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FIELD MEASUREMENTS OF LATERAL EARTH PRESSURES ON A CANTILEVER RETAINING WALL

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RESEARCH REPORT 169-2
STUDY 2-5-70-169
RETAINING WALL DESIGN

FIELD MEASUREMENTS OF LATERAL EARTH PRESSURES ON A CANTILEVER RETAINING WALL

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Determination of Lateral Earth Pressure
for Use in Retaining Wall Design
Research Study Number 2-5-70-169

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ABSTRACT

Terra Tec pneumatic and Geonor vibrating wire earth pressure cells are used to measure the lateral earth pressures acting on a typical cantilever retaining wall. Accurate measurements of the lateral movements of the wall are made during and after backfilling. Data are presented for both pressure measurements and wall movements covering a period of 147 days. Backfill material is tested to determine its physical and engineering properties. Earth pressures are computed based on Rankine and Coulomb theory and compared with measured earth pressures. Procedures used to calibrate the earth pressure cells are presented in some detail.

KEY WORDS: Earth Pressure Cells, Cantilever Retaining Wall, Pressure Measurement, Wall Movement Measurements, Pressure Cell Calibration.

SUMMARY

The information presented in this report was developed during the second year of a five year study on "Determination of Lateral Earth Pressure for Use in Retaining Wall Design." The broad objective of this study is to develop a more economical design procedure for retaining walls.

The limited objective of the second year of this study was to measure the pressure acting on a typical cantilever retaining wall and to compare measured pressures with theoretical pressures determined by Rankine and Coulomb theory. Accurate measurements of the wall movement during and after backfilling were made. The measured and theoretical pressures agree favorably based on the wall movements which occurred.

The procedures used to calibrate the earth pressure cells are presented and calibration problems are defined. Pressure cells which had been in service on a wall instrumented during the first year of this study were uncovered in order to investigate the drift or change in zero gage readings with time for these cells.

Four Terra Tec and two Geonor pressure cells were used to instrument the wall during the second year of this study. Data are presented for both pressure measurements and wall movements covering a period of 147 days. Graphs of lateral earth pressure

and wall movement versus time and graphs of pressure distribution on the back of the wall are presented.

IMPLEMENTATION STATEMENT

Research Report 169-2 is a technical progress report which presents the results of the work accomplished during the second year of a five year study on "Determination of Lateral Earth Pressure for Use in Retaining Wall Design." Four Terra Tec and two Geonor pressure cells were installed in a cantilever retaining wall. Measurements of earth pressure and wall movement were made and will be continued during the third year of this study. Implementation of the results obtained thus far are not possible because of the need to investigate the long-term performance of the wall.

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INTRODUCTION

Present Status of the Program

The findings presented in this report were obtained during the second year of a five year study on "Determination of 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 has been to measure the distribution of pressure on a cantilever retaining wall and to improve calibration procedures for the cells.

The test site for the first and second year of this study is located in Houston, Texas along U. S. Highway 59. There are seven cantilever retaining walls being constructed at this site. The Texas Highway Department has designated these walls as Retaining Wall "A" thru "G." One panel in Retaining Wall "D" was selected for use during the first year of this study. This panel will be designated in this report as Test Wall "D." The data obtained during the first month following backfilling of Test Wall "D" were presented in Texas Transportation Institute Research Report 169-1 (1)* entitled, "Evaluation of Pressure Cells Used for Field Measurements

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*Numbers in parentheses refer to the references listed in Appendix I.

of Lateral Earth Pressures on Retaining Walls." The data obtained during the second year of this study from Test Wall "D" are presented in this report.

One panel in Retaining Wall "G" was selected for use during the second year of this study. This panel will be designated in this report as Test Wall "G." Four Terra Tec cells and two Geonor cells were installed in Test Wall "G" in March, 1972. Backfilling operations started in early April, 1972, and periodic measurements of earth pressures have been made since that time. The data obtained during the period April, 1972 through August, 1972 are presented in this report. Additional measurements of earth pressures on Test Wall "G" will be made during the third year of this research program.

Program Objectives

The ultimate objective of this five year research study is to develop a more economical design procedure for retaining walls. The specific objectives of the work accomplished during the second year of the study are as follows:

1. To measure lateral earth pressures on a cantilever retaining wall using the pressure cells (Terra Tec pneumatic and Geonor vibrating wire) which were shown to be most promising for use in long term measurements during the first year of this study.
2. To improve the procedures used for calibrating these cells and investigate the effects of grouting, temperature, and drift or change in zero gage reading.

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.
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.

TEST WALL "D"

Current Earth Pressure Measurements

The earth pressure data which were recorded during the twenty-eight day period from June 29, 1971 to July 26, 1971 at Test Wall "D" were reported in TTI Research Report 169-1 (1) as mentioned previously. Additional earth pressure data were obtained during the period July 29, 1971 through July 8, 1972. These data are presented in detail in Table 1 and are plotted in graphic form in Figs. 1 through 4. The pressure cells used in Test Wall "D" were the Gloetzl hydraulic, Terra Tec pneumatic, Geonor vibrating wire, and Carlson unbonded strain gage types. The upper row of cells included one of each type cell located at a depth of 7.5 ft below the top of the wall. The lower row of cells included one of each type cell located at a depth of 15.5 ft below the top of the wall. Additional earth pressure data will be obtained from Test Wall "D" in the future in order to evaluate the long term stability and reliability characteristics of these four different type cells.

In August, 1971, a decision had to be made concerning the performance of the four different type pressure cells used in Test Wall "D." The pressure cells which were to be used during the second year of this study had to be purchased in September, 1971. Therefore, it was necessary to choose the most promising cell or

TABLE 1. - MEASURED LATERAL EARTH PRESSURES (in psi),
TEST WALL "D".

DATE	ELAPSED TIME, DAYS	GLOETZL		TERRA TEC		GEONOR		CARLSON	
		UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER
29 Jun 71	1	0	2.17	0	0.53	0	1.36	0	4.90
30 Jun	2	2.97	3.56	3.41	4.33	4.08	4.74	4.50	8.47
1 Jul	3	2.66	4.15	2.73	6.59	3.60	6.30	3.62	10.52
6 Jul	8	1.86	0.72	3.17	4.57	3.46	4.49	3.44	8.88
9 Jul	11	3.27	1.22	2.63	3.90	a	4.13	3.71	8.78
15 Jul	17	2.23	1.70	3.81	4.86	3.60	2.88	3.53	9.39
22 Jul	24	a	a	a	4.28	a	a	4.24	8.78
26 Jul	28	2.04	1.59	3.91	4.09	3.73	1.97	3.80	8.98
29 Jul	31	2.42	0.98	3.61	4.76	3.55	1.77	3.89	8.98
12 Aug	45	2.33	1.03	5.19	3.70	4.31	1.16	4.42	9.19
26 Aug	59	2.52	1.46	4.60	3.80	3.69	d	4.23	9.80
30 Sep	94	3.47	1.22	4.11	3.03	3.55	d	4.06	9.70
16 Nov	141	3.57	1.16	2.63	0.53	1.78	d	4.15	10.1
13 Jan 72	199	a	a	2.78	c	2.22	d	4.33	9.0
21 Feb	238	a	0.25	c	c	1.38	d	4.33	9.80
22 Feb	239	2.50	0.35	c	c	1.55	d	4.42	9.39
25 Feb	242	a	a	3.57	-1.49	1.86	d	e	e

a No reading taken
c Cell not operating properly; liquid noted in pressure line
d Cell completely inoperative
e Broke meter in readout unit

TABLE 1 (CONTINUED). - MEASURED LATERAL EARTH PRESSURES (in psi), TEST WALL "D".

DATE	ELAPSED TIME, DAYS	GLOETZL		TERRA TEC		GEONOR		CARLSON	
		UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER
23 Mar 72	269	2.61	0.54	3.51	-0.63	2.09	d	5.65	10.3
6 Apr	283	a	a	4.84	-0.96	1.64	d	4.24	8.37
7 Apr	284	a	a	5.28	0.05	2.35	d	5.21	9.90
11 Apr	288	a	a	-0.37[b]	-2.16[b]	-2.09[b]	d	1.24[b]	7.86[b]
11 Apr	288	a	a	-0.72[b]	-2.07[b]	-1.95[b]	d	1.24[b]	7.66[b]
14 Apr	291	a	a	-0.28[b]	-1.01[b]	-1.64[b]	d	1.06[b]	7.96[b]
17 Apr	294	a	a	-0.13[b]	-1.83[b]	-2.40[b]	d	1.15[b]	7.15[b]
18 Apr	295	a	a	0.22[b]	-2.08[b]	-2.18[b]	d	1.24[b]	7.86[b]
20 Apr	297	1.2[b]	a	0.07[b]	-0.96[b]	-1.55[b]	d	1.15[b]	7.86[b]
25 Apr	302	a	a	1.55	0.19	1.64	d	2.55	8.78
2 May	309	a	a	0.82	0.34	1.42	d	2.38	9.39
10 May	317	2.2	0.7	0.72	0.63	1.25	d	2.64	10.21
17 May	324	2.4	0.8	1.01	0.24	1.25	d	2.73	8.98
1 Jun	338	a	a	1.30	1.30	1.25	d	2.55	8.57
15 Jun	352	a	a	1.30	1.30	1.25	d	2.73	8.57
18 Jul	385	a	a	1.21	1.35	0.98	d	2.82	8.98

a No reading taken
b Backfill removed from upper row of pressure cells
d Cell completely inoperative

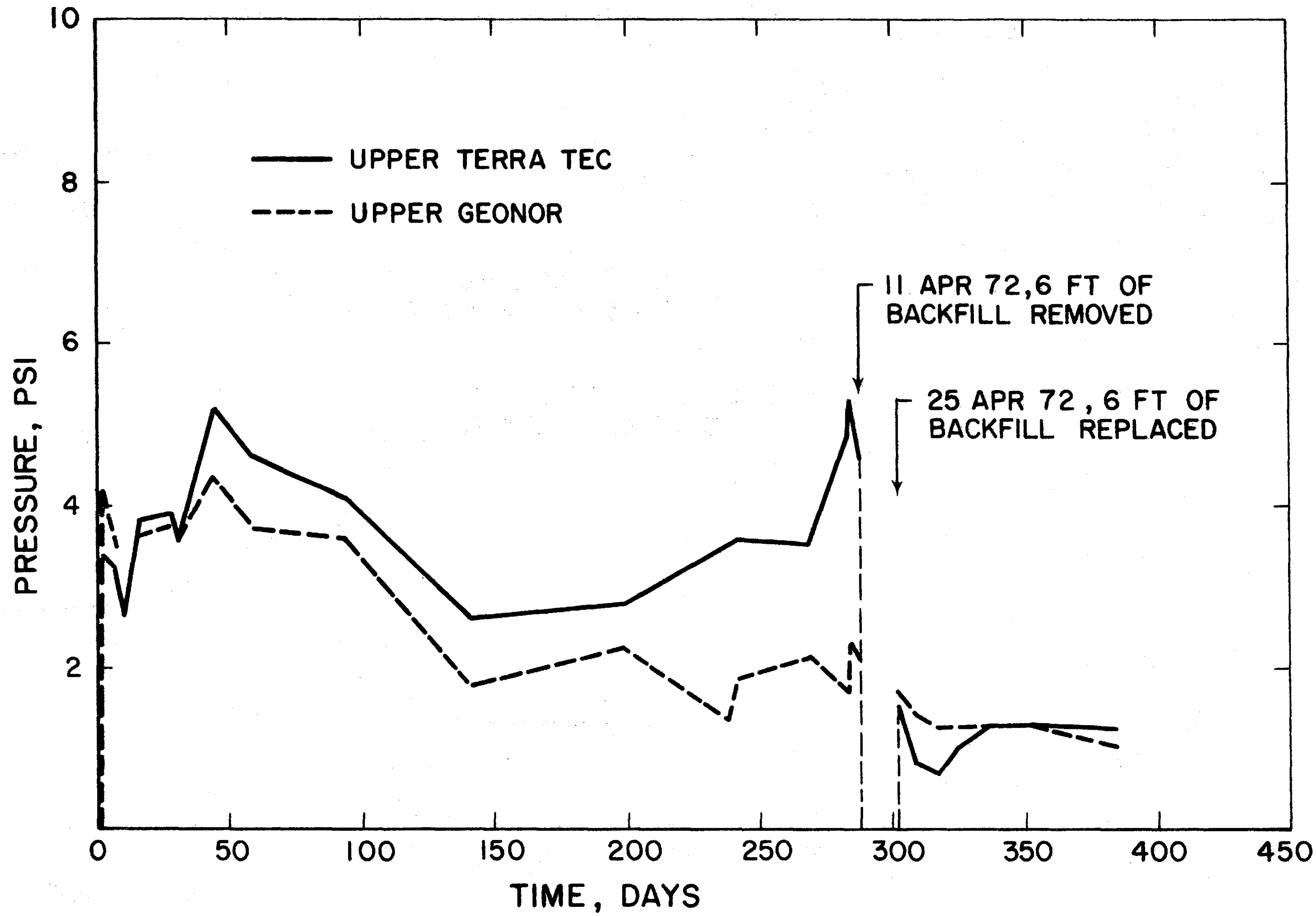

FIG. 1—MEASURED PRESSURE VERSUS TIME, UPPER CELLS, TEST WALL "D"

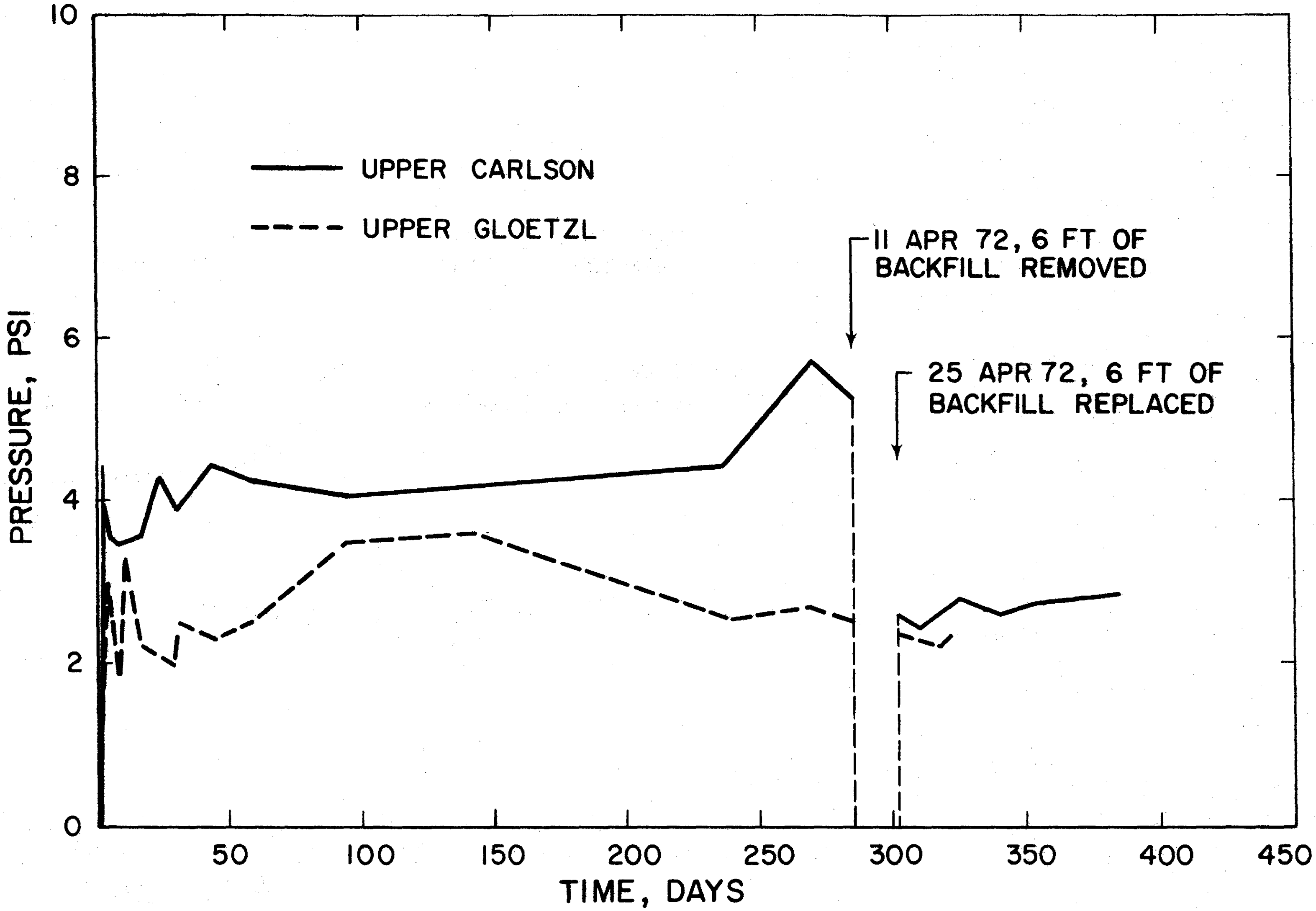

FIG. 2—MEASURED PRESSURE VERSUS TIME, UPPER CELLS, TEST WALL "D"

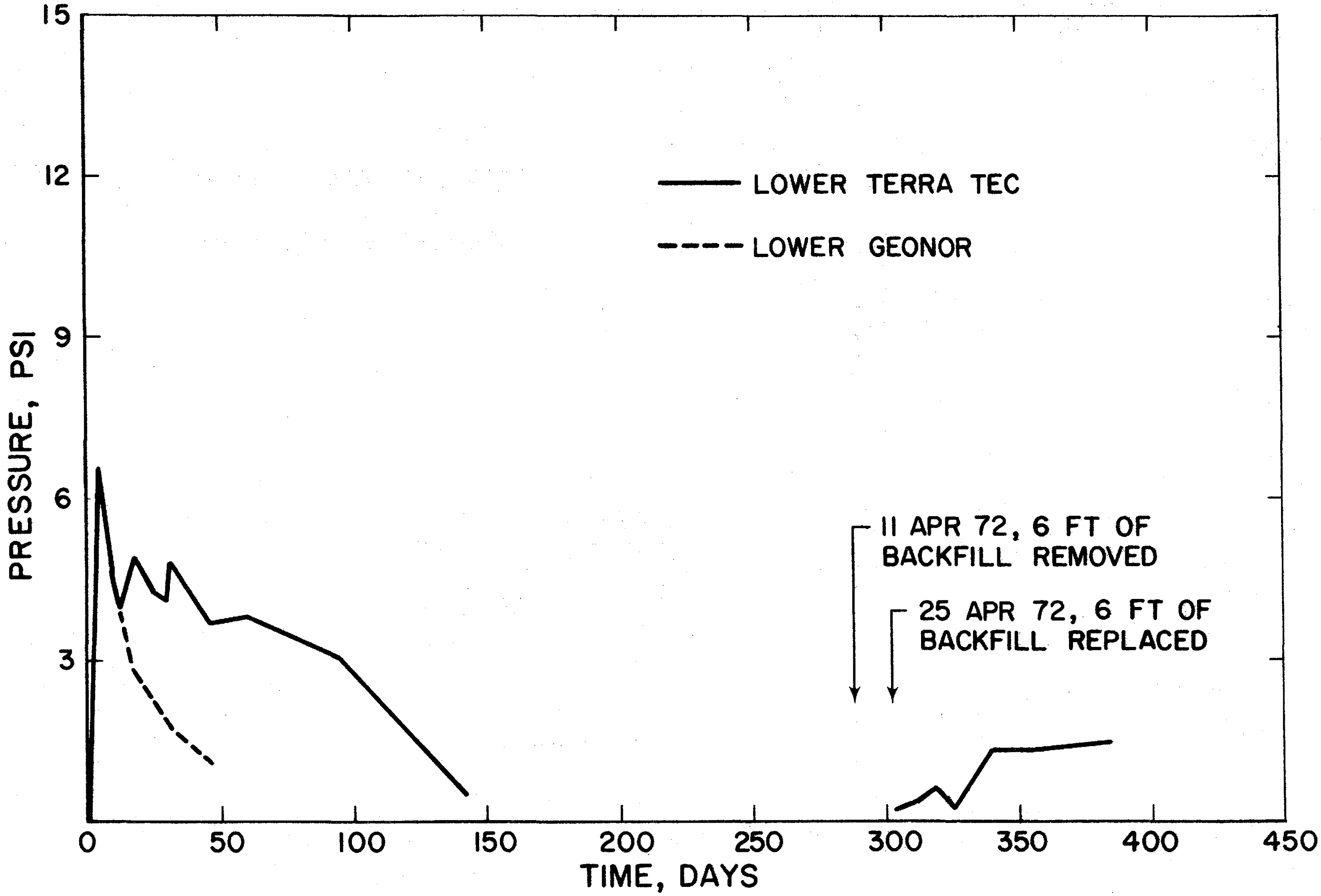

FIG. 3—MEASURED PRESSURE VERSUS TIME, LOWER CELLS, TEST WALL "D"

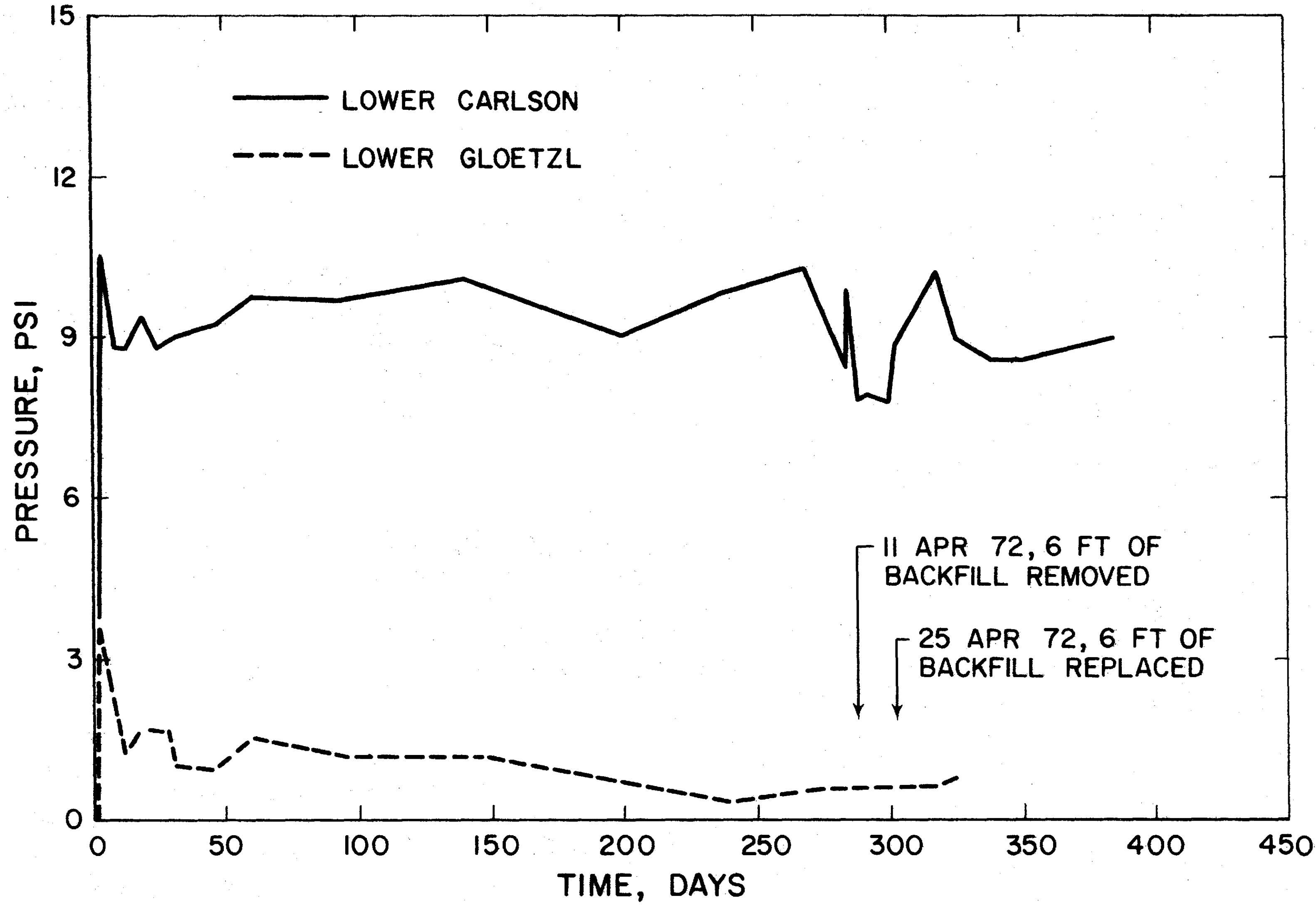

FIG. 4—MEASURED PRESSURE VERSUS TIME, LOWER CELLS, TEST WALL "D"

cells based on earth pressure measurements from Test Wall "D" covering only a one month period. The decision was made to purchase Terra Tec and Geonor cells for the second year study. The reasons for choosing these two cells are given in detail in TTI Research Report 169-1 (1). Briefly, the reasons were as follows:

1. The pressure measurements from the Terra Tec and Geonor cells seemed reasonable when compared with Rankine and Coulomb theory.
2. The pressure measurements from these two cells showed the same general trends in the sense that increases and decreases in pressure occurred generally at the same time.
3. Both cells were easy to install and subsequent operation of the read-out equipment in the field was simple.
4. The purchase cost of these cells was not considered prohibitive.

An examination of the current earth pressure data tabulated in Table 1 and shown graphically in Figs. 1 through 4, which covers approximately a one year period, shows that the decision to use Terra Tec and Geonor cells during the second year study was reasonable. The performance of all four cells used in Test Wall "D" over the one year period has generally been about the same as the performance during the first month. The upper row of cells in Test Wall "D" was uncovered during the period April 11 to April 25, 1972. At this time, it was discovered that the initial zero gage readings on all gages had changed. This created a calibration problem which will be discussed in some detail in the next section.

All four cells on the upper row of Test Wall "D" are still functioning. Figs. 1 and 2 show graphically the changes in the pressure measurements versus time for these cells. Fig. 1 shows that the upper Terra Tec and Geonor cells generally registered the same trends in terms of increasing and decreasing magnitudes of pressure at any given time. Fig. 2 shows that the upper Carlson and Gloetzl cells did not follow the same trends as the upper Terra Tec and Geonor cells, and there was a greater discrepancy in the magnitudes of registered pressures between the Carlson and Gloetzl cells. The decrease in magnitudes of pressure for all four upper cells after April 25, 1972 is due to the change in initial zero gage readings. It should be noted (see Table 1) that only periodic readings were taken from the Gloetzl cells after January 13, 1972 because the operation of the read-out unit for those cells is difficult and time consuming.

All four cells on the lower row of Test Wall "D" are not functioning. As shown in Table 1 and Fig. 3, the lower Geonor cell pressure readings began to decrease on July 15, 1971 and on August 26, 1971 the cell became completely inoperative. The cause of the malfunction of this cell is not known and retrieval of the cell was not possible because of the depth of burial. On January 13, 1972 the lower Terra Tec Cell failed to respond, and on February 21, 1972 the upper Terra Tec cell stopped operating properly. Examination of the air pressure lines for these cells showed that moisture had collected in the lines. It was possible to reverse the flow of air pressure through the Terra Tec cells and purge the system of the entrapped moisture. After back-flushing, the upper Terra Tec cell became operative and gave pressure readings which were consistent with earlier readings. The lower Terra Tec cell became operative after back-flushing but the readings were lower than earlier readings. The lower readings can possibly be attributed to calibration problems which will be discussed later. The ability to back-flush the Terra Tec cells and restore operation is a distinct advantage for long-term pressure measurement studies. Fig. 4 shows the performance of the lower Carlson and lower Gloetzl cells. The Carlson cell has yielded pressure measurements which are consistently high and the Gloetzl cell has registered consistently low and there is a large discrepancy in the magnitude of measured pressures between these two cells.

Calibration Problems

During the initial calibration of the pressure cells used in Test Wall "D" it was discovered that these cells had some undesirable calibration characteristics. One of these undesirable characteristics was the tendency for the zero gage reading, or the gage reading at zero applied pressure on the cell, to drift or shift with both time and temperature. The cells were calibrated at different temperatures and the thermocouples were installed in the wall so that adjustments could be made for changes in temperature. However, the drift or change in zero gage readings with time could not be thoroughly investigated until the pressure on the cells was reduced to zero after a relatively long period of time.

The decision was made to uncover the upper row of cells on Test Wall "D" in April, 1972. As mentioned previously, the backfill was removed during the period April 11 to April 25, 1972. New zero gage readings were taken and the results showed that all cells except the Terra Tec cell experienced a significant change in the zero readings when compared with the readings taken prior to the original backfilling of the wall. As shown in Table 1, the upper Terra Tec and upper Geonor cells indicated negative readings when the old (initial) zero gage readings were used to convert to measured pressure. The old zero gage readings and the new average zero gage readings are shown in Table 2.

TABLE 2. - CHANGE IN ZERO GAGE READINGS FOR UPPER ROW OF PRESSURE CELLS

Cell	Zero Gage Reading		Corresponding Pressure Change (psi)
	Old	New	
Terra Tec	5.53	5.27	-0.26
Geonor	1733.	1710.	-2.05
Carlson	101.14	101.01	+1.15

Also shown in Table 2 are the corresponding changes in measured pressure. The changes in zero gage readings were greater than expected, especially for the Geonor cell.

It is important to note that the Terra Tec cell is giving the best performance because of the smaller change in zero gage reading with time. The data in Table 2 indicates that the Terra Tec cell would be accurate to within approximately 0.25 psi. Also, if the same correction were applied to the lower Terra Tec cell, the pressure readings would be higher and more realistic.

The backfill was replaced on Test Wall "D" on April 25, 1972 and the new zero gage readings were used to convert to measured pressure after that date. As shown in Table 1 and Fig. 1 the measured pressures were then reasonable and consistent, especially for the Terra Tec and Geonor cells. The procedure for calibrating the pressure cells used in Test Wall "G" during the second year of this study was modified in order to better account for changes in zero gage readings. This procedure will be discussed in detail in the next section under calibration of cells for Test Wall "G."

TEST WALL "G"

Selection of Cells

The reasons for selecting the Terra Tec and Geonor cells for use in the second year of this research study have already been presented in some detail in the previous section covering the lateral earth pressure measurements on Test Wall "D," and in TTI Research Report 169-1 (1). The Terra Tec cell is relatively new and has not been proven 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 provided 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 loss of the lower Geonor cell on Test Wall "D" after only two months of operation is not indicative of long-term reliability. However, when this cell was purchased, it was received in pieces and had to be reassembled. It is believed that a mechanical malfunction may have resulted from improper reassembly.

The principle of operation of the Terra Tec and Geonor cells is discussed in some detail in TTI Research Report 169-1 (1) and will not be repeated herein. Calibration problems for both of these cells have been indicated previously and will be discussed in more detail in the next section. The problem of change in the initial zero gage reading appears to be most significant for the Geonor cell as shown in Table 2. An effort was made to improve calibration procedures for both the Terra Tec and Geonor cells used in Test Wall "G," and a continuing effort towards improved calibration will be made during the third year of this study.

Calibration of Cells

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. The calibration procedures used were identical to those used during calibration of the pressure cells which were installed in Test Wall "D" with only minor exceptions.

The definition of pressure sensitivity of the cells as used in this report means the output of the pressure cell in response to an applied pressure, or change in pressure, and 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 psi, 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 one psi in the reading of the pressure gage 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 Hz (1 Hz = 1 cycle per second) of the wire inside the cell is displayed on the read-out unit. The output of the vibrating wire cell is intrinsically non-linear and a graph of applied pressure versus frequency of vibration does not plot as a straight line. Based upon the fundamental mathematical theory of the cell, the manufacturer suggests (2) that the data be transformed in a manner such 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 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 $\Delta f^2 = 708225$. With frequency recorded to four significant figures, Δf^2 is divided by a scale factor of 1000 to obtain numbers which 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 $\Delta f^2/1000$.

During calibration of the pressure cells which were installed in Test Wall "D" each cell was tested three times for pressure sensitivity at each of three temperatures (50°F, 70°F, and 100°F). The test data indicated that temperature variation did not affect the pressure sensitivity of the cells. Therefore, during calibration of cells for Test Wall "G" only three pressure sensitivity tests were run on each cell and temperature was not regarded as a critical factor.

Calibration was accomplished by placing a pressure cell inside a sealed chamber and then increasing the air pressure inside the chamber. A typical calibration run consisted of applying 23 increments of pressure beginning with 0 psi, increasing to 12 psi, and returning to 0 psi. Each increment of pressure was nominally 1 psi. A typical calibration curve for the Terra Tec cells is shown in Fig. 5. Fig. 6 is a typical applied pressure versus frequency plot for the Geonor cells and illustrates the non-linear response of the cell. Fig. 7 shows the linear plot of pressure versus squared-frequency difference obtained from the data of Fig. 6. The pressure sensitivities obtained from the calibration data are shown in Table 3.

TABLE 3. - PRESSURE SENSITIVITY OF PRESSURE CELLS INSTALLED IN TEST WALL "G"

CELL	SENSITIVITY
Terra Tec No. 570	1.00 psi/psi
Terra Tec No. 577	1.00 psi/psi
Terra Tec No. 578	0.99 psi/psi
Terra Tec No. 580	1.00 psi/psi
Terra Tec No. 604	0.99 psi/psi
Geonor No. 1	0.0175 psi/Δf^2/1000
Geonor No. 2	0.0177 psi/Δf^2/1000

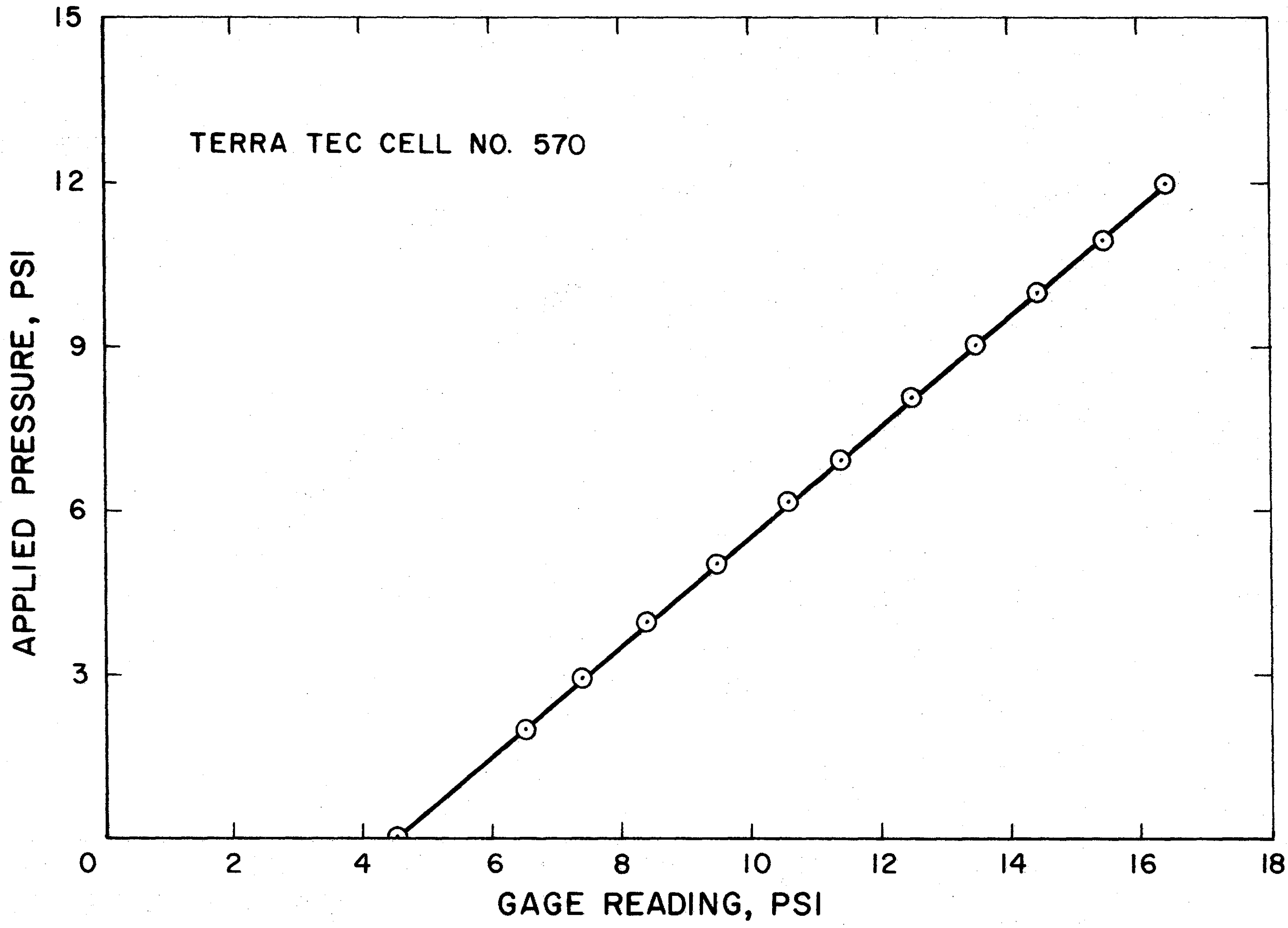

FIG. 5 — TYPICAL CALIBRATION CURVE FOR TERRA TEC CELL

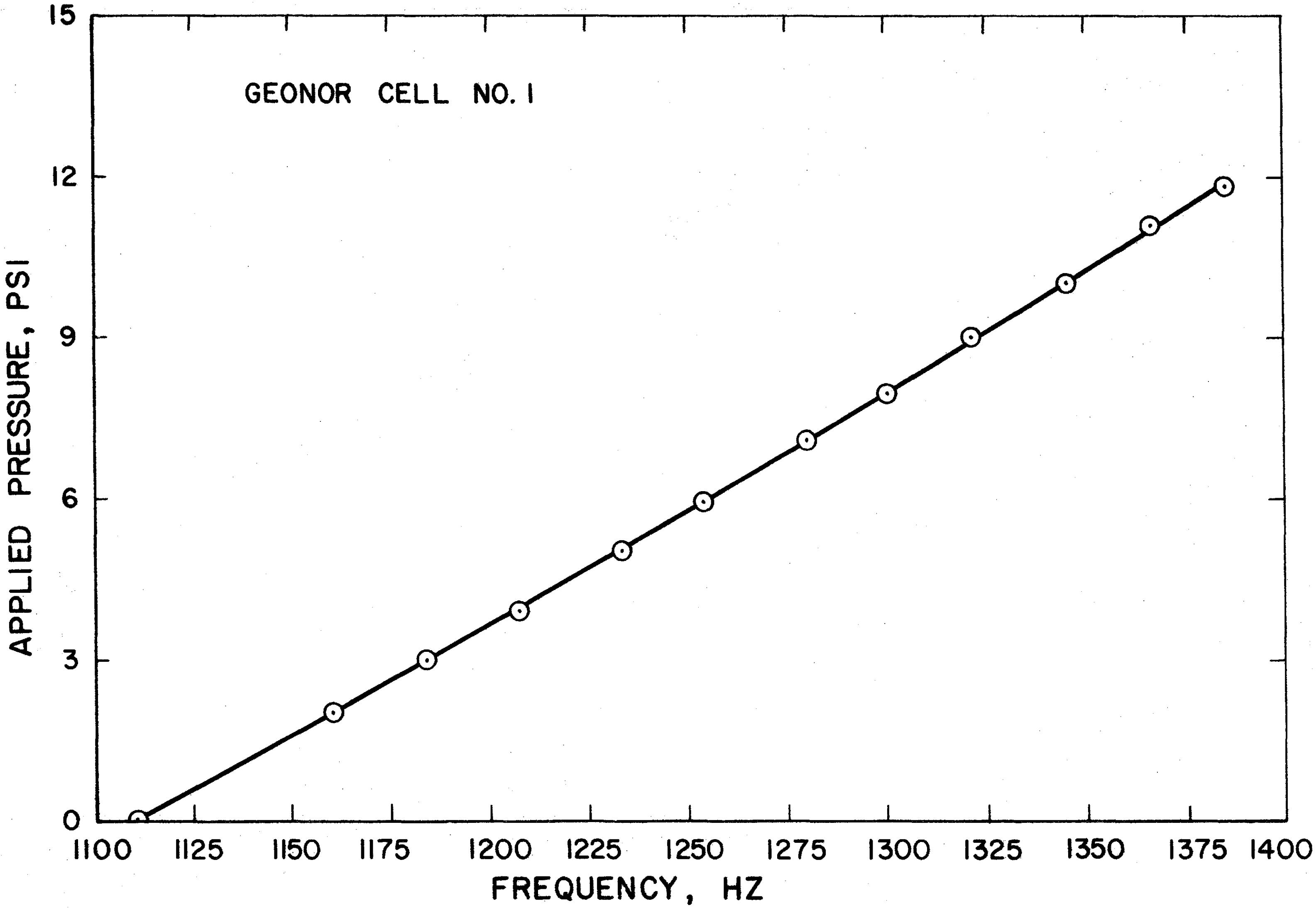

FIG. 6—TYPICAL PRESSURE VERSUS FREQUENCY CURVE FOR GEONOR CELL

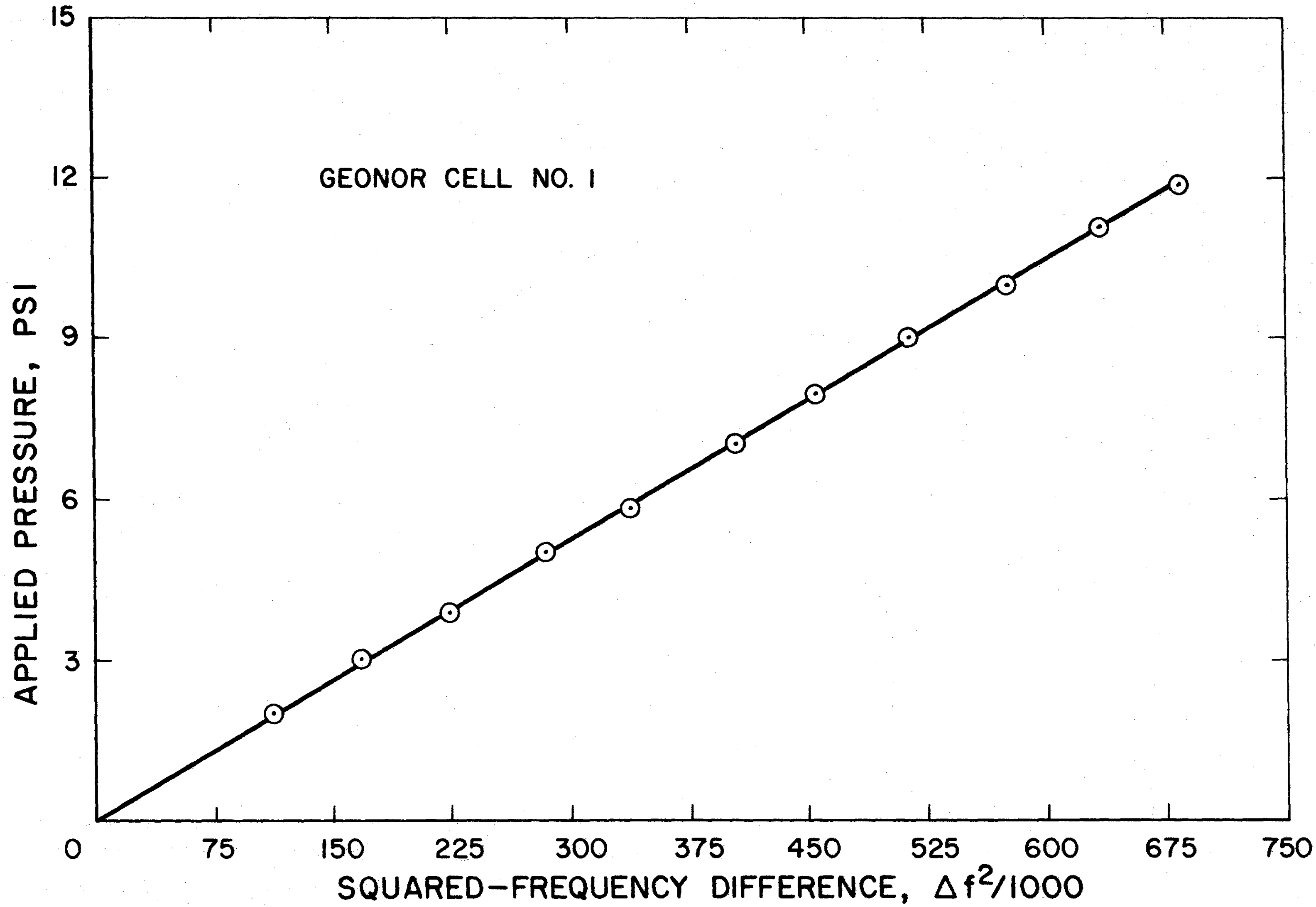

FIG. 7—TYPICAL CALIBRATION CURVE FOR GEONOR CELL

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, Terra Tec cell No. 577 was grouted into a 4-in. thick, 16-in. diameter 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 for the non-embedded cells. 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. Time limitations precluded similar tests on a Geonor cell. However it is believed that the Geonor cell is much less susceptible to any effect of grouting because the active area of the cell is completely surrounded by the relatively massive solid piece of steel which forms the base of the cell.

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. All the cells were placed inside a room wherein the temperature was maintained constant at one of the above test temperatures. A 24-hr waiting period was allowed for the cells to reach equilibrium with the ambient temperature. A second 24-hr period was allowed during which time the zero gage readings of the pressure cells were checked periodically. All cells were found to exhibit an increase in the zero gage reading with an increase in temperature. Table 4 presents the temperature coefficients, in terms of the increase in zero gage reading per one-degree Fahrenheit temperature increase, as determined in the laboratory.

TABLE 4. - LABORATORY DETERMINED COEFFICIENTS OF ZERO GAGE READING INCREASE DUE TO TEMPERATURE

CELL NUMBER	COEFFICIENT
Terra Tec No. 570	0.012 psi per °F
Terra Tec No. 577	0.016 psi per °F
Terra Tec No. 578	0.013 psi per °F
Terra Tec No. 580	0.010 psi per °F
Terra Tec No. 604	0.021 psi per °F
Geonor No. 1	0.040 Hz per °F
Geonor No. 2	0.038 Hz per °F

After the cells were installed in the retaining wall, additional data were obtained for evaluation of the temperature effect on zero gage 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, readings were taken both during the day and night. The recorded temperatures were those of the concrete immediately adjacent to the pressure cells. They were obtained by means of thermocouples which were mounted directly on the surface of the concrete, one thermocouple being mounted approximately one inch from each of the pressure cells. In this manner, a range of temperature from 71 to 91°F 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. Fig. 8 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. A considerable amount of scatter is present in the data from each cell, but a noticeable trend is evident. The zero gage readings tend to increase with temperature. The method of least squares was used to obtain the linear regression curve of zero reading on temperature for each cell. The coefficients of zero gage reading increase due to temperature which were computed from the field data are given in Table 5.

Installation of Cells

The test site for Test Wall "G" is located along U. S. Highway 59 near its intersection with Interstate Highway 45 in Houston,

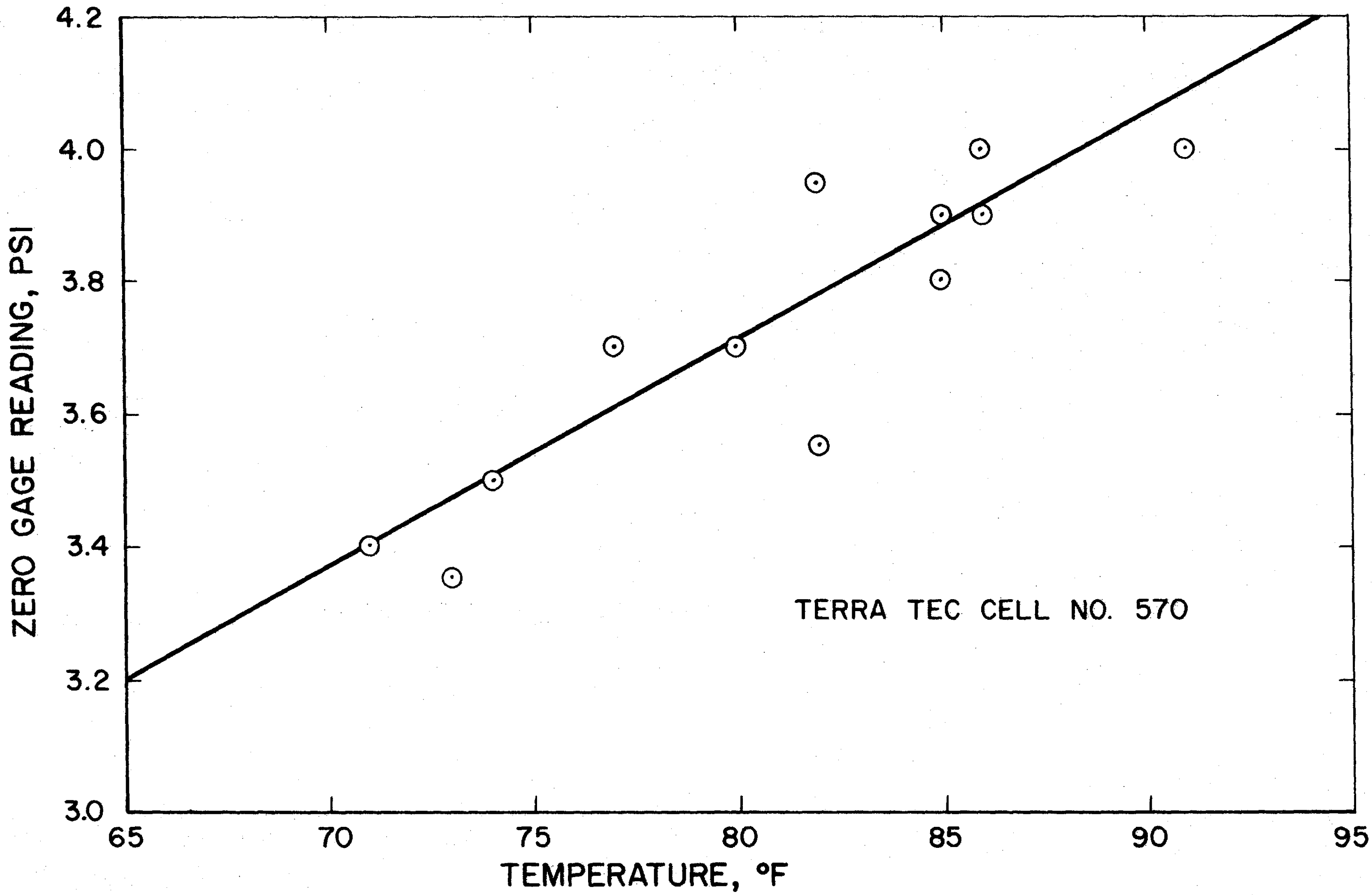

FIG. 8—TYPICAL FIELD RELATIONSHIP BETWEEN ZERO GAGE READING AND TEMPERATURE

TABLE 5. - COEFFICIENTS OF ZERO GAGE READING INCREASE DUE TO TEMPERATURE, COMPUTED FROM FIELD DATA

CELL NUMBER	COEFFICIENT
Terra Tec No. 570	0.034 psi per °F
Terra Tec No. 578	0.023 psi per °F
Terra Tec No. 580	0.023 psi per °F
Terra Tec No. 604	0.037 psi per °F
Geonor No. 1	0.42 Hz per °F
Geonor No. 2	0.34 Hz per °F

Texas. The footing for the cantilever retaining wall is resting on H piles. A typical cross-section of the cantilever retaining wall is shown in Fig. 9. The groundwater table is located below the footing of the wall. Weep holes are provided to allow drainage and thus 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 Fig. 10. 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 upper and lower Terra Tec cells so that a check could be made of the magnitudes of the measured pressures at the 4 ft and the 13 ft depths. Also, the upper Terra Tec (No. 570) and upper Geonor (No. 1) can be uncovered at a future time in order to check the zero gage readings for these two cells. A thermocouple

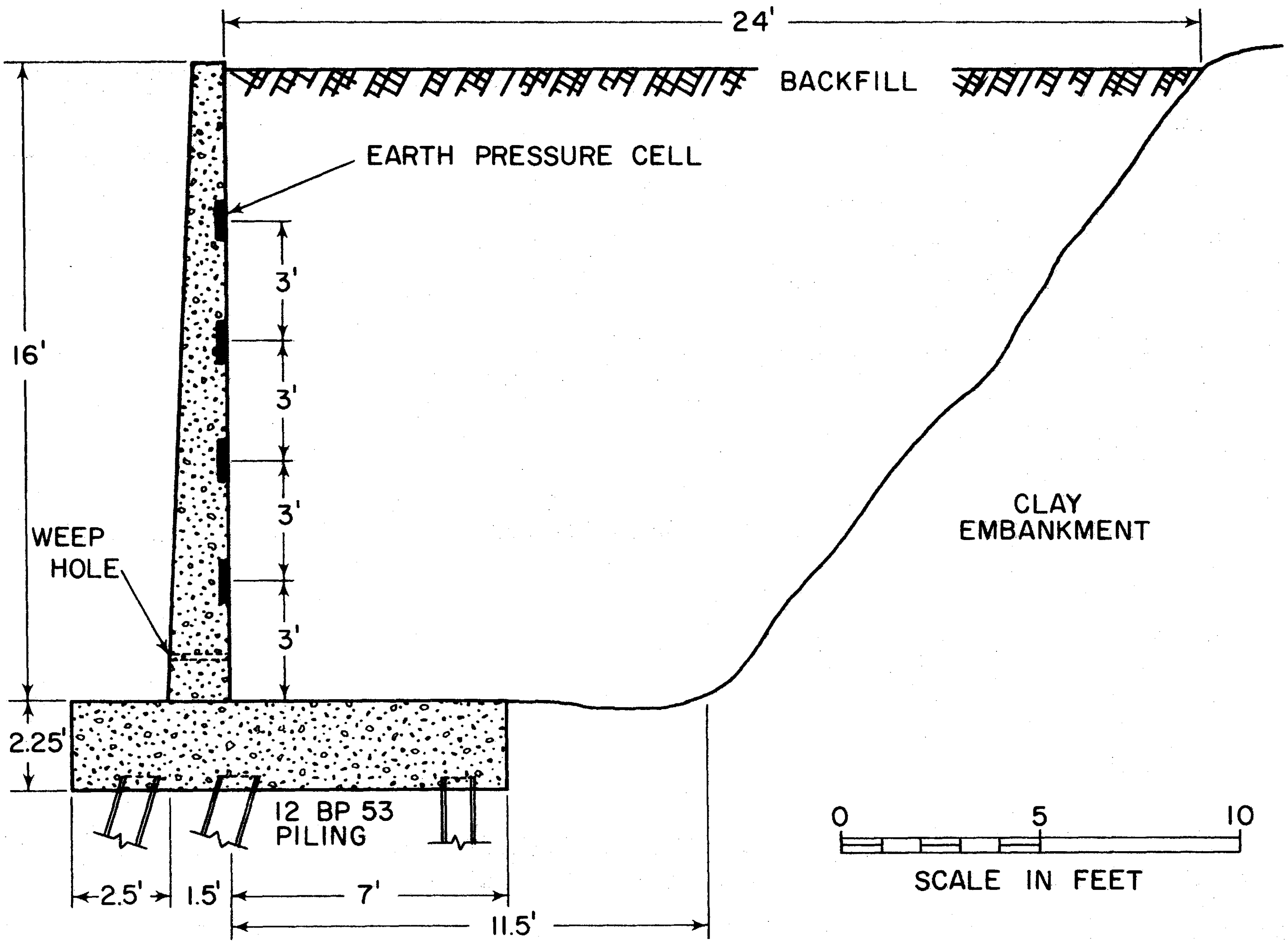

FIG. 9 — CROSS SECTION OF TEST WALL "G"

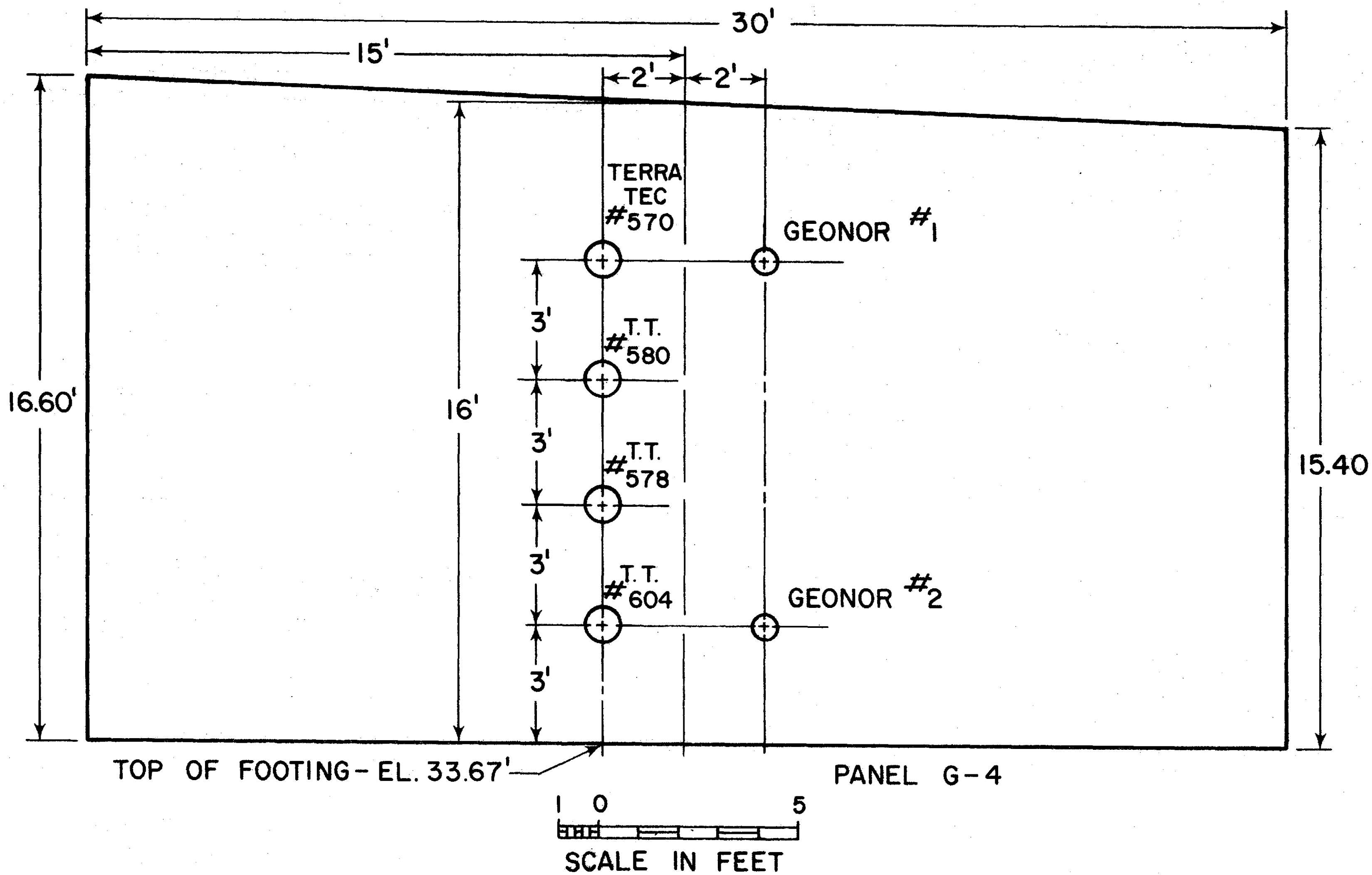

FIG. 10 - LOCATION OF EARTH PRESSURE CELLS, TEST WALL "G"

was installed at each pressure cell location so that temperature could be determined at the time the pressure readings were taken.

Since 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. The face of each installed pressure cell was flush with the back of the wall. The thermocouples were attached to the wall with epoxy. All cables and wires were run to a central location at the top of the wall. A detailed discussion on the installation procedure of the pressure cells and thermocouples is given in TTI Research Report 169-1 (1).

Backfilling Procedure

The backfill operation for Test Wall "G" took place over a period of six days. The backfill procedure was essentially the same as the one followed for Test Wall "D." The backfill material was dumped and roughly spread by heavy scrapers. The completed spreading and compaction was done with a bulldozer. The backfill material was spread in approximately eight inch lifts, and the bulldozer made approximately three passes on each lift. Care was taken to insure that none of the instrumentation on the test wall panel was damaged by the earth moving equipment. Earth pressure measurements were made during the backfilling operation. These data were tabulated and are presented in the section on pressure measurements for Test Wall "G."

Properties of the Backfill Material

Samples of backfill material were taken during backfilling in order to determine the placement moisture content and wet and dry unit weight (density). The data obtained are given in Table 6.

TABLE 6. - PLACEMENT MOISTURE CONTENT AND DENSITY AT TEST WALL "G"

	Wet Unit Weight (pcf)		Dry Unit Weight (pcf)		Moisture Content (Per Cent)
	Next to Wall	Center of Fill	Next to Wall	Center of Fill	
Minimum	78.4	84.8	65.0	69.2	15.3
Maximum	116.1	122.0	98.3	98.7	23.2
Average	91.6	101.3	77.4	83.4	20.4
No. Samples	4	5	4	5	16

The observed dry unit weights may be somewhat lower than the unit weight 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. The water inside the hole is contained within a balloon to prevent the water from escaping through the voids and into the surrounding soil. 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.

This would have the effect of reducing the apparent density of the material removed from the hole. This effect is even more likely to occur in samples taken within approximately two feet of the wall where the backfill is in a very loose condition.

Direct shear tests were run on representative samples of the backfill material to determine the angle of shearing resistance. The samples were 1-in. high and 2.5-in. in diameter and were tested at a strain rate of 0.0004 in. per min. Normal stresses of 5, 10, and 20 psi were applied. The material was found to have an angle of shearing resistance of 32°.

The grain size distribution curve for the backfill material placed behind Test Wall "G" is very similar to that of the Test Wall "D" material. However, the Test Wall "G" material contains approximately a 5% greater amount of fines passing the No. 200 sieve. Therefore, based on the Unified Soil Calssification System, the Test Wall "G" material is classified as SP-SM.

DATA COLLECTION - TEST WALL "G"

Measured Earth Pressures

The lateral earth pressures measured on Test Wall "G" are given in Table 7 and illustrated graphically in Figs. 11 through 13. In general it may be stated that the overall set of data obtained at Test Wall "G" is very good. The most notable exception is with the earth pressures recorded at a depth of 4 ft by Terra Tec cell No. 570 and Geonor cell No. 1 (See Fig. 11). The difference between the readings of these two cells is generally around 1 psi, with the maximum difference of 2 psi occurring 35 days after backfill. The other exception worthy of noting is that the pressures being measured by Geonor No. 1 at 4 ft and Terra Tec No. 580 at 7 ft are almost identical (See Fig. 11). It would therefore appear that the upper Geonor cell is tending to slightly over-register by about 1 psi. This difference of approximately 1 psi is not considered significant at these shallow depths. On the other hand, Geonor No. 2 and Terra Tec No. 604, both at the greater depth of 13 ft, are registering nearly identical pressures (See Fig. 12).

Another aspect of the measured pressures is most encouraging with respect to the performance of the pressure cells. Referring to Table 7 and Fig. 13 it can be seen that all pressure cells indicated either a simultaneous increase or a simultaneous decrease

TABLE 7. - MEASURED LATERAL EARTH PRESSURES (IN PSI), TEST WALL "G"

DATE	ELAPSED TIME IN DAYS	TERRA TEC				GEONOR	
		570	580	578	604	1	2
12 Apr 72	0	0.08	0.03	0.09	0.11	0.07	-0.07
		0.32	0.10	0.23	0.64	-0.19	0.46
13 Apr	1	-0.05	-0.09	0.02	0.07	0.10	0.16
		-0.13	-0.12	-0.29	1.32	0.24	1.19
		0.02	0.09	-0.14	1.45	0.04	1.31
		0.20	0.13	0.1	1.97	-0.19	1.79
14 Apr	2	-0.04	-0.18	0.07	1.23	0.16	1.22
		-0.34	-0.37	-0.49	1.20	0.05	1.19
17 Apr	5	-0.65	-0.58	0.82	2.33	0.32	2.09
		-0.37	-0.6	1.23	3.05	0.21	2.87
		0.03	-0.15	2.24	3.05	0.0	3.08
		0.14	1.65	4.0	4.55	-0.16	4.23
18 Apr	6	0.0	1.87	3.1	5.90	-0.12	5.66
		0.08	2.92	4.5	5.6	0.0	5.49
		1.14	3.57	5.07	6.15	1.24	5.96
		1.91	3.43	5.4	6.75	2.10	6.28
		1.74	2.93	6.35	8.05	2.92	7.89
20 Apr	8	1.66	2.87	6.65	8.59	2.40	8.27
25 Apr	13	1.1	2.48	6.2	8.49	1.80	8.64
2 May	20	1.24	2.54	5.97	8.30	2.64	8.23
10 May	28	1.7	2.98	6.78	8.97	2.89	8.71
17 May	35	0.4	2.6	6.03	8.2	2.31	8.34
1 Jun	50	1.08	2.27	6.27	8.4	2.40	8.35
15 Jun	64	2.18	2.68	6.56	9.13	3.22	8.35
18 Jul	97	1.42	2.24	6.00	8.35	2.40	8.07
6 Sep	147	2.16	2.51	6.43	9.24	2.30	8.52

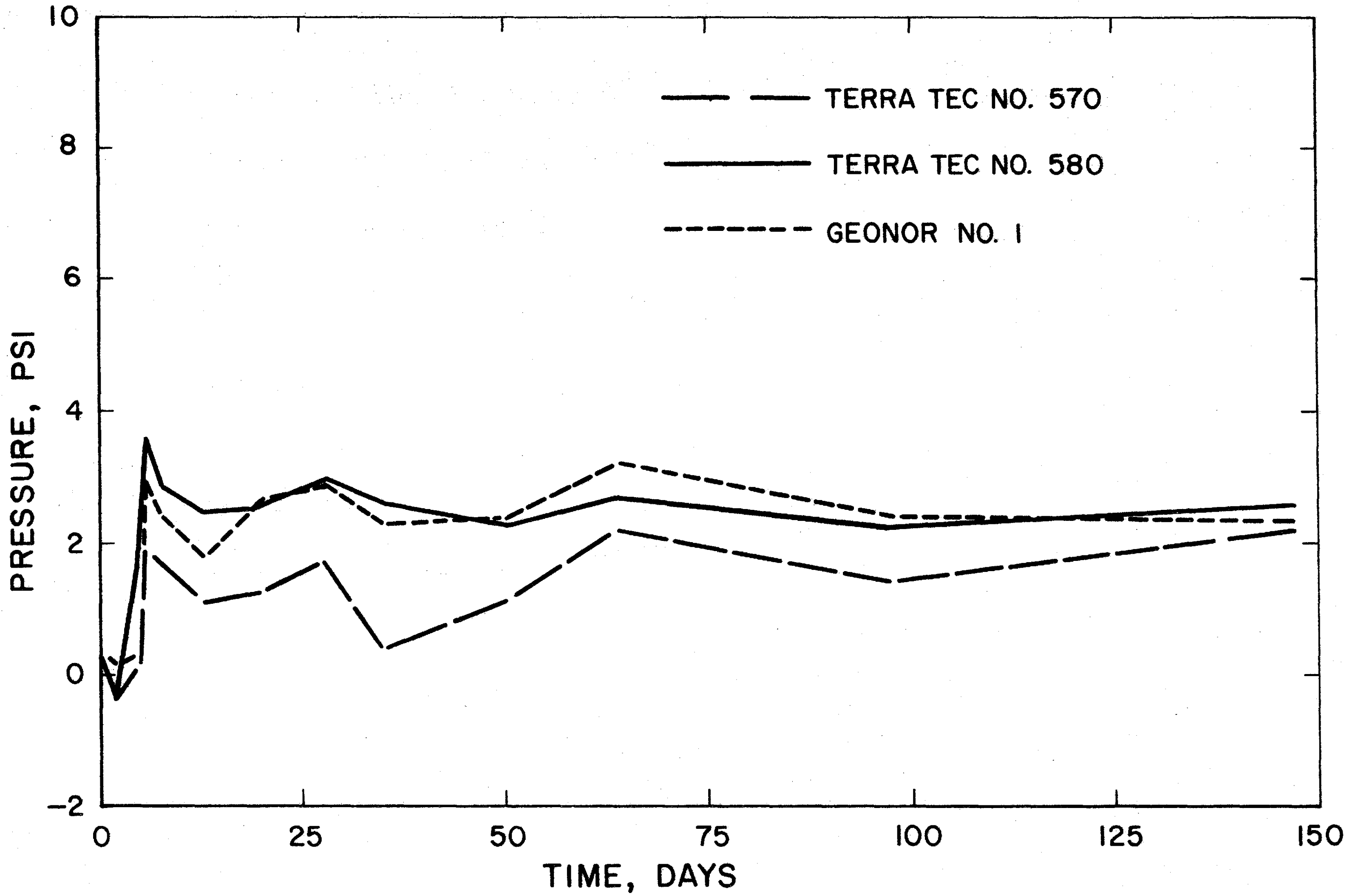

FIG. 11 — MEASURED PRESSURE VERSUS TIME, TEST WALL "G"

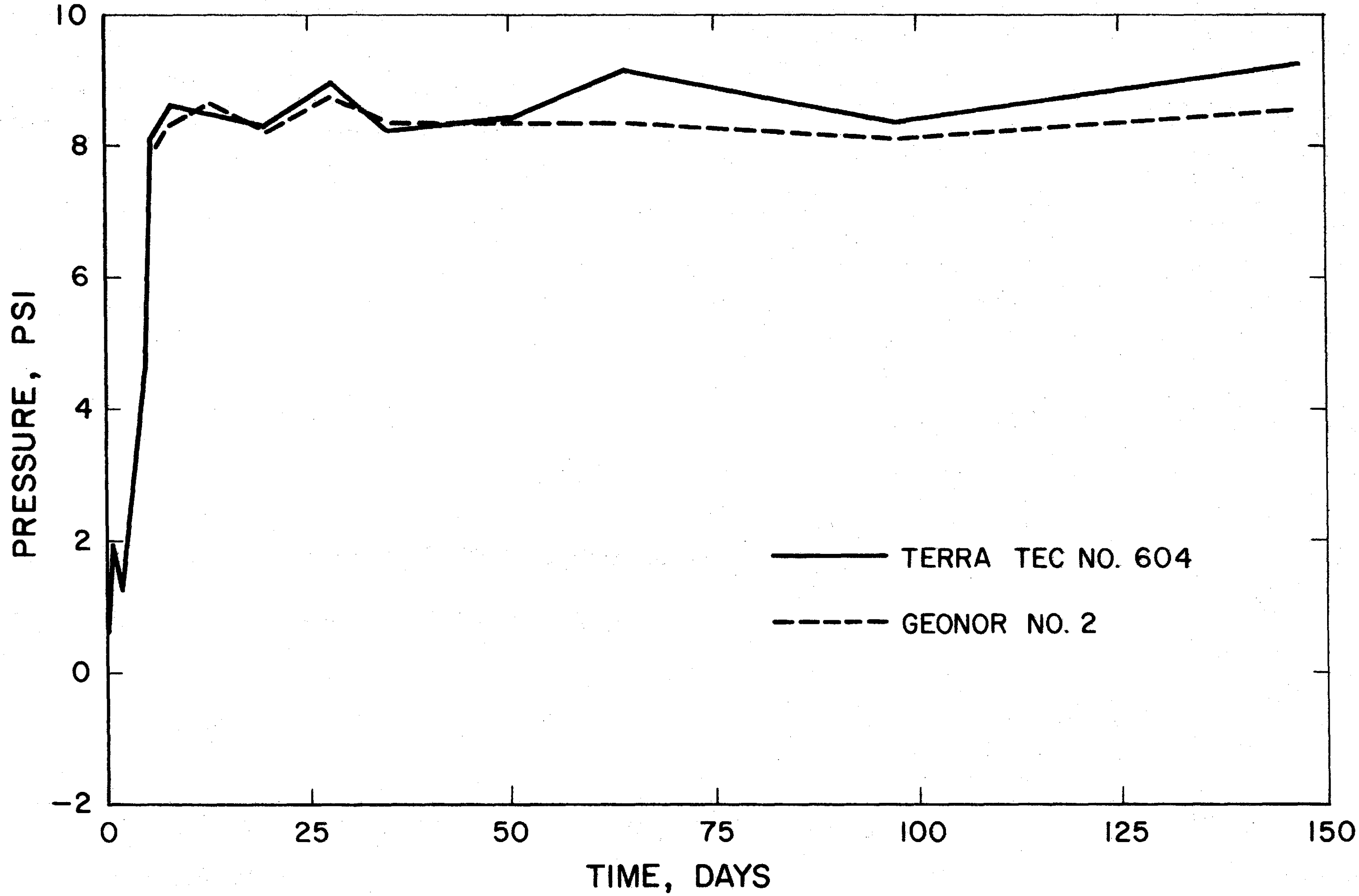

FIG. 12—MEASURED PRESSURE VERSUS TIME, TEST WALL "G"

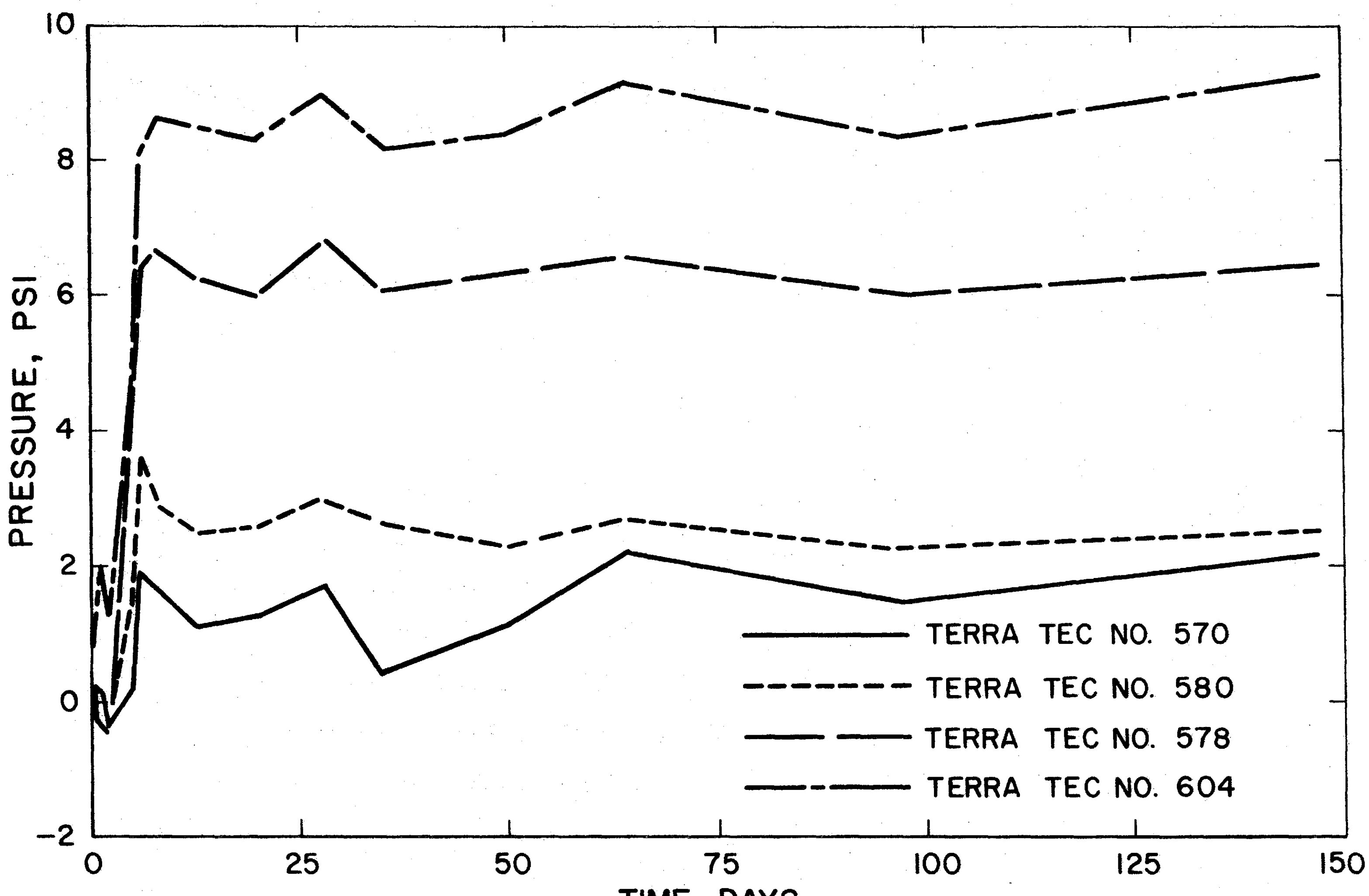

FIG. 13-MEASURED PRESSURE VERSUS TIME, TEST WALL "G"

in pressure during any given period. The only exception occurred between day 35 and day 50, when Terra Tec No. 580 registered a decrease in pressure whereas all other cells registered an increase.

Earth pressure measurements were made periodically throughout the day when the backfill material was being placed behind Test Wall "G." In addition, attempts were made to measure the "dynamic" earth pressures caused by the hauling and compacting equipment as it passed directly in front of the pressure cells. Neither the Geonor nor the Terra Tec cell is well adapted for this kind of measurement. Either system requires a certain time period during which the read-out unit senses the signal being sent by the pressure cell. The pressure acting on the cell cannot be displayed on the read-out unit before the time period is complete. Of the two cells the Geonor has the shorter period and it is approximately three to four 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 which 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.

Measured Wall Movements

Measurements of wall movements are needed to establish the expected type of earth pressure distribution. A detailed discussion concerning the effect of wall movement on distribution of pressure is given in the next section under theoretical versus measured pressures for Test Wall "G."

In order to determine the lateral movement of the wall a point was set on the top. 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 reinforced concrete drilled shaft. The nominal distance from the fixed point to the top of the wall was 67 ft. 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 insure a constant 25-lb 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 plumb-bob from a frame which was rigidly attached to the top of the wall. With respect to the top of the wall the fixed points were located at 1-, 4-, 7-, 10-, 13-, and 14 1/2-ft heights on a vertical row. The vertical row of points was positioned laterally on the wall such 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 displacement 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. Fig. 14 represents the measured translational and rotational displacements at the end of one, five, six, thirteen, and twenty-eight days after the beginning of backfill operations. The level of backfill was at 6 ft (38% complete) at the end of the first day, 9 ft (56% complete) at the end of the fifth day, and 16 ft (100% complete) at the end of the sixth day. The data shown in Fig. 14 indicate that the major amount of tilting or rotation occurred after the backfill was more than approximately 60% complete.

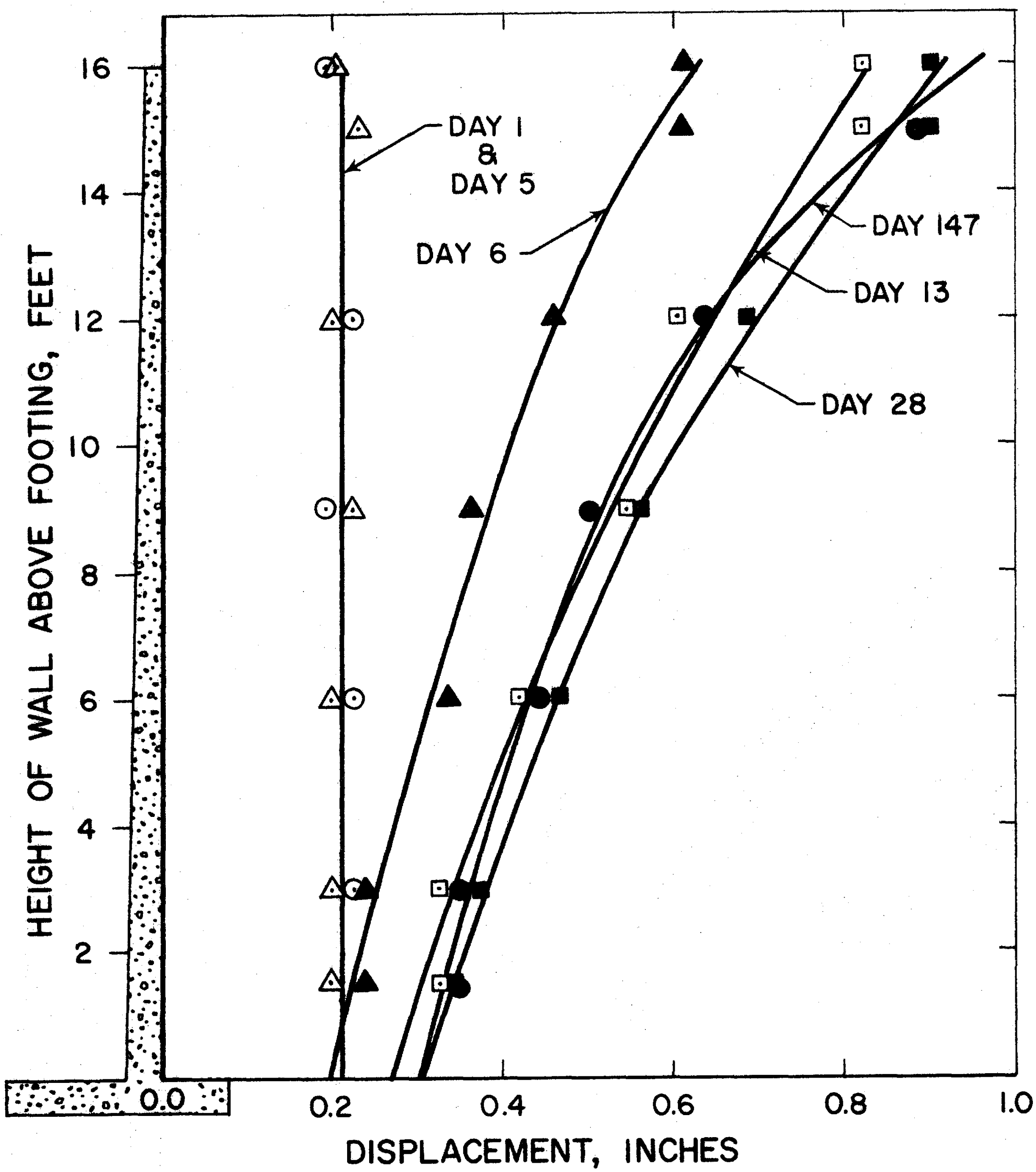

FIG. 14—DISPLACEMENT OF TEST WALL "G" DURING AND AFTER BACKFILL

THEORETICAL VERSUS MEASURED PRESSURES - TEST WALL "G"

Rankine and Coulomb Pressures

The primary objective of this research program is to develop a more economical retaining wall design. In order to accomplish this objective, it is necessary to determine whether or not 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 which has been derived from a theoretical analysis, as opposed to an equation resulting from empirical correlations. There are two earth pressure theories which have attained almost universal acceptance throughout the literature and which 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. In order 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 in TTI Research Report 169-1 (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°;

β = slope of backfill with respect to horizontal = 0°;

ϕ = angle of shearing resistance of soil = 32°;

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 (5) states that for smooth concrete δ is often 1/2 ϕ to 2/3 ϕ. 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 equal to 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 $\delta = 1/2\ \phi$, $K_a = 0.278$; for $\delta = 2/3\ \phi$ and $\delta = 0.88\ \phi$, $K_a = 0.275$. 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 are given in Table 8. The value of $\delta = 2/3\ \phi$ was used to compute the Coulomb value of K_a, the unit weight of the backfill was taken to be 120 pcf, and the depths correspond to the location of pressure cells.

TABLE 8. - 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

Comparison with Measured Pressures

The data presented in Fig. 15 represent the measured earth pressures at each depth on a given day. The earth pressure distributions have been plotted for six, thirteen, twenty-eight, fifty, and ninety-seven days following 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, note the change which occurs in the slope of the pressure versus depth curve at a depth of 7 ft. From the surface down to 7 ft the lateral pressure increases at an average rate of about 0.4 psi per ft. From 7 ft to 13 ft the average rate of pressure increase is approximately 1 psi per ft. A possible explanation for this increase in pressure gradient can be obtained from a consideration of the displacements which occurred in the upper and lower portions

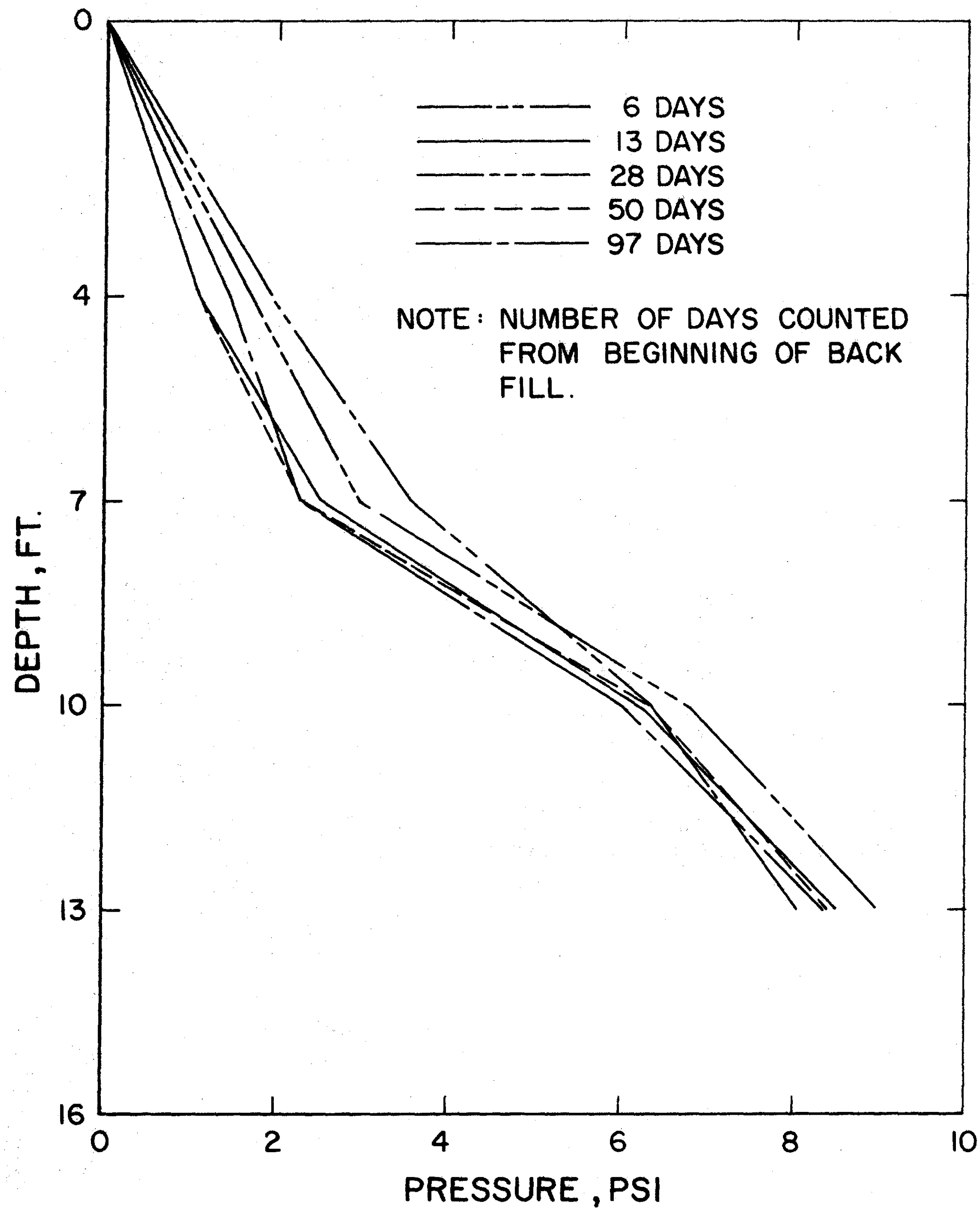

FIG. 15 - PRESSURE DISTRIBUTION CURVES, TEST WALL "G"

of the retaining wall. Referring to the retaining wall displacement curves shown in Fig. 14 it is apparent 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 Fig. 14 it is evident that some bending occurred in the upper 7 ft (approximately) of the wall. Stated another way, if two tangents are drawn to the curves in Fig. 14, one tangent being drawn to the lower 9 ft of the wall and the other being drawn tangent to the upper 7 ft of the wall, the upper tangent would have a greater inclination with respect to the vertical than would the lower tangent. Essentially, this would indicate that 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 which occurred near the base. In this context the at-rest pressure is that pressure which would be exerted on the wall after the backfill is placed provided that no wall movement occurs. This may, therefore, be one explanation for the change in pressure gradient which appears to occur at a depth of 7 ft below the surface.

Fig. 14 also indicates that the base of the retaining wall experienced approximately 0.2 in. or 2/3 of the total lateral displacement before the backfill had reached approximately the 2-ft level 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. A trench on the front side of the wall had been standing full of water two to three weeks previously. It is believed that the heavily loaded earth moving equipment compacted the soil on the back side of the footing and pushed the wall outward. Taylor (6) also states that "If the top of the wall moves outward an amount roughly equal to 1/2 of 1% 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." In this case, 1/2 of 1% of the wall height equals 0.96 in. The data of Fig. 14 indicate a movement of approximately 0.7 in. 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 has been attained although the wall movement may not have been sufficient to achieve the totally active case.

Fig. 16 is a plot of the minimum and maximum pressures recorded at each cell location from April 18 through September 6, 1972. Also shown on Fig. 16 is the average of all earth pressure measurements made throughout the period. Note that April 18, 1972 is the date

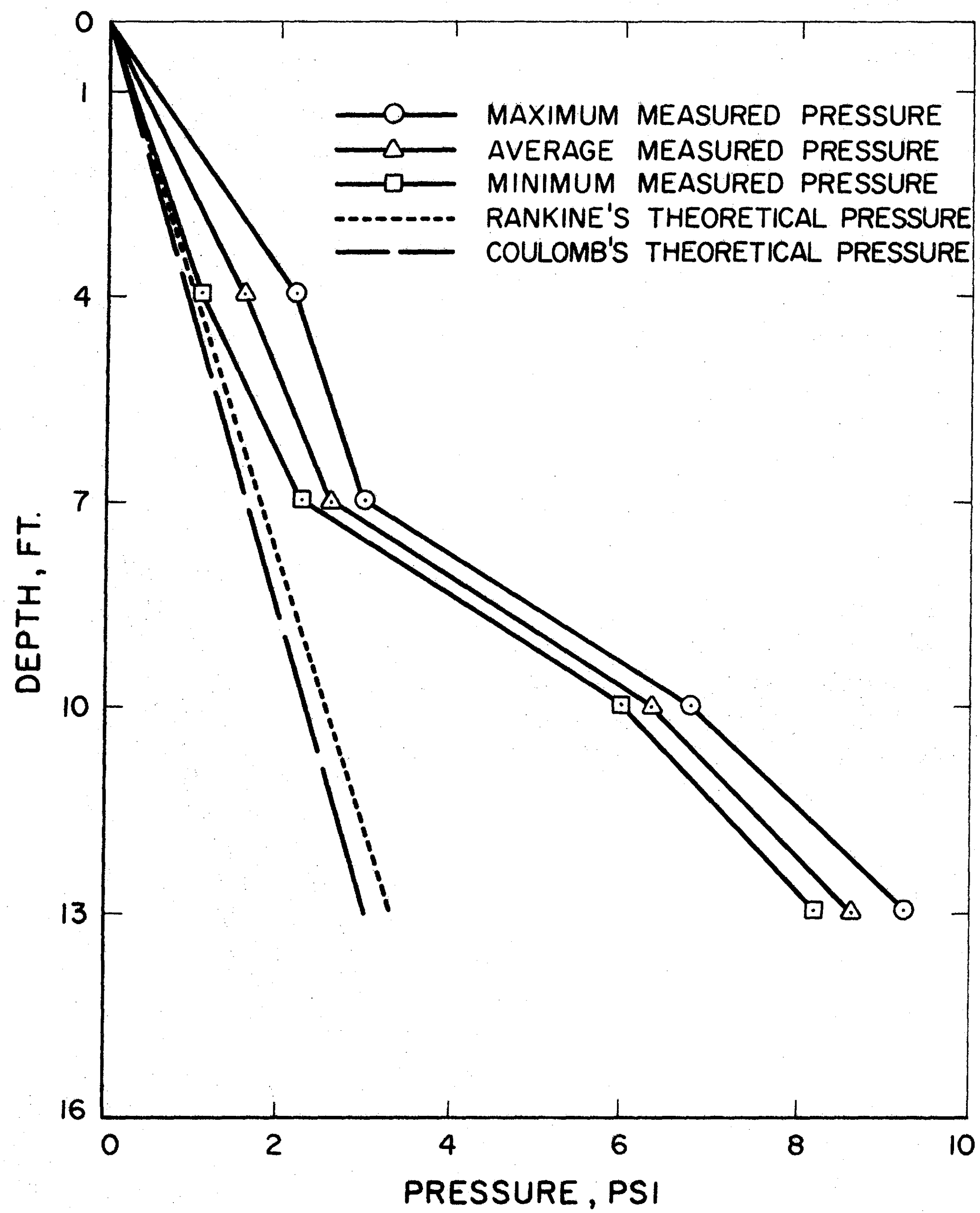

FIG. 16 - COMPARISON OF MEASURED PRESSURES WITH THEORETICAL PRESSURES, TEST WALL "G"

on which backfilling was completed (See Table 7). The dotted line in Fig. 16 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. Assuming the at-rest coefficient to equal 0.5, the computed pressure at the 13 ft level would be 5.4 psi or approximately 35% less than the minimum measured pressure at that depth. Taylor's at-rest coefficient is predicated on the assumption that "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_o, Terzaghi and Peck (7) state the following: "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_o 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_o = 0.8 yields a computed pressure equal to 8.7 psi at a depth of 13 ft. This value is nearly identical to the average maximum pressure observed at that depth. Hence, the earth pressures which are being recorded at this time 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 induced near 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 such that near at-rest conditions still exist, the measured pressures appear to be reasonable based on Terzaghi and Peck's $K_o = 0.8$ for compacted backfills.

Two other factors may be involved which could possibly account for the measured pressures being larger than the theoretical pressures. One factor involves pressure cell calibration. The question of whether or not the pressure cell responds differently to pressure applied by or through the soil as compared to a pneumatically or hydraulically applied pressure is still unresolved. This problem has received considerable attention; tests will be performed during 1972-1973 which hopefully will provide the basis for an accurate solution. The other factor involves the question of hydrostatic pressure in the backfill due to the presence of standing water. The probability of this condition occurring is believed to be small because of the presence of weep holes. During the third year of this study a test hole will be drilled down to the top of the footing in an attempt to evaluate the moisture conditions in the vicinity of the pressure cells.

SUMMARY AND RECOMMENDATIONS

Summary

The broad objective of this five year study is to verify or modify the earth pressure criteria presently used by the Texas Highway Department in the design of retaining walls and thru the use of field measurements to develop improved design procedures for determination of lateral earth pressures. Achievement of this broad objective will not be possible until the fourth or fifth year of this program. The specific objectives for the second year of this study as presented in this report have been achieved. Results of the work done during the second year have been presented in detail in this report and are summarized as follows:

1. Earth pressure measurements on Test Wall "D" which was instrumented near the end of the first year of the study were continued. In general, the selection of the Terra Tec and Geonor cells as being the most promising for long term use was verified. Both Terra Tec cells on Test Wall "D" became inoperative because of moisture collection in the air pressure lines, but it was possible to back-flush these cells and make them operative again. When the upper row of cells on Test Wall "D" was uncovered to check zero gage

readings, the Terra Tec cell gave the best performance because it had the smallest change in zero gage reading over a long period of time.

2. Procedures used in calibrating the four Terra Tec and two Geonor cells used in Test Wall "G" were improved. Temperature effects were taken care of thru 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. Results of these tests indicated that there was no effect on the pressure cell response due to the grouting of the cell in concrete. The effect of change in zero gage reading with time was investigated both in the laboratory and in the field before backfilling. Sometime during the third year of this study the upper Terra Tec and upper Geonor cells on Test Wall "G" will be uncovered and the zero gage readings will be checked.

3. Improved procedures were developed and used to measure the lateral movements of Test Wall "G." Measurements of wall movement were made each time that pressure measurements were made starting at the time of the backfilling operation. The accuracy of the measurements of wall movements for Test Wall "G" as compared with measurements made for Test Wall "D" has been greatly improved.

Wall movement measurements on Test Wall "G" will be continued during the third year of this program.

4. Samples of the backfill material used with Test Wall "G" were taken and tested in order to determine the physical and engineering properties of the soil. These properties were used to make theoretical determinations of lateral earth pressures on Test Wall "G."

5. Computed lateral earth pressures based on Rankine and Coulomb theories were compared with measured lateral earth pressures. It was found that measured pressures agreed with the theoretical pressures to a depth of about 7 ft on Test Wall "G." 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 depth indicated the state of the soil in the backfill as being 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. Based on the wall movements, the measured pressures seem reasonable. All earth pressure cells used in Test Wall "G" were operating effectively 147 days after the backfilling operation began.

Several major problem areas were identified at the end of the first year of this study. The problem of making accurate measurements of wall movements has been overcome since accurate measurements are being made on Test Wall "G." This is fortunate because the small movements at the base of the wall indicate the at-rest condition which in turn could explain why the measured pressures are higher than the theory indicates. Other possible reasons for higher measured pressures could be hydrostatic pressure in the backfill due to standing water or improper calibration of the pressure cells. Continued investigation in these areas will be made during the third year of this study.

Recommendations

The following recommendations are made concerning continued research in this program:

1. Continue making both pressure and movement measurements on Test Wall "G." If the movements on Test Wall "G" ever indicate the totally active case, then the measured pressures should drop and be in closer agreement with the theoretical pressures.
2. Investigate the possibility of hydrostatic water pressures existing behind Test Wall "G." This will be accomplished by digging test holes behind the wall and checking for standing water.

3. Continue to develop improved calibration procedures for the pressure cells. Particular attention should be given to the following areas:

   a. A method of calibrating the earth pressure cells in a manner which simulates field loading conditions should be developed. The real problem here is to determine if the pneumatic calibration is valid.

   b. The amount of drift or change in zero gage reading with time must be accurately determined so that the overall accuracy of the pressure cells can be established.

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APPENDIX II. - NOTATION

The following symbols are used in this report:

f = frequency of vibration of Geonor cell with pressure applied, in Hz;

f_o = frequency of vibration of Geonor cell with zero pressure applied, in Hz;

Δf^2 = squared-frequency difference, $f^2 - f_o^2$;

K_a = coefficient of active lateral earth pressure;

K_o = coefficient of at-rest lateral earth pressure;

α = angle of back of retaining wall with respect to horizontal;

β = slope of backfill with respect to horizontal;

δ = angle of wall friction;

ϕ = angle of shearing resistance of soil.