Field Measurements of Lateral Earth Pressures and Movements on Retaining Walls

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Field data were obtained and analyzed from two instrumented full-scale retaining walls. The data presented in this paper cover a period of 1156 d for a cantilever wall founded on H-piles and a period of 769 d for a precast panel wall founded on drilled piers. The data consist of pressure cell and movement measurements from both walls. For the precast panel wall, the force transmitted from the panel to the supporting pilasters was measured with force transducers. Analysis of the data indicates that movements near the bases of both walls were not large enough to develop active pressures. Earth pressure measurements near the bases of both walls were close to at-rest pressures. Earth pressures changed with seasonal variations in temperature. Pressure changes occurred as a result of construction equipment activity both during and after backfilling. Vehicular traffic after completion of construction did not produce measurable pressure changes during the time periods covered by this study.

Since the publication in 1932 of earth pressure tests on large-scale retaining wall models by Terzaghi (10), designers have accepted Terzaghi's conclusion that a small yield of the structure will cause shear resistance to develop in a sand backfill. When sufficient movement has occurred, the developed shear stress reduces the earth pressure on the wall to the active state.

Using the principles of limiting equilibrium, wall design is based not on a determination of the expected forces but on an analysis of the forces that would exist if the wall started to overturn or slide outward (5). Terzaghi observed during his large-scale model tests (10) that the lateral earth pressure existing after backfilling and before the wall yielded "undoubtedly depends to a considerable extent on the method of compaction." Terzaghi and Peck (11) observed that for rigid structures the magnitude of earth pressure depends to a large extent on the methods of placing the fill. Casagrande (1) cited the results of field measurement that revealed that even light compaction could result in the development of greater than active earth pressures. Lambe and Whitman (5) pointed out that "if the thrust against a retaining wall were greater than the active value it would not mean that potentially the wall was in trouble. On the contrary it would mean that the soil underlying the wall is much stronger than it need be." They further observed that "long before a wall can fail, it must move enough to mobilize the shear strength of the soil and to drop the thrust to its active value." The term "failure" refers to foundation failures, i.e., to overturning or sliding outward.

The designer is concerned with limiting equilibrium mechanics analysis used for foundation design and with the maximum loads that the structure will be required to support at any time. As previously stated, lateral pressures greater than those predicted by limiting equilibrium analysis may exist immediately after backfilling. Once established, these pressures will continue until outward movement occurs. This movement develops shear stresses in the backfill. As shear stresses increase, the pressure reduces, until at pending failure the active state exists. The total design of a retaining structure must consider both the effects of residual stress caused by placement of the fill and the earth pressures existing at failure.

A 5-year research study was begun at Texas A&M University in 1970 to measure lateral earth pressures in the field on full-scale retaining walls. The first year was devoted to selecting earth pressure cells that would provide both accuracy and long-term reliability. Nine cell types were considered, four of them field tested (2). Two types, Terra Tec and Geonor, were used for installation in the cantilever test wall (3) during the second year of the study. Terra Tec cells were used for installation in the precast panel wall (6) during the third year of the study. During the fourth and fifth years of the study, field data were collected and analyzed for both the cantilever and the precast panel walls. This paper presents the results and analysis of the data collected for 3 years on the cantilever wall and for 2 years on the precast panel wall.

CANTILEVER TEST WALL

Test Wall

The instrumented cantilever retaining wall was located near the intersection of US-59 and I-45 in Houston, Texas. A total of seven cantilever retaining walls were constructed at this site. One panel in a retaining wall supporting an access road was selected for instrumentation.

The test wall is of typical cantilever retaining wall design, except that it was founded on steel H-piles. A cross section of the cantilever test wall is shown in Figure 1. The test panel was approximately 4.9 m (16 ft) high and 9.2 m (30 ft) long. The significant dimensions of the cantilever wall and the location of the pressure cells are shown in Figure 2. The groundwater table was located below the footing of the wall. Weep holes were provided to allow drainage and thus prevent hydrostatic forces from building up behind the wall. The wall was instrumented in March 1972, and the backfilling operation was completed in April 1972. Paving of the access road began in May 1973. Vehicular traffic began in October 1974.

Instrumentation

The cantilever wall was instrumented with four Terra Tec and two Geonor cells, located as shown in Figure 2. The four Terra Tec cells were placed in a vertical row to measure pressure distribution behind the wall. The Geonor cells were located adjacent to the upper and lower Terra Tec cells. The cells were grouted flush with the back of the wall. A thermocouple was installed at each pressure cell location. Connecting cables and wires were secured with a strip of raw tread rubber, and a steel box on top of the wall protected the cable ends.

Results of pressure cell calibration revealed that, with no pressure applied, initial zero cell readings vary with temperature. These calibration studies are described in detail in other reports (2, 3). Calibration tests were performed at the test site after the wall was instrumented and before it was backfilled. Pressure cell temperature variations from 21 to 32°C (70 to 90°F) were observed. Temperature correction curves were developed for each cell, and these were used to correct measured pressures. Pressure measurements were made at approximately 1-month intervals. The field measurements included cell pressure and temperature from the adjacent thermocouple. Sources of measurement error include nonlinearity, hysteresis, read-out resolution, and reading stability with temperature change. Initial calibration indicated that the cell response, i.e., pressure change measured in accordance with pressure applied, was linear within 1 percent. The effect of installation by grouting into a wall was investigated, and no effect on pressure cell response was indicated. Hysteresis was also found to be negligible. Read-out resolution of the Terra Tec cells was improved by replacing the 1724-kPa (250-lb/in^2) gauge on the read-out device with a more sensitive 241-kPa (35-lb/in^2) gauge. Read-out resolution error was 0.345 kPa (0.05 lb/in^2). Temperature corrections were made based on field calibration data. The estimated maximum error of pressure cell measurements with temperature corrections made from the field calibration was ±3.45 kPa (0.5 lb/in^2).

Wall movement was determined by two measurements: lateral translation and offset from a vertical line. Lateral translation was determined by measuring the change in distance from a fixed point on a bridge bent column to a reference point on top of the wall. The change in distance was measured to the nearest 0.51 mm (0.0017 ft) by using an engineer's scale and a steel tape. The steel tape was always pulled with the same tension, and a correction was made for tape temperature variation.

Offset measurements from a vertical reference line were used to determine relative movements of six points aligned in a vertical row. The reference line was established by suspending a plumb-bob from a permanent frame at the top of the wall. Offsets were measured

Figure 1. Cross section of cantilever wall.

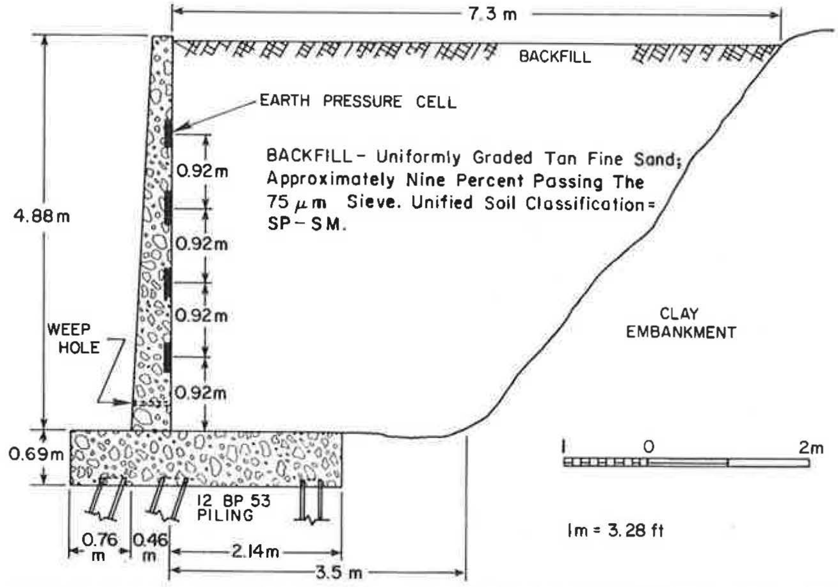
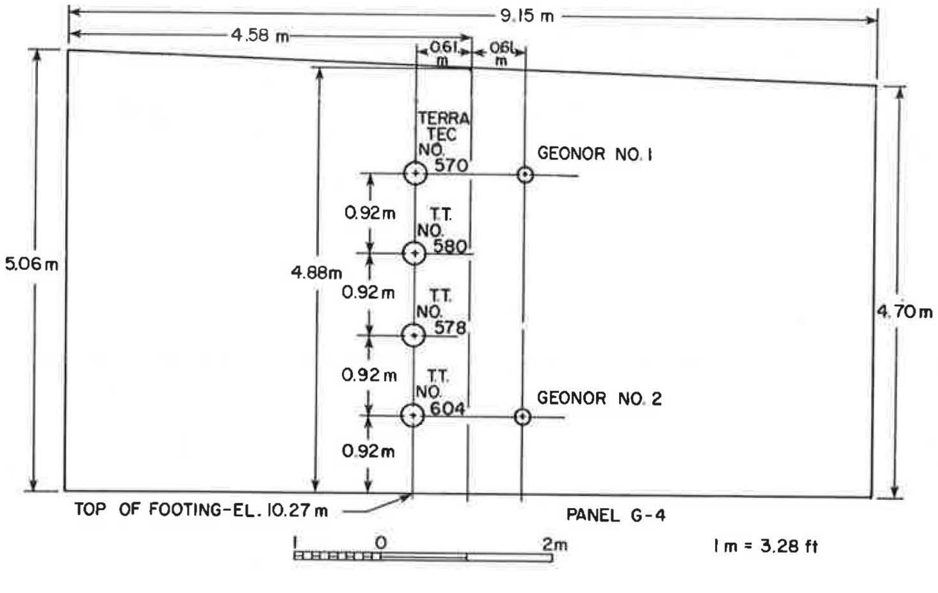


Figure 2. Location of earth pressure cells, cantilever wall.



horizontally from the reference line to each of the wall points. Initial offsets were obtained before backfilling. Accuracy of the wall-movement measurements was limited by the constraints of the test site. Continual construction required the establishment of the fixed reference point above ground level on a bridge bent column, but this resulted in possible error in establishing the horizontal movement of the wall. The relatively high flexibility of the wall reduced the accuracy of the offset measurements. The combination of these factors undoubtedly affected the accuracy of the horizontal movement computation. Thus, the long-term relationship between horizontal movement and time is of questionable accuracy. The only conclusions that can be drawn concern the amount of movement occurring during backfilling because these movements were relatively large. The offsets were measured to 0.079 cm ($^1/_{32}$ in).

PRECAST PANEL TEST WALL

Test Wall

The test site for the precast panel test wall was in northwest Houston, Texas. The freeway portion of US-290 is being extended in that area, and the test site was located at the intersection of the freeway extension and Dacoma Street.

This retaining wall differs in design from the cantilever wall in that it is founded on a series of drilled shafts placed at regular intervals. Footings were constructed on the drilled shafts, and T-shaped pilasters were formed on the footings. Precast panels were then placed between the pilasters and rested on neoprene bearing pads. The flange of the T-shaped pilasters supported the panels after the backfill was placed. At the test panel location the drilled shafts were 0.91 m (3 ft) in diameter, 6.10 m (20 ft) deep, and spaced at 3.66-m (12-ft) intervals. The wall was 3.05 m (10 ft) high and the footings were 0.97 m (3 ft 2 in) square and 0.4 m (16 in) high. Figures 3 and 4 show the retaining wall and its construction elements.

In Figures 3 and 4 there are several items of interest that should be noted. Fill was placed against the fronts of all walls except the instrumented panel to a height of 0.9 m (3 ft). A timber barrier was placed against the pilasters on which the instrumented panel was placed. This prevented the development of earth pressure on the front face of the instrumented panel. All panels except the instrumented one were grouted to the pilasters. A concrete gutter was placed on the backfill behind the wall, and 2 months after completion of the sand backfill a clay surcharge was placed above it at a 3:1 slope and varied in thickness from 15.2 cm (6 in) near the wall to 76.2 cm (30 in) near the top at the embankment. A drain for the backfill was placed directly behind the lower row of pressure cells.

The instrumented panel was supported at six points. Vertical support was provided by the footings through the neoprene pads, which measured 12.7 by 25.4 cm (5 by 10 in) and were 0.95 cm ($^3/_8$ in) thick. Lateral support was provided at four points on the front face of the panel. Two force transducers were installed between the pilasters and the panel on each side. The location of the force transducers and the neoprene pads is shown in Figure 5.

Instrumentation

Lateral earth pressures acting on the panel were measured by two methods. Nine Terra Tec pressure cells placed symmetrically in three rows as shown in Figure 5 measured the lateral earth pressures on the back of the panel. The second measurement method used force transducers located between the panel and the supporting pilasters (also shown in Figure 5). The transducers measured the force transmitted by the panel to the supporting pilasters.

The pressure cells and the force transducers were both installed in cavities, made during forming, in the panel for the pressure cells and in the pilasters for the force transducers. In the field the force transducers were grouted into the pilasters before the panel was installed. The precast panel was then seated against the transducers. After the panel had been installed, the pressure cells were grouted into the back of the panel flush with the surface, and a thermocouple was placed at the location of each pressure cell and force transducer. Temperature was recorded when the pressure cell and force transducer readings were taken. Connecting cables and wires were secured to the wall by strips of raw tread rubber. A steel box at the top of the wall protected the cable ends.

Terra Tec cell calibration studies (6) had shown that with no applied load the pressure readings varied with temperature. Additional calibration tests were performed after instrumentation and before backfilling. The gauge readings with no force applied were recorded over a temperature range of 7 to 23°C (45 to 74°F). A temperature correction curve for each cell and transducer was developed from these data.

Regular monthly cell pressure and temperature measurements were taken during the course of this study. The correction for zero-offset with temperature was made. The accuracy of the Terra Tec cells has been discussed previously, and based on calibration tests the accuracy of the cells installed in the panel wall was estimated to be ±3.45 kPa (0.5 lb/in^2). Calibration of the force transducers revealed negligible errors caused by nonlinearity, hysteresis, and read-out resolution. The zero-force reading versus temperature relationship was established in a manner similar to that used for the earth pressure cells; the force was calculated by correcting the field reading for temperature; and the difference was then multiplied by the transducer's calibration factor to obtain the actual force indicated by the transducer. Calibration tests indicated that the force transducer's accuracy was ±445 N (100 lbf).

Wall-movement measurements were made in a manner similar to that used for the cantilever wall. Lateral translation was determined by measuring the distance from a fixed point on a curb to a reference point on the panel. Offset measurements from a vertical reference line (suspended plumb-bob) were used to determine relative movements of seven points in a vertical row at the center of the panel. Construction activities did not interfere with our study. The fixed reference point was close to the panel wall, and the panel was very rigid. Therefore, the accuracy of the panel wall measurements was considered better than that of those made on the cantilever wall.

PRESENTATION AND ANALYSIS OF RESULTS

Cantilever Wall

Presentation of Results

The pressure cell measurements corrected for temperature are plotted versus time in Figure 6. The upper three cells were not covered until near the end of the backfilling operation on days 5 and 6. As shown in Figure 7, cell pressures increased rapidly on days 6

Figure 3. Cross section of panel wall.

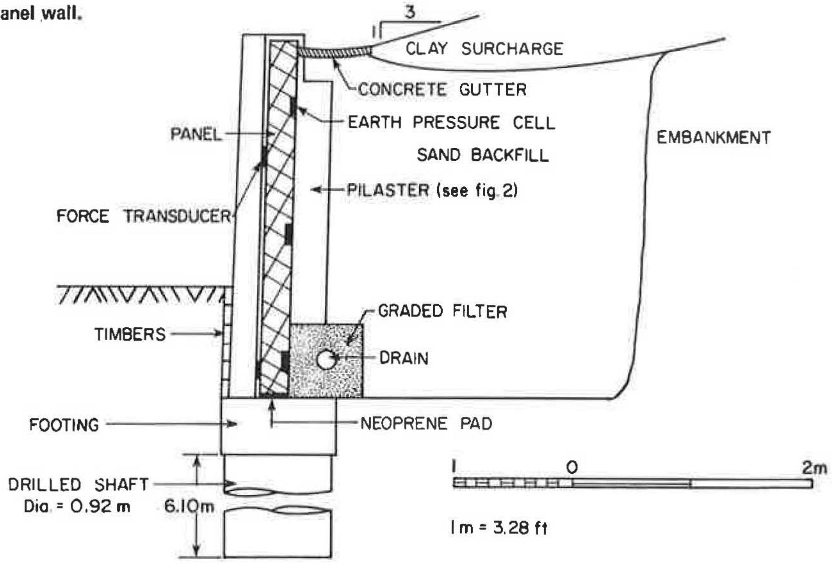


Figure 4. Front view of panel wall.

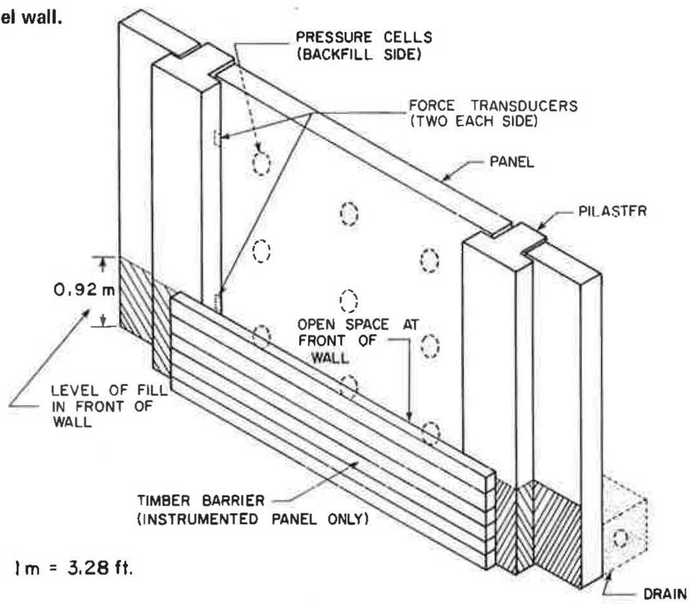


Figure 5. Location of earth pressure cells and force transducers, panel wall.

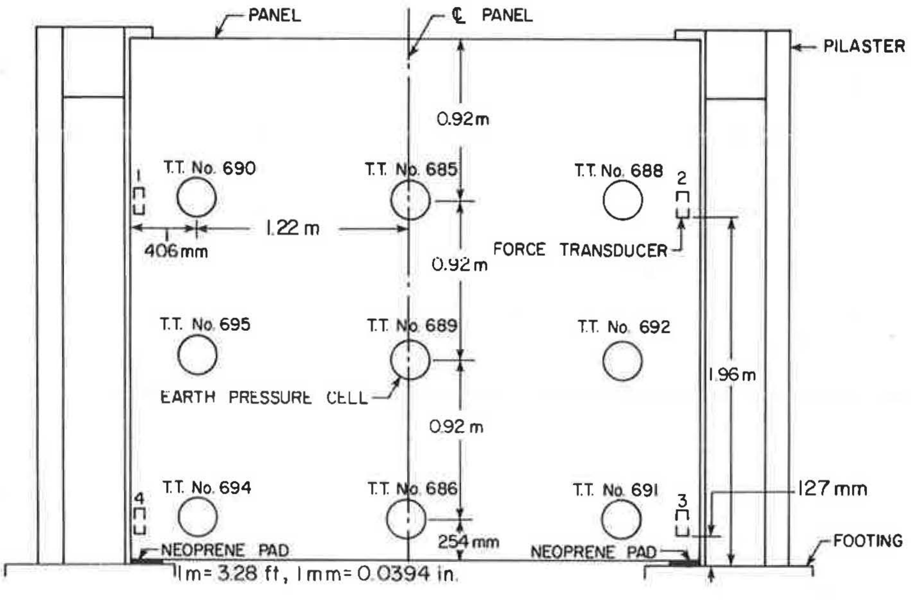


Figure 6. Measured earth pressures for cantilever wall.

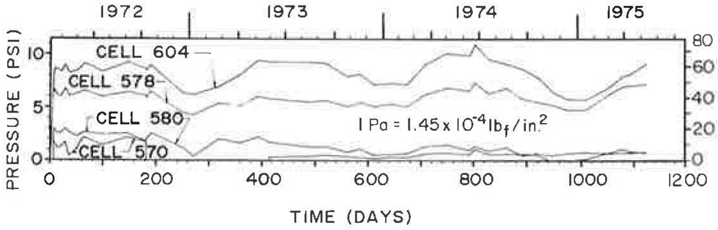


Figure 7. Pressure changes during backfilling.

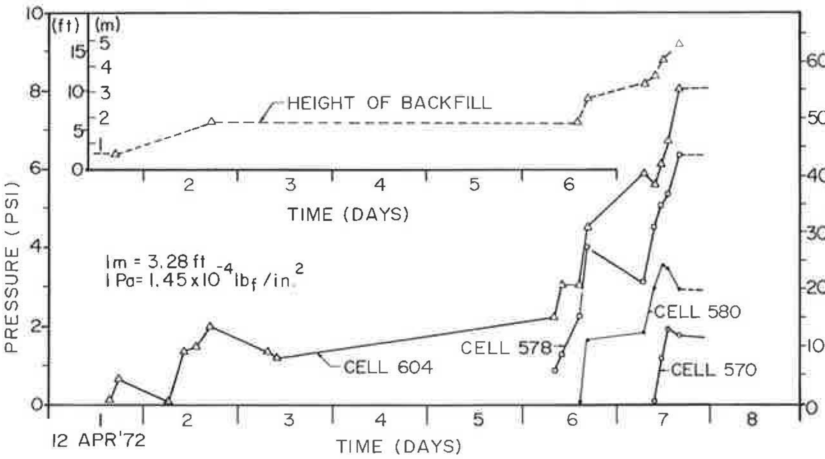
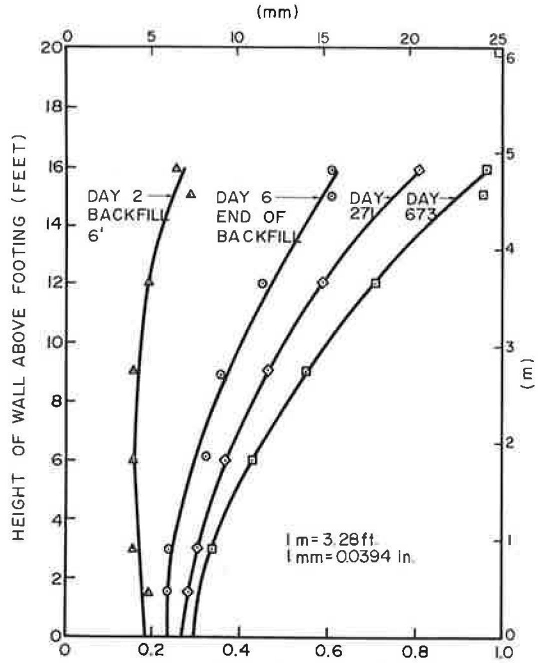


Figure 8. Typical displacements, cantilever wall.



and 7. At the end of backfilling the two middle cells, 578 and 580, attained pressures near the maximum measured during the entire study. The upper cell, 570, reached a pressure within 3.45 kPa (0.5 lb/in^2) of its maximum. The lower cell, 604, was 59.3 kPa (8.6 lb/in^2) at the completion of backfilling. This was exceeded seasonally.

Obvious seasonal variations of cells 604 and 578 are shown in Figure 6. These cell pressures were lower in the winter and reached peak values during the warm months of June, July, and August. Sharp drops began in September or October; lowest readings were recorded in December or January; and recovery occurred in early spring. The range of the seasonal variation of cell 604 was approximately 24.1 kPa (3.5 lb/in^2), corresponding to 40 percent of the mean pressure, which is about that established at the end of backfilling.

Cell 570 was uncovered on day 181. The temperature calibration for zero-offset was checked and found to be unchanged. The backfill was replaced, but significant pressures were not measured for 234 d. This cell became active again on day 415. Since road surfacing work above the wall was in progress at this time, these pressure changes may have resulted from arching.

The wall-movement instrumentation system was limited by the physical constraints of the site. The movement associated with each cell is not precisely known. Analyses of these data were limited to characterizing and quantifying the movements. Typical wall displacements are pictured in Figure 8. The large deflections and horizontal movements during backfilling and the high flexibility near the top of the wall are all quite evident.

Analysis of Results

The saturated condition of the backfill material and the lack of compaction near the wall resulted in a zone of loose soil along the wall. The average total unit mass of 1623 kg/m^3 (101.3 lb/ft^3) when compared with those typical of fine sands indicated that the density was loose to medium.

The coefficients of earth pressure at rest (K_o) at the end of backfilling were computed and are shown in Figure 7. Terzaghi and Peck (11) reported that if backfilling involves no artificial compaction by tamping the value of K_o ranges from about 0.40 to 0.50 and that tamping in layers may increase K_o to about 0.8. K_o for the lower two cells, 578 and 604, are somewhat higher than 0.80. The soil at this level of backfill was allowed to drain between days 2 and 6 and was probably denser than the soil at cells 580 and 570, where the measured K_o was slightly lower than 0.80.

Terzaghi (8) reported that at the end of construction the coefficient of lateral earth pressure depends on the relative density of backfill material, the method of compaction, and the wall movements during backfilling. As stated previously, the measurement scheme used in this study was not sufficiently accurate to allow correlation of individual pressure cell readings with movements. Movement occurred as the backfill, which was saturated at that time, was being placed. As a result, the compacted soil had a soft, plastic consistency and could have moved with the wall as compaction continued. Movements slowed abruptly when backfilling was completed.

The seasonal variations in pressure readings probably result from temperature changes in the backfill. As shown in Figure 9, these variations correlate with the seasonal changes in temperature. Pressure cell calibration tests indicated that the variations are not the result of instrument error. Water pressure buildup was not possible because the cells were located above weep holes from which frequent drainage was observed. Also, maximum pressures occurred during the summer months when rainfall was lowest.

The wall tilt required to obtain the Rankine pressure distribution was determined by Terzaghi (9) to be 0.005 times the wall height. For movements less than this the coefficient of earth pressure lies between the at-rest coefficient (K_o) and the active coefficient (K_a). The pressure distribution for an interim state is unknown but depends on wall movements.

The measured wall movement of approximately 0.76 cm (0.3 in) at the top of the wall was not sufficient to obtain the Rankine active pressure distribution over the entire height of the wall. However, pressure reductions to the active Rankine values did occur in the upper cells. These pressure reductions probably resulted from movements associated with the higher flexibility of the wall in that region. The lower two cells showed seasonal variations but on the average maintained at-rest pressures.

Precast Panel Wall

Presentation of Results

All of the pressure cell measurements corrected for temperature for the panel wall are presented in Figure 10. The cells were grouped into vertical rows. Figure 10 illustrates the pressure distribution on the left, center, and right portions of the wall.

Cells located near the pilasters exhibited similar pressure increases after the completion of backfilling. The lower cells, 694 and 691, at the panel ends recorded a rapid rise in pressure through day 38. Between days 29 and 58 a clay surcharge was added to the sand backfill, and the lower cells followed different trends during this time. These changes are depicted in Figures 11 and 12. The lower right cell (691) pressure began to register a steady decrease, dropping below the Coulomb active value about day 240; by day 560 its output had become steady at about a third of the calculated active pressure. The lower left cell (694) continued to show an increase that reached a peak about day 65, after which it exhibited a seasonal pressure variation similar to the lower cell of the cantilever wall. The seasonal variation was about 20.7 kPa (3 lb/in^2) as compared with 24.1 kPa (3.5 lb/in^2) for cell 604 of the cantilever wall. The pressures of other cells at the edges of the panel have consistently measured smaller than Coulomb active pressures.

The vertical row of cells at the center of the panel showed a different pressure distribution pattern. The upper and lower cell pressures were erratic but generally increased during the first 38 d. During the surcharge period the upper cell pressure dropped below that of the lower cell pressure and continued to remain slightly lower. Except for a brief period during the winter of 1974, the upper cell pressure has been above the Coulomb active value. The lower cell (686), despite readings higher than those of the upper cell, has shown near active pressures since day 58. The middle cell in the center vertical row has consistently shown the lowest pressure.

The movement measurement system was not sufficiently accurate to determine wall movement at specific cell locations. Since measurements were restricted to the center of the panel, determination of the estimated wall movements at the base near the pilasters was based on an analysis of the support restraints.

Unlike the cantilever wall, the panel was relatively thick in comparison to its height. Very little curvature due to flexure was detected. The base of the wall was located 0.91 m (3 ft) below ground level and was not accessible for measurement, but horizontal movement at the base was estimated. Observations with regard to wall tilt were that

1. Less than 20 percent of the tilt occurred during backfilling;
2. Tilt increased rapidly after backfilling, reaching a constant value about day 150; and
3. Tilt has not shown consistent increasing or decreasing trends.

Observations with regard to horizontal movement at base were that

1. About 30 percent of the movement occurred during backfilling and
2. Two periods of increasing movement were from backfilling to day 100 and from day 300 to day 500.

Displacement plots for some of the data are shown in Figure 13. The rotational and translational nature of early movements as well as the predominantly lateral translation later in the program are evident.

Analysis of Results

The panel-wall data indicate that increases in earth pressures after backfilling are not in agreement with the earth pressure theories of Coulomb or Rankine, who predicted that lateral earth pressures will be highest at the completion of backfilling if the wall moves outward from the backfill and external loads are not added to the backfill.

The study data show that a general trend of outward movement and increasing pressure took place between backfilling and day 38, when the clay surcharge was being placed on the backfill. Although this activity may have accounted for part of the increase, it was not responsible for the early pressure increases. There was no construction activity on the backfill from completion to day 29.

After day 38 the changes in pressures were similar to those that occurred on the cantilever wall after backfilling. Most cell pressures remained near their day-38 level. Some cell pressures decreased while others entered a seasonal cycle. In general, a steady-state condition with no long-term trends had been reached. The pressure distribution over the panel as a whole was complex.

For a typical dense sand Taylor (7) gave rough quantitative values of amounts of yield needed for two types of active cases:

1. If the mid-height point of the wall moves outward a distance roughly equal to 1/20 of 1 percent of the wall height, an arching-active case is attained. This criterion holds whether or not the wall remains vertical as it moves; however, the exact pressure distribution depends considerably on the amount of tilting of the wall.
2. If the top of the wall moves outward an amount roughly equal to ½ of 1 percent of the wall height, the totally active case is attained. This criterion holds if the base of the wall either remains fixed or moves outward slightly.

Figure 9. Temperature and pressure relationship, cell 604, cantilever wall.

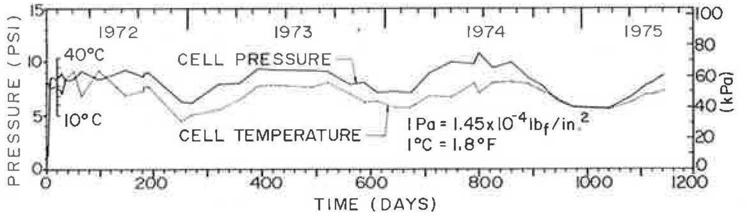


Figure 10. Pressure variations with time, panel wall.

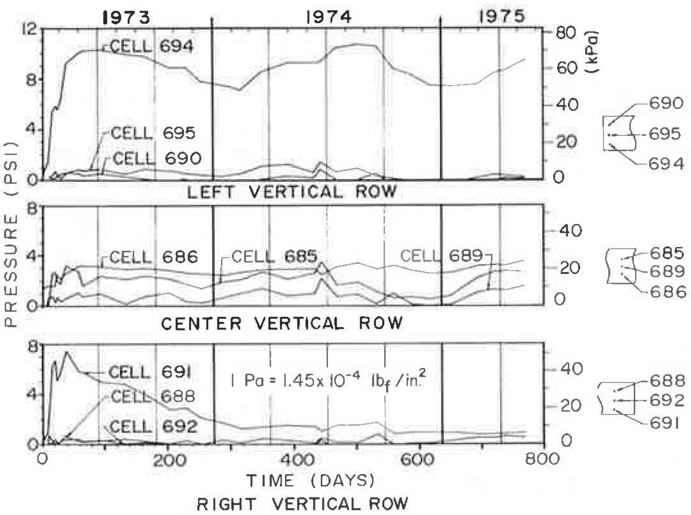


Figure 11. Pressure distributions days 38 and 65, panel wall.

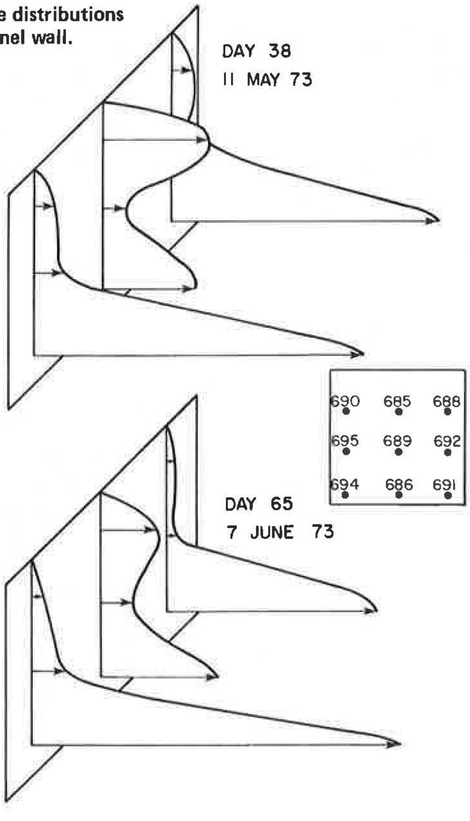
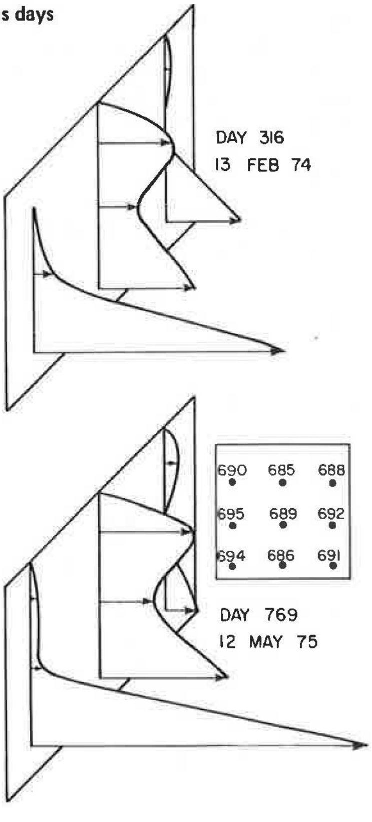


Figure 12. Pressure distributions days 316 and 769, panel wall.



For the panel wall 1.50 cm (0.59 in) of movement at the top would be required to attain a hydrostatic, totally active pressure distribution. Only 0.074 cm (0.029 in) of movement at the midheight would be required to attain the arching active case. As pointed out by Taylor (7), essentially the same total thrust on the wall occurs for both active cases. The pressure distribution for the arching active case is not hydrostatic.

If the effective yield is considered to be the movements since completion of backfilling, an estimated 1.40 cm (0.55 in) of the movement occurred at the top of the wall by day 150. This movement further increased to about 1.65 cm (0.65 in) between days 325 and 425. The smaller yields required for the arching active case occurred within 5 d after backfilling. These early movements were not accompanied by pressure reductions, and hydrostatic pressure distributions were not attained.

Lack of agreement with Taylor's estimates suggests that the state of stress in the backfill was affected by other factors as significant as movement. This was also indicated by the continuing increase in earth pressure after backfilling. The average force on the wall reached a maximum on day 38, but construction activity on this day probably caused stress changes. Pressure cell readings stabilized or began dropping at this time. The wall movements associated with the stabilized and dropping pressures were those recorded after day 38. If the effective yield is taken as the movement since day 38, the movements are not sufficient to reduce the pressures to the hydrostatic distribution of the totally active case. The reductions in total force associated with the arching active case could occur.

The force transducer data shown in Figure 14 indicate that the panel was probably not bearing evenly. Highest forces were measured by the transducers located diagonally on the lower left (4) and upper right (2) of the panel. Lowest forces were measured at the other diagonal corners. Highest forces were measured by transducer 4. Pressure cell 694 was located 35.6 cm (14 in) from transducer 4. Pressure changes of cell 694 closely correspond with force changes for transducer 4. This suggests that transducer 4 was in good contact with the wall after backfilling.

The measured forces on the upper right transducer (2) were about two-thirds of those measured on transducer 4. The total force measured by transducers 2 and 4 accounts for 70 to 75 percent of the total measured force. Although high forces were measured at transducer 2, small pressures, less than 6.9 kPa (1 lb/in^2), were measured at the closest pressure cell (688). Forces could have been transferred to transducer 2 through the panel from areas of higher pressure near the center of the panel. Transducer 3, with was located at the lower right panel corner, was close to pressure cell 691. Comparison of measured values between force transducer 3 and pressure cell 691 indicate that the large pressures measured by cell 691 during the first 29 d after backfilling were not transferred to force transducer 3. After day 38 a steady decrease in pressure was measured on cell 691. The force measurements from transducer 3 increased about 3.56 kN (800 lbf) after day 38 and remained fairly constant. The data from transducer 1 does not indicate a sharp rise associated with backfilling. This may be an indication that the panel was not bearing against this force transducer until afterward. The forces measured from transducer 1 were about 10 percent of the total for the four transducers.

As noted previously, movement measurements were made at the middle of the panel. The movements at the base of the wall, near the pilasters at the location of the neoprene support pads, were not measured directly. Since shear forces that could be developed in the pads were not accounted for in the original force computations, a test was conducted to determine the magnitude of these shear forces and is discussed in another report (6). A displacement of 0.25 cm (0.1 in) produced a shear force of about 8 kN (1800 lbf). The movements at the force transducers were estimated to be less than 0.25 cm (0.1 in). This estimate was based on a consideration of the restraint conditions in this area of panel. Since the transducers responded immediately to the placement of backfill, it was assumed that no displacement of the wall was required to engage the transducer. Thus, based on the neoprene pad shear test and the estimated movements, the forces developed in these pads were probably less than 10 percent of the approximate average of 89 kN (20 000 lbf) measured by the force transducers.

The panel wall data also suggest that earth pressure changes seasonally. The changes in earth pressure cell readings correlate with the temperature changes measured adjacent to the cells as shown in Figure 15. The force cell measurements follow a similar trend. We must emphasize again that the results of calibration studies have shown that when temperature corrections are made, the pressure cell data are accurate to within ±3.45 kPa (0.5 lb/in^2).

Arching and apparent cohesion of the backfill material could have affected the distribution of earth pressures. The phenomenon of arching provides a convenient means of explaining pressure transfer in the backfill soil and could account for both the variations in pressure cell readings across the panel and the pressure changes resulting from construction on the backfill on day 38.

Apparent cohesion can be caused by capillary forces in the sand backfill, for example, with the periodic percolation of runoff water through the backfill. An increase in effective cohesion increases the shear strength of the soil, thus reducing the lateral earth pressures on the wall. This phenomenon could also explain the seasonal reductions in earth pressures. Arching and apparent cohesion could not be measured, and the magnitude of their effect, if any, is not known.

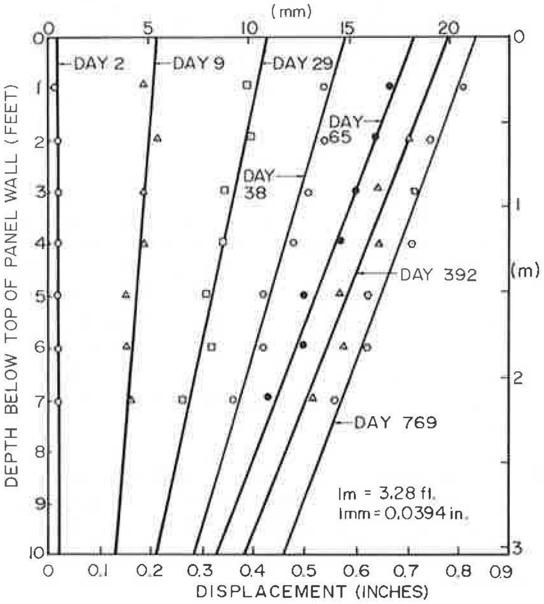
The pressure cells and the force transducers provided independent methods of obtaining the total earth pressure forces acting on the panel. These forces were computed and are presented in Figure 16. Total forces measured by the transducers were computed by adding the force transducer readings for each set of measurements. Total forces measured by the pressure cells were determined by integration of the pressures over the entire panel.

As shown in Figure 16, there was good agreement between the cells and the transducers after about day 200. Differences were within the accuracy of the pressure cell readings and the pressure distribution assumptions. Between day 24 and day 200 the forces computed from the pressure cells were greater than the forces computed from the force transducers because cell 691 pressures were initially very high. These high pressures were not measured by the closest force transducer (3). The reasons for lack of agreement between cell 691 and transducer 3 have been discussed. The total force plot as shown in Figure 16 suggests that cell 691 pressures were not transferred to other force transducers. The reasons for these discrepenacies are not known.

SUMMARY AND DISCUSSION OF RESULTS

The test study results apply only to retaining walls of the two types tested. The most significant similarity between these structures is that they were founded on deep foundations, i.e., H-piles and drilled shafts. An important aspect of this test study is the opportunity to compare results from two structures with similar instrumentation and consistent measurements over a long period of time. Analysis of the data from both walls has shown areas with similarities in results and areas with significant differences.

Figure 13. Displacement of panel wall.



Pressure Increases After Backfilling

Earth pressures continued to increase after backfilling the panel wall. In contrast, the pressures on the cantilever wall essentially leveled off at the end of backfilling. The pressure changes after backfilling may be related to the method of compaction of the fill, as suggested by the difference in compaction procedures used for the two walls. The heavy compaction of the panel wall backfill material may have resulted in the development of residual shear stresses that continued to increase the pressures after backfilling. Placement of the clay surcharge on the panel wall around day 38 could have resulted in a redistribution of stresses in the backfill and a corresponding change in pressure at that time. On the other hand, the lighter compaction at high moisture content may not have caused residual stress to build up on the cantilever wall. The argument that residual shear stresses can cause pressure changes of the type measured is subjective. Additional field data or laboratory tests or both are required.

Earth Pressure Distributions

Four vertical distributions of earth pressure were mea-

Figure 14. Force variation with time, panel wall.

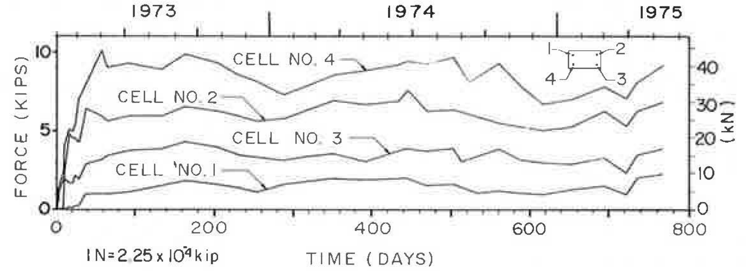


Figure 15. Temperature and pressure relation, cell 694, panel wall.

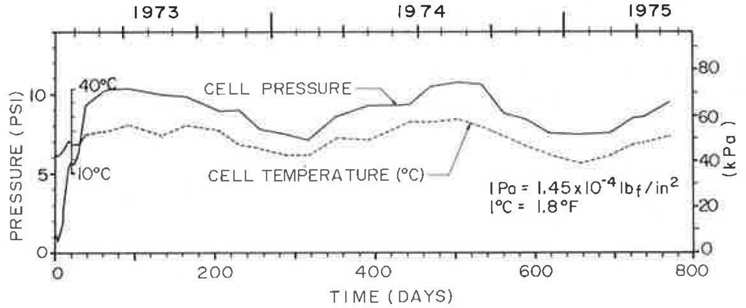
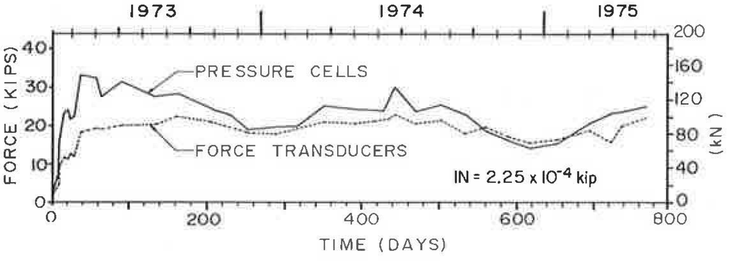


Figure 16. Total force on panel wall.



sured: three on the panel wall and one on the cantilever wall. After backfilling, earth pressures near the base of the cantilever wall and on the panel wall at the bottom of the panel near each pilaster were approximately equal to the at-rest values reported by Terzaghi and Peck (11) for dense sands compacted by tamping in layers. The pressures near the top of the wall for these distributions were lower than the at-rest values. Two of these distributions changed only slightly throughout the test study, but the lower cell at the right side of the panel wall began to decrease after day 38. Although the movements of the panel wall near the pilasters were not measured, the restraint condition at these locations was similar to that of the cantilever wall. In contrast to the center of the panel, the ends were directly bearing on the pilasters that were formed on drilled shafts. This produced the same kind of restraint as the H-piles of the cantilever wall. The principal difference was that the massive pilasters provided higher resistance to tilting. The rigidity of the pilasters was probably not important because the measured earth pressures above the lower cells at both ends was well below even the Coulomb active value. For walls founded on drilled shafts or piles the amount of yield required to effect a reduction in pressure can probably be attained only on the upper portions of the wall. This would depend on the stiffness or flexibility of the stem.

According to Kezdi (4) this type of pressure distribution may result from simple tilting about the top of the wall. Kezdi contended that the displacements required to produce frictional forces along a plane from the base of the wall to the backfill cannot be produced. Such a plane surface of sliding is assumed in the Coulomb and Rankine earth pressure theories. Kezdi therefore suggested that, based on the results of model tests, the surface of sliding originates some distance above the base. The result is that the earth pressures will remain at rest, as they have during this test study, below the point of intersection of the plane of sliding and the wall.

Effects of External Loads

Construction loads during and after backfilling did have an effect on the pressure cell readings, but vehicular traffic did not produce noticeable changes in earth pressures measured on the cantilever wall.

During the backfilling period sharp random increases and decreases in cell pressures occurred until the backfill was a few feet above the cells. This suggests that the increase in pressure as the backfill rises is accompanied by complex stress changes in the backfill caused by compaction.

Two instances of pressure changes resulting from construction after the completion of backfilling were observed: the revival of cell 570 on the cantilever wall and the high pressures occurring on the panel wall on day 38. Both of these events were associated with the movement of heavy construction equipment on the backfill near the wall.

Vehicular traffic was active on the cantilever wall for the last 239 d of the test. Cell pressures during this period followed their established pattern of pressure reduction during the winter months. Only the upper cell tended to remain constant. The panel wall was open to traffic just prior to the last set of measurements. Pressures continued to show their usual seasonal increase during early summer. The number of measurements is not large enough, however, to evaluate the effects of vehicular traffic on the panel wall.

Seasonal Pressure Variations

The most striking long-term characteristic of the study data was the seasonal increase and decrease of lateral earth pressure. These seasonal pressure variations were measured on both walls. The variations correlated closely with temperatures measured near the pressure cells and could not be accounted for by instrument error. On the panel wall, earth pressure variations were measured simultaneously by force transducers and pressure cells. These variations in pressure on both walls probably resulted from a temperature-related phenomenon occurring in the backfill material. The cause of these variations was not determined and will require additional study.

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The contents of this paper reflect only our views, and we 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 sponsors.

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Permeability and Related Properties of Coal Refuse

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Perpetual treatment of acid water from coal waste dumps or from embankments constructed with coal refuse may be uneconomical. The only practical and economical method available for controlling this pollution problem appears to be the isolation of acid-generating ingredients such as pyrite from the other reagents, oxygen and water. Accordingly, controlling the permeability and air content of mine waste has become one of the most important measures in achieving this purpose. This paper focuses on the permeability of coal refuse. Data from both foreign and domestic sources were used to determine the relationship between the permeability found in the laboratory and the various index properties and to assess the effect of the reduction in void ratio caused by compaction, or other means, on the permeability of coal refuse. Traditional relationships between permeability and void ratio of soils were examined for coal refuse. Better regression models between permeability and other properties for both coarse and fine refuse were developed by using stepwise regression analysis. Some established relationships for soils were found to be unsuitable for coal refuse. Good models were developed for both coarse and fine refuse, despite the fact that the data obtained for the analyses were widely scattered in range.

Increased coal production, since the energy crisis, has generated more coal refuse, which in turn creates many environmental problems and sometimes tragic events (2, 3). Large-scale utilization of coal waste material in engineering construction and properly planned economical transformation of disposal areas into reclaimed land are believed to be the most effective measures to ameliorate the coal waste disposal problem.

In addition to the conventional engineering aspects of earthwork design, the following special considerations in using coal mine waste as a construction material should be observed: degradation, combustion, and pollution. Degradation and combustion problems have been discussed by Elnaggar, Chen, and Bullen (4, 5). The pollution problem is greatly affected by permeability. Consequently this paper focuses on the permeability of coal refuse by (a) determining the relationship between the permeability found in the laboratory and various index properties and (b) by assessing the effect of the reduction in void ratio, caused by compaction or other means, on the permeability of coarse and fine coal refuse.

NOTATION

The following notation is used in this paper:

C.I. = confidence interval,
R^2 = coefficient of determination of sample,
$\bar{R}^2$ = coefficient of determination corrected for degree of freedom,
s = standard deviation of sample,
S_{yx} = standard error of estimate,
t = t-statistic assuming null hypothesis is true,
K = number of regressors,
k = permeability,
e = void ratio,
F = fine fraction,
D_{50} = average size, and
D_{10} = effective size.

SOURCES OF DATA

A total of 57 sets of laboratory permeability results with void ratios and gradation curves were obtained from four different sources for coarse refuse (6, 7, 8, 9). Thirty-eight sets of laboratory permeability results with void ratios and gradation curves for fine refuse were also obtained from two different sources (9, 10).

ANALYSIS AND DISCUSSION

As a first step toward determining the effect of void ratio on permeability, the straight-line relationships between k and e^2 and between log k and e (11, 12, 13) were examined for both coarse and fine refuse. For coarse refuse, the linear relationship was found to have an $R^2 = 0.023$ for k versus e^2 and an $R^2 = 0.068$ for log k versus e, indicating that these two models lack explanatory power. Other statistics of these analyses further support this conclusion. As for fine refuse, a similar analysis for both models showed even poorer results. The equations obtained from regression analyses suggest two intuitively incorrect models; i.e., k decreases as e increases. Consequently, those models suggested in the literature for soils do not apply to coal refuse, particularly fine refuse.

Considering prior knowledge from soil mechanics regarding the influence of void ratio and grain size on permeability (11, 12, 13, 14), the variables used in establishing regression models for k versus void ratio and various grain sizes for mill tailings (15), and study conducted on tailing sands (16), we decided that the void ratio, average size, fine fraction, and their various products would be used as independent variables in regression analyses for coarse refuse. Subsequently, simple regression analyses were performed by using $\ln(k)$ as the dependent variable and $\ln(eD_{50})$, $\ln(e/F)$, $\ln(F)$, $\ln(e)$, $\ln(D_{50})$, and $\ln(e^2D_{50})$ as independent variables.