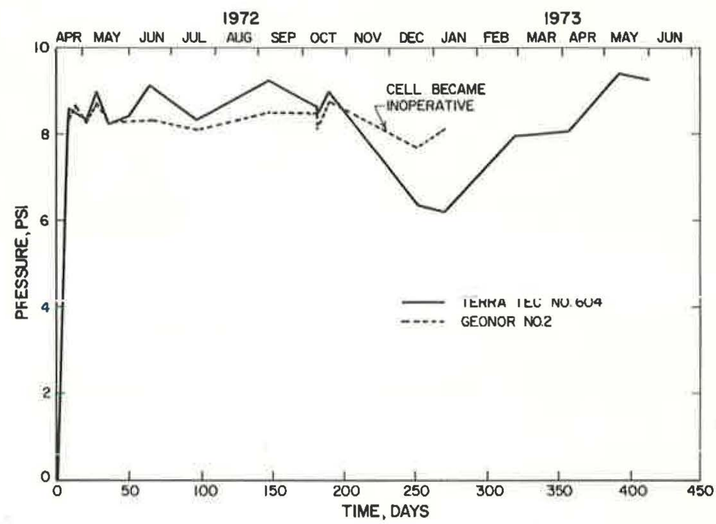


Figure 14. Measured pressure versus time, Terra Tec No. 604 and Geonor No. 2.

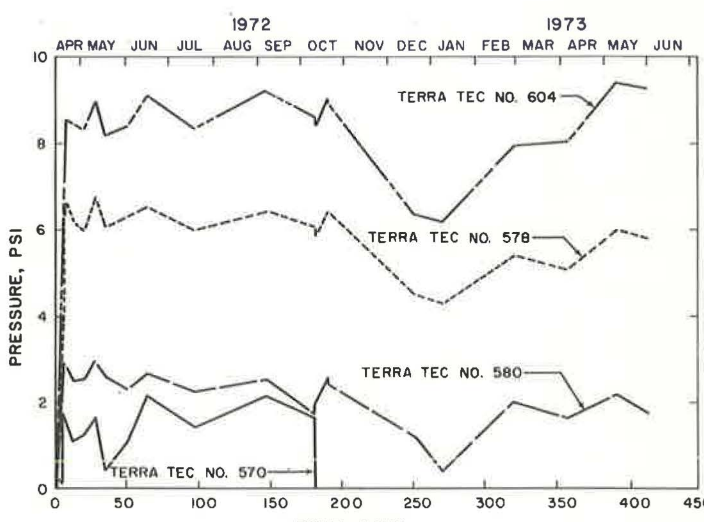


Figure 15. Measured pressure versus time, Terra Tec No. 578, 580, and 604.

1973 and Geonor No. 1 became inoperative in May 1973. Efforts have been made to restore these cells to an operating condition but have not been successful. All Terra Tec cells are still operating.

Pressure measurements were made periodically during the backfilling operation in an attempt to measure dynamic pressures caused by the hauling and compacting equipment. Neither the Geonor nor the Terra Tec is well adapted for this kind of measurement. Either system requires a certain time period during which the readout unit senses the signal being sent by the pressure cell. The pressure acting on the cell cannot be displayed on the readout unit before the time period is complete. Of the two cells, the Geonor has the shorter period; it is approximately 3 to 4 seconds. For this reason the majority of dynamic measurements were made with the Geonor cell. Check measurements attempted with the Terra Tec cell yielded dynamic pressures that were in general agreement with the Geonor indications. Throughout the course of the dynamic measurements it was observed that the maximum observed dynamic pressure at any time did not exceed the maximum recorded static pressure after the backfill was completely in place. Moreover, as one would expect, at a given point on the wall the influence of the compaction equipment on the pressure at that point decreased as the height of backfill increased.

Measurements of wall movements are needed to establish the expected type of earth pressure distribution. In order to determine the lateral movement of the wall a point was established on the top of the wall. The distance to this point from a fixed point was recorded each time a set of measurements was made. The fixed point was located on a 36-in.-diameter (910 mm) reinforced concrete drilled shaft. The nominal distance from the fixed point to the top of the wall was 67 ft (20.4 m). The distance was measured with an engineer's 100-ft steel tape supported at the 0 and 67-ft marks. The fixed point was located on the drilled shaft at the same elevation as the top of the retaining wall to eliminate the need for slope corrections. Each time a distance was measured the tape temperature was recorded so that observed distances could be corrected for temperature. Tape tension handles were used to ensure a constant 25-lb (111-N) tension when measurements were made.

Displacements due to tilting or rotation were determined by measuring the horizontal offset distance from a vertical line fixed with respect to the top of the wall to several fixed points on the front face of the wall. The vertical reference line was established by suspending a 25-lb (11.3-kg) plumb bob from a frame that was rigidly attached to the top of the wall. With respect to the top of the wall the fixed points were located at heights of 1, 4, 7, 10, 13, and 14½ ft (0.305, 1.2, 2.1, 3.1, 4, and 4.4 m) on a vertical row. The vertical row of points was positioned laterally on the wall so that the four interior points were directly behind the four Terra Tec pressure cells on the back face.

An initial set of measurements was made immediately before the placement of backfill began. The displacements of points on the front side of the wall relative to the top of the wall and to each other during and after backfilling were desired, rather than the exact and true shape of the wall at any time. It was therefore assumed that the front face of the wall was perfectly vertical at the time of the initial measurement. Figure 16 shows the measured translational and rotational displacements at the end of 1 day, 1 week, 1 month, 1 year, and on May 31, 1972. The data shown in Figure 16 indicate that a considerable amount of displacement occurred during the backfilling operation, and very little occurred after 1 month.

THEORETICAL VERSUS MEASURED PRESSURES

The ultimate objective of the research study is to develop a more economical retaining wall design. To accomplish this, it is necessary to determine whether the computed lateral earth pressure on a retaining wall compares favorably with the measured pressure on the real structure. The computed pressure is usually obtained from an equation derived from a theoretical analysis, as opposed to an equation resulting from empirical correlations. There are two earth pressure theories that have attained almost universal acceptance throughout the literature and can be found in nearly all textbooks on soil mechanics. These theories were postulated by Coulomb in the year

1776 and by Rankine in 1857. To arrive at a solution using their theoretical formulation of the problem, Coulomb and Rankine made various assumptions regarding the physical behavior of the soil and the interaction between the soil and the retaining wall. These assumptions and the equations used to compute the coefficient of active earth pressure, K_a, have been presented in detail elsewhere (1). The active earth pressure is the minimum pressure exerted on a structure by a mass of soil. It is the result of an outward movement of the structure with respect to the soil. The parameters used to compute K_a for the conditions at test wall G are α = angle of back of retaining wall with respect to horizontal = 90 deg; β = slope of backfill with respect to horizontal = 0 deg; ϕ = angle of shearing resistance of soil = 32 deg; and δ = friction angle between wall and soil.

The wall friction angle δ is a difficult parameter to evaluate. Approximate values of δ for various types of wall surfaces and finishes may be found in some texts on soil mechanics and foundations. Sowers and Sowers (5) state that, for smooth concrete, δ is often $\frac{1}{2}$ to $\frac{2}{3}\,\phi$. Tomlinson (8) lists $\delta/\phi = 0.88$ for grained concrete (made in timber formwork) in contact with dense dry sand. Terzaghi and Peck (7) suggest that the coefficient of wall friction, tan δ, can be assumed as equal to $\frac{2}{3}$ tan ϕ for fairly permeable soils. Without a doubt this is a very wide range of values for wall friction. However, it is fortunate that δ exerts little influence on Coulomb's value of K_a for the conditions given above by α, β, and ϕ. For $\delta = \frac{1}{2}\,\phi$, K_a equals 0.278, and for $\delta = \frac{2}{3}\,\phi$, K_a equals 0.275. The Rankine theory assumes no wall friction, and for the conditions stated K_a is equal to 0.307.

The theoretical totally active pressures computed by the Coulomb and Rankine theories for test wall G are given in Table 2. The value of $\delta = \frac{2}{3}\,\phi$ was used to compute the Coulomb value of K_a, the unit weight of the backfill was taken to be 110 pcf (1760 kg/m^3), and the depths correspond to the locations of the pressure cells.

Figure 17 shows the measured earth pressures at each depth on a given day. The earth pressure distributions have been plotted for 7, 182, 321, and 415 days after the start of backfilling. The data indicate that, in general, the lateral earth pressure distribution behind test wall G is triangular, i.e., the pressure increases more or less linearly with increased depth. However, the slope of the pressure versus depth curve changes at a depth of 7 ft (2.1 m). From the surface down to 7 ft the lateral pressure increases at an average rate of about 0.4 psi per ft (9 kPa per m). From 7 to 13 ft (2.1 to 4 m) the average rate of pressure increase is approximately 1 psi per ft (22.6 kPa per m). A possible explanation for this increase in pressure gradient can be obtained from a consideration of the displacements that occurred in the upper and lower portions of the retaining wall. It is apparent from the retaining wall displacement curves shown in Figure 16 that the wall tended to rotate about some point near the top of the footing. According to Taylor (6), the pressure distribution on a retaining wall will be triangular if the wall rotates away from the backfill about a point near the base of the wall. Furthermore, from Figure 16 it is evident that some bending occurred in the upper 7 ft (approximately) of the wall. Apparently, the upper portion of the wall experienced a greater movement (yield) per unit depth with respect to the backfill than did the lower portion. If the gross movement of the wall were such that the totally active pressure distribution were approached but not completely achieved at all points along the wall, one would expect the greater movement in the upper portion of the wall to cause a greater reduction in pressure below the at-rest level than the smaller yielding that occurred near the base. In this context the at-rest pressure is the pressure that would be exerted on the wall after the backfill is placed provided that no wall movement occurs.

Figure 16 also shows that the base of the retaining wall experienced approximately 0.2 in. (5 mm) lateral displacement, or two-thirds of the total, at the end of the first day. [Backfill level was only 2 ft (0.6 m) above the footing.] This seemingly large displacement can be attributed to the ground conditions at the site. The footing, although supported by H-piles, was built on top of clay. It is believed that the heavily loaded earthmoving equipment compacted the soil on the back side of the footing and pushed the wall outward. Taylor (6) states, "If the top of the wall moves outward an amount roughly equal to $\frac{1}{2}$ of 1 percent of the wall height, the totally active case is

Figure 16. Displacement of test wall G (1 in. = 25.4 mm).

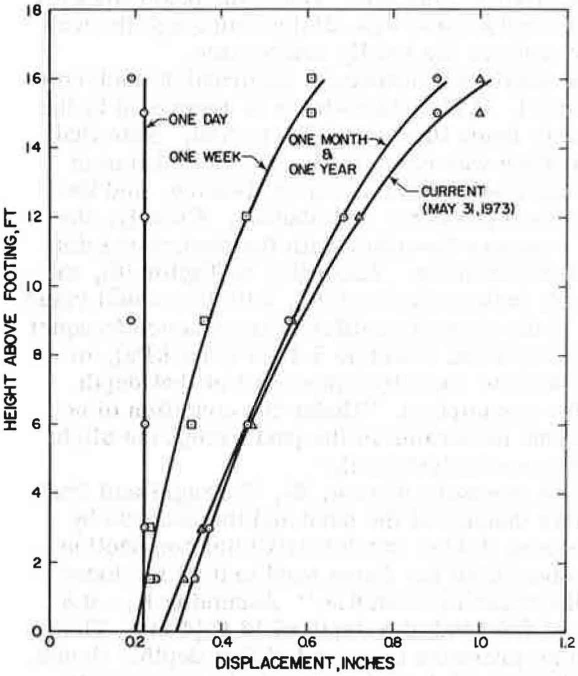


Table 2. Theoretical earth pressures based on Coulomb and Rankine theories.

Depth, ft	Pressure, psi Coulomb	Rankine
4	0.92	1.02
7	1.60	1.79
10	2.29	2.56
13	3.00	3.32

Note: 1 ft = 0.305 m; 1 psi = 6.9 kPa.

Figure 17. Pressure distribution curves.

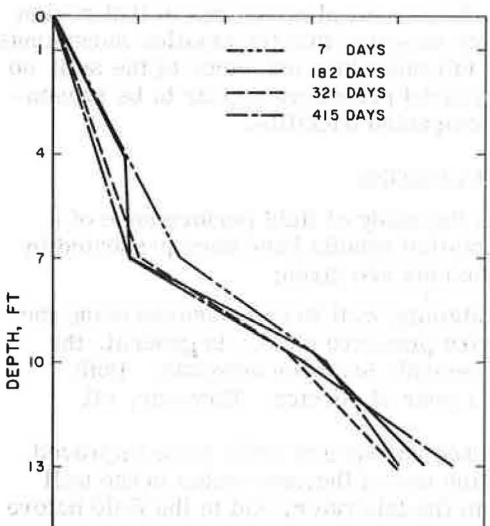
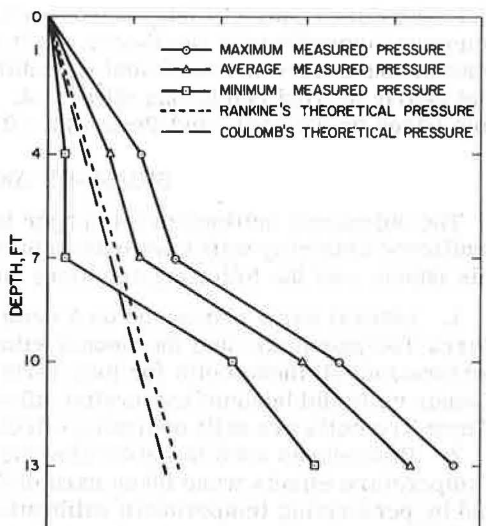


Figure 18. Theoretical versus measured pressure.



attained. This criterion holds if the base of the wall either remains fixed or moves outward slightly." In this case, ½ of 1 percent of the wall height equals 0.96 in. (24.4 mm). Figure 16 shows a movement of approximately 0.7 in. (18 mm) at the top of the wall after the initial lateral translation occurred. Thus, the observed wall movements would seem to indicate that the active case was attained although the wall movement may not have been sufficient to achieve the totally active case.

Figure 18 is a plot of the minimum and maximum pressures recorded at each cell location from April 18, 1972, through May 31, 1973. Also shown in Figure 18 is the average of all earth pressure measurements made throughout the period. Note that April 18, 1972, is the date on which backfilling was completed. The dotted line in Figure 18 indicates the theoretical pressure distribution based on Rankine, and the broken line illustrates the Coulomb theoretical pressure distribution. Clearly, the measured pressure distribution does not compare favorably with the theoretical distribution forecast by the Coulomb or Rankine theories. According to Taylor (6), the at-rest earth pressure coefficient may vary between 0.4 and 0.5, with the actual value dependent on the density of the backfill. If the at-rest coefficient is assumed to equal 0.5, the computed pressure at the 13-ft (4-m) level would be 5.4 psi (37.3 kPa), or approximately 35 percent less than the minimum measured pressure at that depth. Taylor's at-rest coefficient is based on the assumption, "Under the condition of no movement of the wall, the soil has undergone no strains in the past except the slight vertical compression caused by the placing of overlying soil."

With reference to the coefficient of earth pressure at rest, K_0, Terzaghi and Peck (7) state, "Its value depends on the relative density of the sand and the process by which the deposit was formed. If this process did not involve artificial compaction by tamping, the value of K_0 ranges from about 0.40 for dense sand to 0.50 for loose sand. Tamping in layers may increase the value to about 0.8." Assuming $K_0 = 0.8$ yields a computed pressure equal to 8.7 psi (60 kPa) at a depth of 13 ft (4 m). This value is very close to the average maximum pressure observed at that depth. Hence, the earth pressures that are being recorded would at first appear to be contrary to the theoretical pressures. However, it must be remembered that the theoretical equations based on the Coulomb and Rankine theories give the pressure for totally active conditions. If the assumption is made that the larger movements in the upper 7 ft (2.1 m) induced nearly totally active pressures, the measured pressures in that region compare favorably with the theory. If it is further assumed that the smaller movements near the base were not sufficient to mobilize the full shearing resistance of the soil, so that nearly at-rest conditions still exist, the measured pressures appear to be reasonable based on Terzaghi and Peck's $K_0 = 0.8$ for compacted backfills.

SUMMARY AND CONCLUSIONS

The objectives outlined in this paper involving the study of field performance of a cantilever retaining wall have been achieved. Detailed results have been presented in this paper, and the following summary and conclusions are given:

1. Lateral earth pressures on a cantilever retaining wall were measured using the Terra Tec pneumatic and the Geonor vibrating wire pressure cells. In general, the performance of these cells for long-term measurements has been adequate. Both Geonor cells did become inoperative after about 1 year of service. However, all Terra Tec cells are still operating effectively.
2. Procedures used in calibrating the Terra Tec and Geonor cells were improved. Temperature effects were taken care of through the use of thermocouples in the wall and by performing temperature calibration both in the laboratory and in the field before backfilling. One Terra Tec cell was grouted into a block of concrete and calibrated pneumatically in the laboratory. Based on the results of these tests, it is concluded that there is no effect on the pressure cell response due to the grouting of the cell in concrete. The effect of change in zero gauge reading with time was investigated both in the laboratory and in the field before and after backfilling. It was found that the zero gauge reading did not change significantly when the backfill material was removed after 6 months.

3. Lateral displacement of the test wall was measured accurately. Measurements of the wall movement were made each time that pressure readings were taken, starting at the time of the backfilling operation. This was done so that wall movements could be correlated with measured pressures.
4. Samples of the backfill material were taken and tested to determine the physical and engineering properties of the soil. These properties were used to make theoretical determinations of lateral earth pressure.
5. Computed lateral earth pressures based on Rankine and Coulomb theories were computed with measured lateral earth pressures. It was found that measured pressures agreed with the theoretical pressures to a depth of about 7 ft (2.1 m) on the test wall. Wall movements were large enough above the 7-ft depth to indicate the totally active case. Below the 7-ft depth, the measured earth pressures were larger than the theoretical pressures. Wall movements between the 7-ft and the 13-ft (4-m) depth indicated that the state of the soil in the backfill was somewhere between the totally active and the at-rest case. At the 13-ft depth the movements were small enough to indicate the at-rest condition.

The most recent data given in this paper were taken in May 1973. Pressure readings and wall movements have been made once a month since that time. Readings will be taken continually during the third and fourth years of the study. Surcharge loads in the form of highway pavements were to be applied to the test wall in the fall of 1973. Therefore, it will be possible to study the effects of these surcharge loads on the test wall.

ACKNOWLEDGMENTS

This investigation was conducted as a part of Research Study 2-5-70-169, entitled "Determination of Lateral Earth Pressure for Use in Retaining Wall Design". The cooperative research study is sponsored jointly by the Texas Highway Department and the Federal Highway Administration of the U.S. Department of Transportation. Receipt of this research support is gratefully acknowledged.

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration.

REFERENCES

1. Corbett, D. A., Coyle, H. M., Bartoskewitz, R. E., and Milberger, L. J. Evaluation of Pressure Cells Used for Field Measurements of Lateral Earth Pressures on Retaining Walls. Texas Transportation Institute Research Report No. 169-1, Texas A&M University, Sept. 1971.
2. Calibration of Earth Pressure Cell P-100. Geonor A/S, Calibration Report 71442, Oslo, Norway, unpublished.
3. Hamilton, J. J. Earth Pressure Cells: Design, Calibration, and Performance. Technical Paper No. 109, Division of Building Research, National Research Council, Canada, Nov. 1960.
4. Scott, J. D. Experience With Some Vibrating Wire Instruments. Canadian Geotechnical Journal, Vol. 4, No. 1, Feb. 1967, pp. 100-123.
5. Sowers, G. B., and Sowers, G. F. Introductory Soil Mechanics and Foundations, Second Ed. Macmillan Company, Toronto, Ontario, 1961.
6. Taylor, D. W. Fundamentals of Soil Mechanics. John Wiley and Sons, Inc., New York, 1948.
7. Terzaghi, K., and Peck, R. B. Soil Mechanics in Engineering Practice, Second Ed. John Wiley and Sons, Inc., New York, 1967.
8. Tomlinson, M. J. Foundation Design and Construction. John Wiley and Sons, Inc., New York, 1963.