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16. Abstract

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Reasonably good correlation between the forces calculated from the pressure cell measurements and those measured by the force transducers tend to verify the adequacy of the pneumatic pressure cell calibration procedures. Measured pressures in the upper elevations of the wall correlate fairly well with theoretical pressures computed according to Coulomb and Rankine. However, measured pressures in the lower elevations are considerably higher than the theoretical pressures.

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FIELD MEASUREMENTS OF LATERAL EARTH PRESSURES ON A PRE-CAST PANEL RETAINING WALL

by

David M. Prescott
Research Assistant

Harry M. Coyle
Research Engineer

Richard E. Bartoskewitz
Engineering Research Associate

and

Lionel J. Milberger
Research Associate

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Determination of Lateral Earth Pressure for
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ABSTRACT

Terra Tec pneumatic earth pressure cells are used to measure lateral earth pressures acting on a pre-cast panel retaining wall. Force transducers are used between the panel and the supporting structural members to measure the total force exerted on the panel by the backfill material. Accurate measurements of panel movements are made during and after backfilling. Data are presented for measured pressures, forces, and movements covering a period of 65 days. Physical and engineering properties of the backfill material are determined.

Reasonably good correlation between the forces calculated from the pressure cell measurements and those measured by the force transducers tend to verify the adequacy of the pneumatic pressure cell calibration procedures. Measured pressures in the upper elevations of the wall correlate fairly well with theoretical pressures computed according to Coulomb and Rankine. However, measured pressures in the lower elevations are considerably higher than the theoretical pressures.

KEY WORDS: Earth Pressure Cells, Pre-cast Panel Retaining Wall, Wall Movement Measurements, Pressure Cell Calibration.

SUMMARY

The information presented in this report was developed during the third 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 verify or modify the earth pressure coefficients used to predict lateral earth pressures acting on retaining walls.

The limited objective of the third year of this study was to measure the earth pressure acting on a pre-cast panel retaining wall. Nine Terra Tec pressure cells were used to measure the earth pressure distribution on the panel. Four force transducers were used to measure the total force exerted on the panel. Measurements of panel movement were made during and after the backfilling operation. Data are presented in this report for measured pressures, forces, and movements covering a period of 65 days.

The total force calculated from the pressure cell measurements was compared with the total force measured by the force transducers. Reasonably good correlation between these forces indicates that the pneumatic pressure cell calibration procedures used are adequate. The measured pressures on the upper part of the panel agreed fairly well with the theoretical pressures determined by Rankine and Coulomb theory. The measured pressures on the lower part of the panel were considerably higher than the theoretical pressures.

IMPLEMENTATION STATEMENT

Research Report 169-3 is a technical progress report which presents the results of the work accomplished during the third year of a five-year study on "Determination of Lateral Earth Pressure for Use in Retaining Wall Design". Nine Terra Tec pressure cells and four force transducers were installed in a pre-cast panel retaining wall. Measurements of lateral earth pressure, transducer forces, and wall movements were made and will be continued during the fourth year of this study. Pneumatic calibration of the earth pressure cells was shown to be adequate. Implementation of the results obtained thus far are not possible because of the need to investigate the long-term performance of the panel.

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INTRODUCTION

Present Status of the Question. - An engineer designs a retaining wall based on the pressure the soil is expected to exert on the structure. While there are many ways to predict this pressure (4)* the theories presented by Coulomb or Rankine are usually used to determine the distribution of pressures on a retaining wall (1). According to these theories the lateral earth pressure is equal to a coefficient of lateral earth pressure times the unit weight of the backfill material. This coefficient of lateral earth pressure is a function of wall movement, the engineering properties of the backfill material, and geometry of the wall and backfill material.

A literature survey has revealed that little research work has been done during the past 25 years in connection with determination of lateral earth pressures through field measurements. Terzaghi (8) obtained some experimental data concerning the relation between the lateral yield of the wall, the location of the center of pressure, and the hydrostatic pressure ratio as a

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

result of some large scale earth pressure tests at Massachusetts Institute of Technology in 1929.

An extensive Soil Mechanics fact finding survey which included an investigation on soil pressure cells was conducted by the Waterways Experiment Station, Corps of Engineers, U.S. Army, during the 1940's (10). The consultant, D. W. Taylor, concluded that the amount of useful data that had been obtained by earth pressure measurements was limited--it could not be classified as sufficiently dependable for use in checking existing theories or in developing improved methods (7).

In 1970 a five-year study was begun at Texas A&M University to measure lateral earth pressures in the field on full-scale retaining walls. The first year of the study was devoted primarily to choosing pressure cells which would provide both accurate and long term measurements of the earth pressures (2). Nine types of commerically available total earth pressure cells were considered. The cells were rated for accuracy, range of pressure reading, size of pressure contact area, availability, cost, durability, and ease of installation and opeartion. These ratings were made on the basis of technical specifications and other performance data obtained from manufacturer's literature and reports by other investigators.

The four cells that seemed most likely to give the best results were used to instrument a full-scale cantilever type retaining wall. Pressure measurements and wall movements were recorded. The cells performances were observed to determine which ones would give the best results in the field. The results of the first year's study indicated that the Terra Tec pneumatic cell and the Geonor vibrating wire cell would perform adequately in order to accomplish the objectives of this study (2).

Another full-scale cantilever type retaining wall was instrumented with these two cells in the second year of the study (3). Accurate measurements of the wall movements were made and correlated with the pressure measurements of the cells. Initial and long term measurements were taken. The measured pressures agreed with the theoretical values in the upper elevations of the wall. In the lower elevations the measured pressures were considerably higher than the theoretical values.

During the third year of this study a new type full-scale retaining wall was built. The wall was constructed of precast panels placed between pilasters supported on drilled shafts.

Objectives of this Study. - The broad objective of this research study is to verify or modify the lateral earth pressure coefficients predicted by the Rankine and Coulomb theories through the use of field measurements on full-scale retaining walls. The specific objectives of the study for the phase involving a pre-cast panel retaining wall are as follows:

1. To measure lateral earth pressures on a pre-cast panel retaining wall.

2. To measure the force transmitted from the pre-cast panel to the structural members (pilasters) supporting the panel.

3. To measure the lateral displacement of the retaining wall and determine the effect of wall movement on measured pressures.

4. To verify pressure cell calibration.

5. To determine the physical and engineering properties of the backfill material for use in computing lateral earth pressures according to the Coulomb and Rankine theories.

6. To compare measured pressures with those computed using the Coulomb and Rankine theories.

TEST WALL

Test Site. - The test site for this project is in northwest Houston, Texas. The freeway portion of U.S. Highway 290 is being extended in that area and the test site is located at the intersection of the freeway extension and Dacoma Street. Four retaining walls were built at this intersection. The instrumented panel is part of the southwest wall.

Test Wall Description. - The design of the retaining walls at this location is different from the walls previously instrumented. Drilled shafts were placed at regular intervals. Footings were constructed on top of the drilled shafts and T-shaped pilasters were formed on the footings. Pre-cast panels were placed between the pilasters. The panels rested on neoprene rubber 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 3 ft in diameter, 20 ft deep, and were spaced at 12 ft intervals. The wall was 10 ft high and the footings were 3 ft 2 in. square and 16 in. high. The neoprene rubber pads were 5 x 10 x 3/8 in. Figs. 1 and 2 show the retaining wall and its construction elements.

There are several items shown in Figs. 1 and 2 which should be noted. Fill was placed in front of all walls to a height of

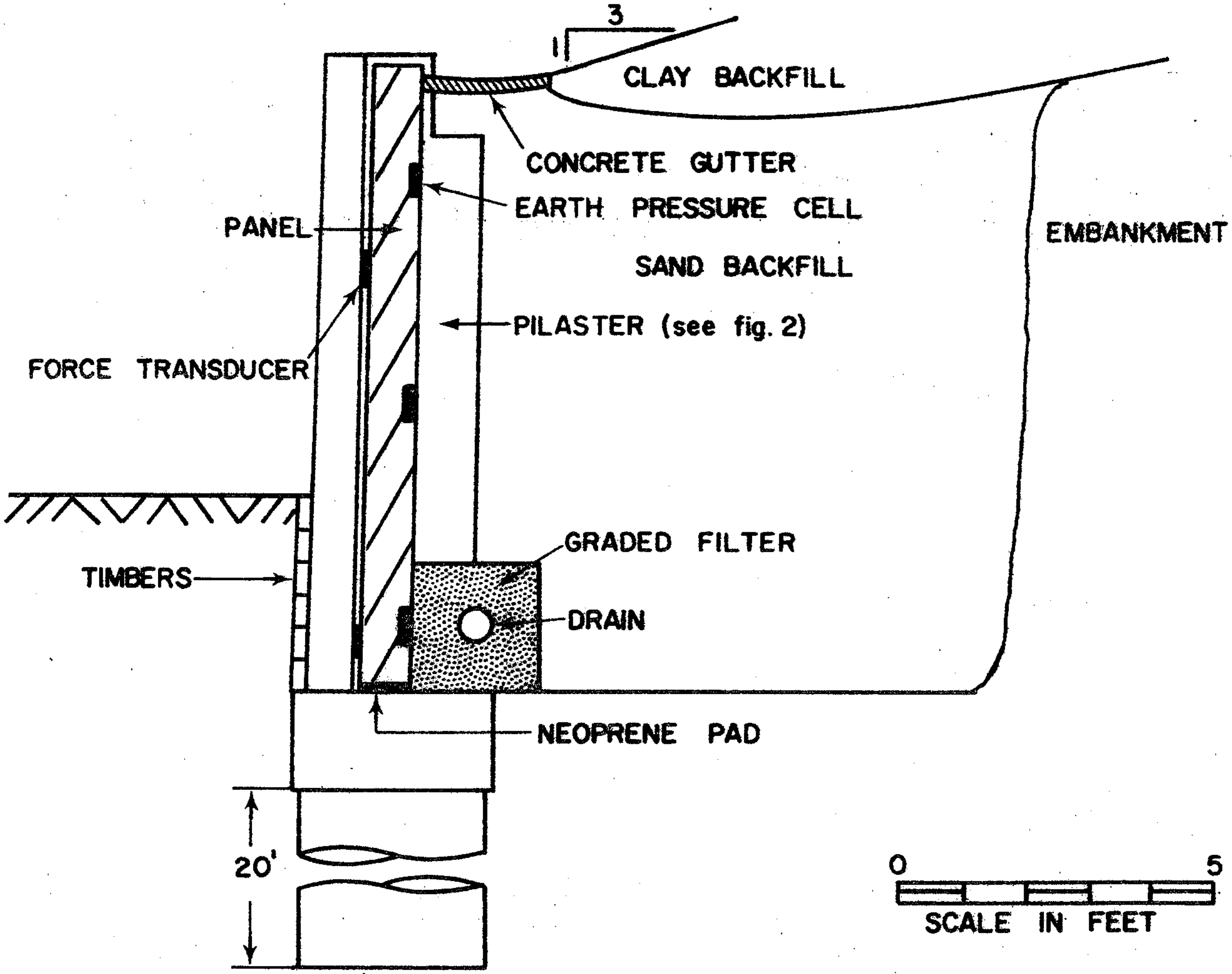

FIG. 1— CROSS SECTION OF TEST WALL

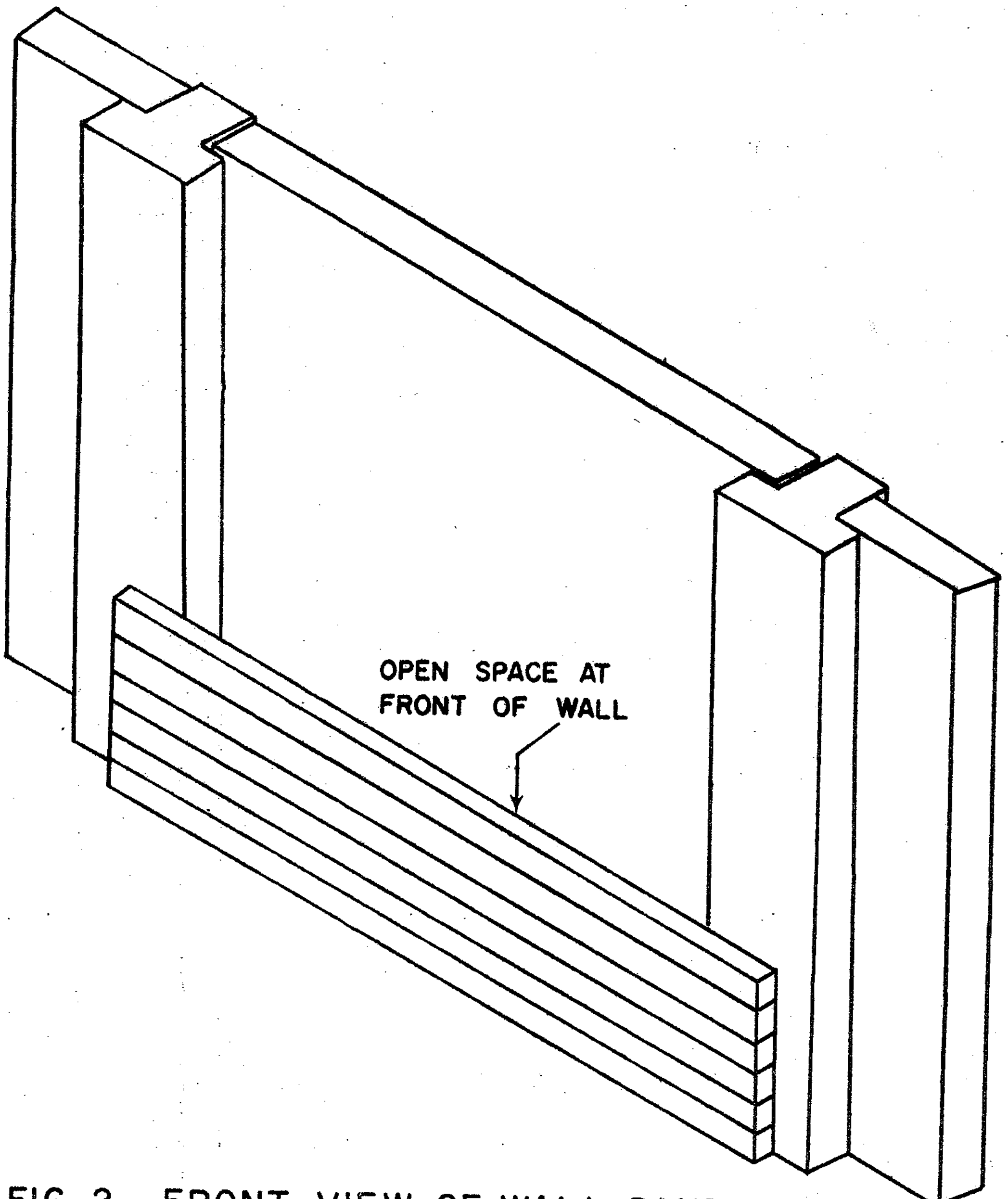

FIG. 2 — FRONT VIEW OF WALL PANEL

3 ft except for the test panel. An open space was provided by placing a timber barrier in front of the pilasters. This prevented the problem of passive pressures in front of the panel. All panels at the site were grouted to their pilasters except the test panel. A concrete gutter was placed immediately behind the top of the wall. The clay backfill has a 3 to 1 slope and varies in thickness from 6-in. near the wall to 30 in. near the back of the embankment. The drain for the backfill is directly in front of the lower row of pressure cells.

Instrumentation. - The unique design of the retaining wall made it possible to measure the lateral earth pressure two separate ways. First the backfill side of the panel was instrumented with nine Terra Tec pneumatic earth pressure cells. The cells were arranged in the grid pattern shown in Figs. 3 and 4. Both the vertical and horizontal distributions of the lateral earth pressures could be determined.

Secondly, two force transducers were installed on each pilaster to measure the force exerted on them by the panel. The locations of the transducers are also shown in Figs. 3 and 4. The force which is measured by the transducers is the force transmitted to the pilaster by the pre-cast panel. This force is caused by the lateral earth pressure of the soil acting on the back of the panel. The transducers are not in contact with soil and will not be affected by nonuniformity of the backfill

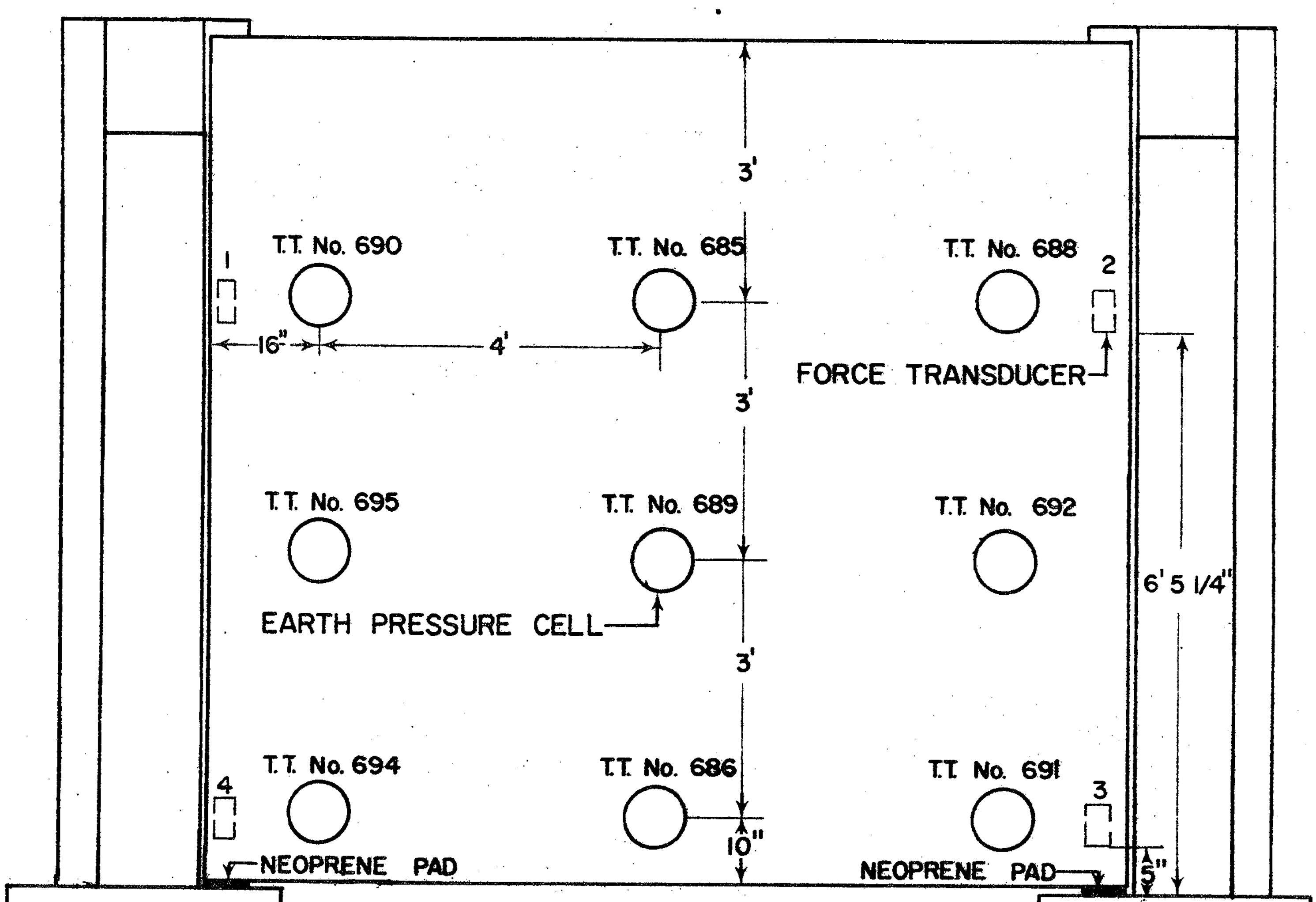

FIG. 3—LOCATION OF EARTH PRESSURE CELLS AND FORCE TRANSDUCERS

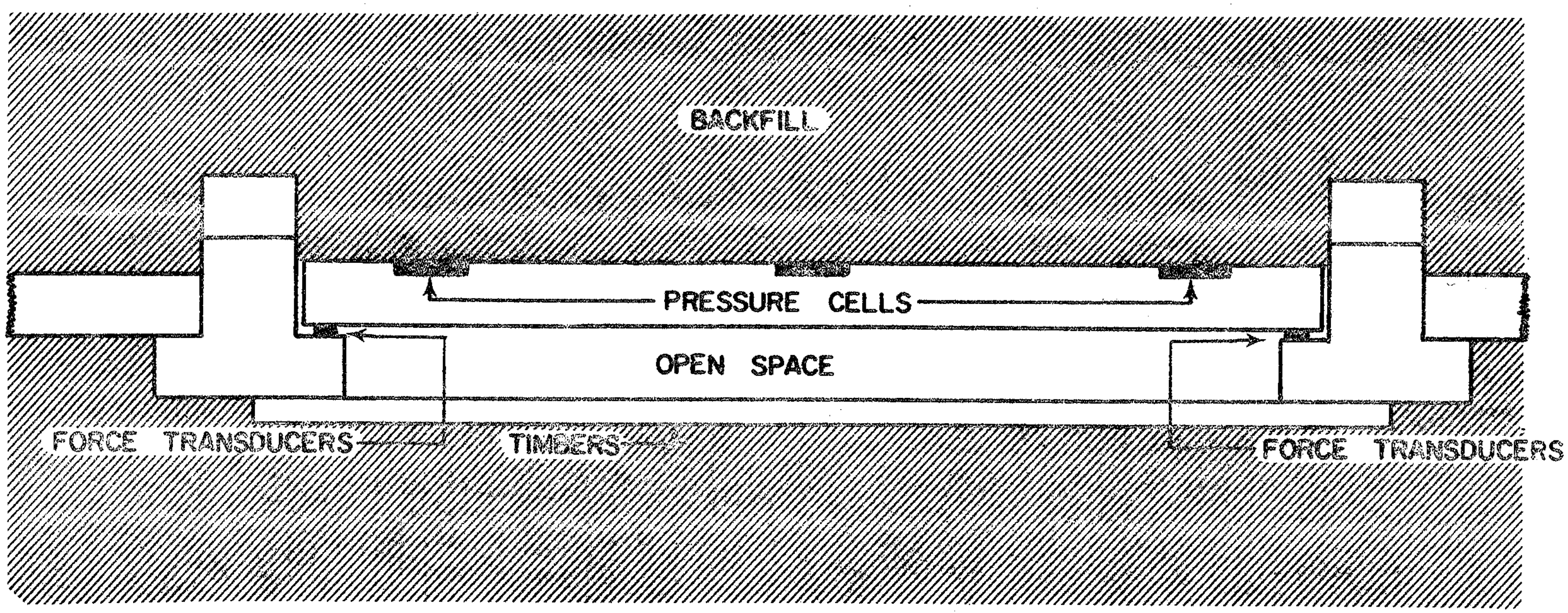

FIG. 4—TOP VIEW OF WALL

material and arching in the soil.

Installation of Pressure Cells and Transducers. - The pressure cells and force transducers were installed in much the same manner. Wooden blocks of the appropriate size were placed in the form while the panel and pilasters were being constructed. After the concrete hardened the wooden blocks were removed. The force transducers were installed before the panel was placed. The pressure cells were not installed until after the panel had been placed.

The cells and transducers were grouted into place and secured with a metal strap bolted across the face of the instruments. The grout used was a special type manufactured by the Dewey Supply Company known as "Patch All Special". Uniform contact was attained on the seating surfaces of the instruments. Thermocouples were installed in the epoxy grout, before it hardened, 1/4 to 1/2 in. from each cell and transducer. The metal straps were removed after the grout had hardened. The holes drilled for bolting the metal straps into place were patched with grout. Wire leads from the pressure cells, force transducers, and thermocouples were terminated at a permanent, waterproof, metal box on top of the wall. Exposed wires were covered with soft, raw, tread rubber to protect them during the backfill operations.

Backfilling Procedure. - The backfilling was accomplished in several stages. First, a 6 inch diameter perforated drain pipe was placed in the center of a 2 ft high by 2 ft wide layer of river sand. The drain runs the entire length of the wall. Then the remainder of the backfill material, consisting of clean sand, was placed in 6 in. lifts. The sand was compacted with small, hand operated vibratory rollers. Care was taken to compact the sand directly in front of the wall without damaging the cells or their wire leads. The backfilling operation was begun on 4 April and completed on 13 April 1973.

Properties of the Backfill Material. - The backfill material is classified as SP according to the Unified Soil Classification System. Its grain size distribution is given in Table 1.

TABLE 1. - SIEVE ANALYSIS OF BACKFILL MATERIAL

Sieve No.	Percent Passing
4	100.00
10	99.74
20	98.95
40	96.85
80	26.88
200	8.16

The material has a coefficient of uniformity of 3.50 and a coefficient of curvature of 1.96. It has a compacted average dry unit weight of 95 pcf as determined by the Texas Highway Department using the balloon volumeter test. The backfill material has an in place moisture content of approximately 10% and a total unit weight of 105 pcf. Direct shear tests have been performed on the material and the effective angle of internal friction is 32°.

Placement of Clay Backfill. - The clay backfill was placed between day 38 and day 58 and is to be used as a top soil for future construction. The clay has a compacted average dry unit weight of 107 pcf and an average natural moisture content of 15%. Its average total unit weight is 122 pcf.

DATA COLLECTION

Earth Pressure Cell Measurements. - Each cell was calibrated in the laboratory before installation in the panel. During this pneumatic calibration cell hysteresis tendencies, linearity, and calibration factors were established. Based on this calibration two of the cells were replaced by the manufacturer because of poor linearity and excessive hysteresis. The replacement cells exhibited negligible deviations in linearity and hysteresis. Fig. 5 shows an example pneumatic calibration curve.

The zero stress reading or zero offset for each cell varies with change in temperature. After the cell was installed in the panel the zero stress reading versus temperature relationship was established. This was done by recording zero stress readings over as wide a temperature range as possible so as to include the actual operating range. Fig. 6 shows this relationship for cell 691.

To determine the pressure measured by a particular cell the field reading and temperature are recorded. The zero offset for that temperature is subtracted from the field reading. This difference multiplied by the cell's calibration factor (one) gives the measured pressure indicated by the cell. Table 2 gives the pressures measured by each cell through 65 days. These pressures are plotted in Figs. 7, 8 and 9 for this time period.

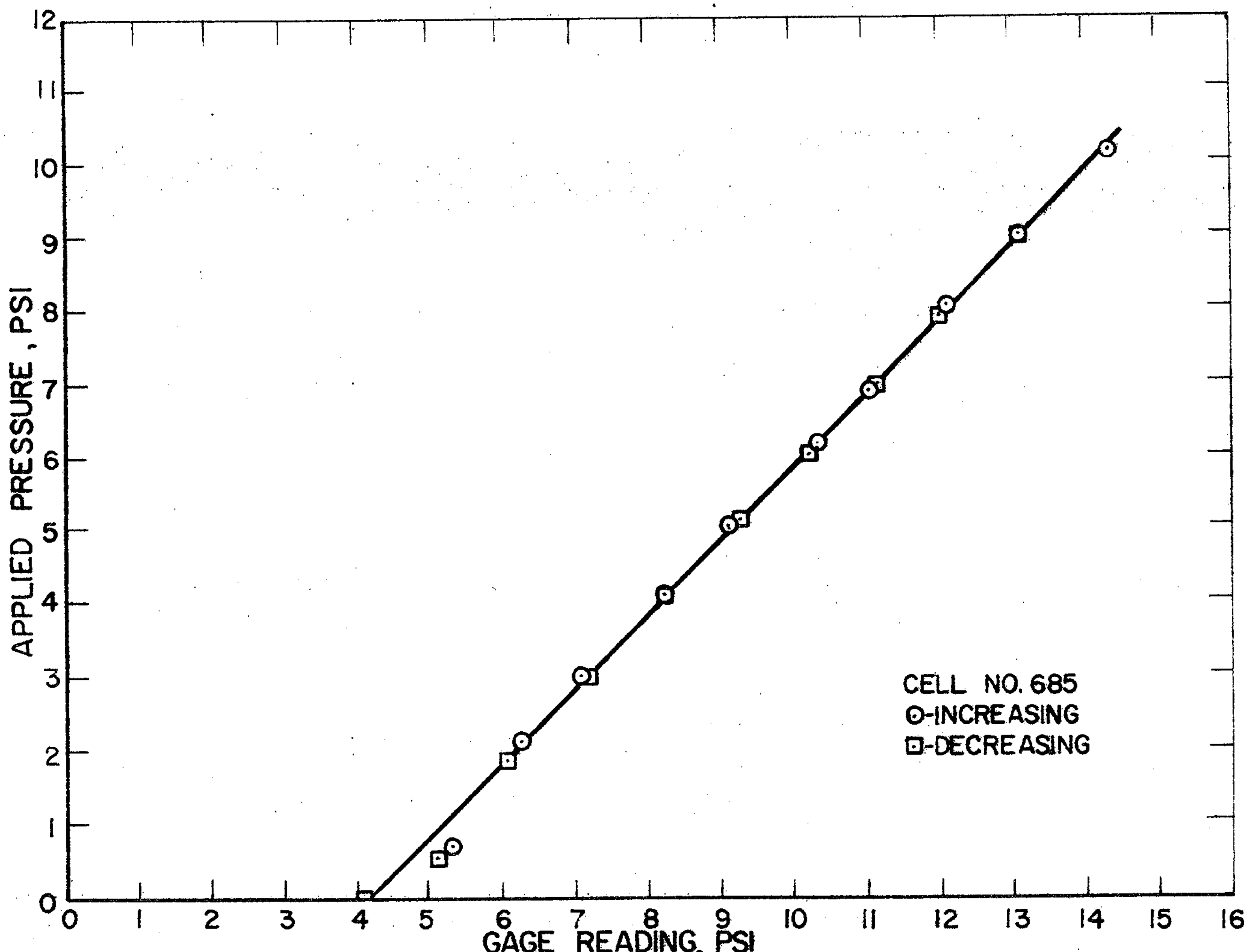

FIG. 5 — TYPICAL CALIBRATION CURVE FOR TERRA TEC CELL

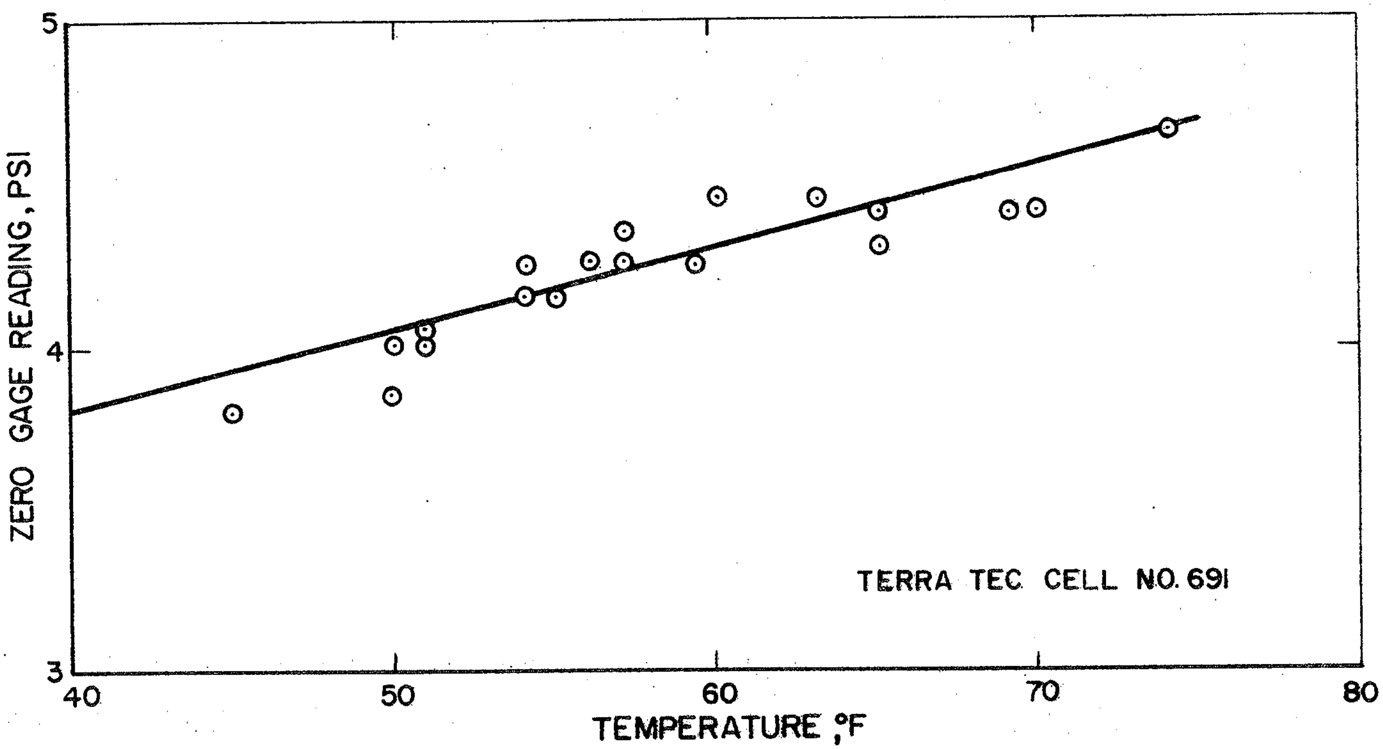

FIG. 6 — TYPICAL FIELD RELATIONSHIP — ZERO STRESS READING VERSUS TEMPERATURE FOR PRESSURE CELL

TABLE 2. - LATERAL EARTH PRESSURES
MEASURED BY PRESSURE CELLS (PSI)

DAY	UPPER ROW			MIDDLE ROW			LOWER ROW		
	690	685	688	695	689	692	694	686	691
1	0	0	0	0	0	0	0.95	1.65	0.80
2	0	0	0	0	0	0	1.10	1.30	0.80
3	0	0	0	0	0	0	0.70	1.50	0.35
9	0	0	0	0.40	0.25	0.25	1.75	1.60	1.55
10	0.95	0.55	0.40	1.30	0.70	0.75	2.65	0.95	3.55
16	0.35	2.65	0.20	0.20	0.85	0.25	5.35	1.80	6.15
21	0.75	2.70	0.45	0.15	0.25	0.15	5.85	1.55	6.75
24	0.30	1.95	0.20	0.30	0.75	0.15	5.55	2.25	5.05
29	0.45	1.75	0.25	0.25	0.30	0.25	6.25	2.15	5.70
38	0.60	3.25	0.70	0.55	0.65	0.45	9.25	2.60	7.50
58	0.50	2.75	0.30	0.85	1.10	0.45	10.05	3.15	5.85
65	0.30	1.65	0.25	0.75	0.80	0.25	10.25	3.25	5.80

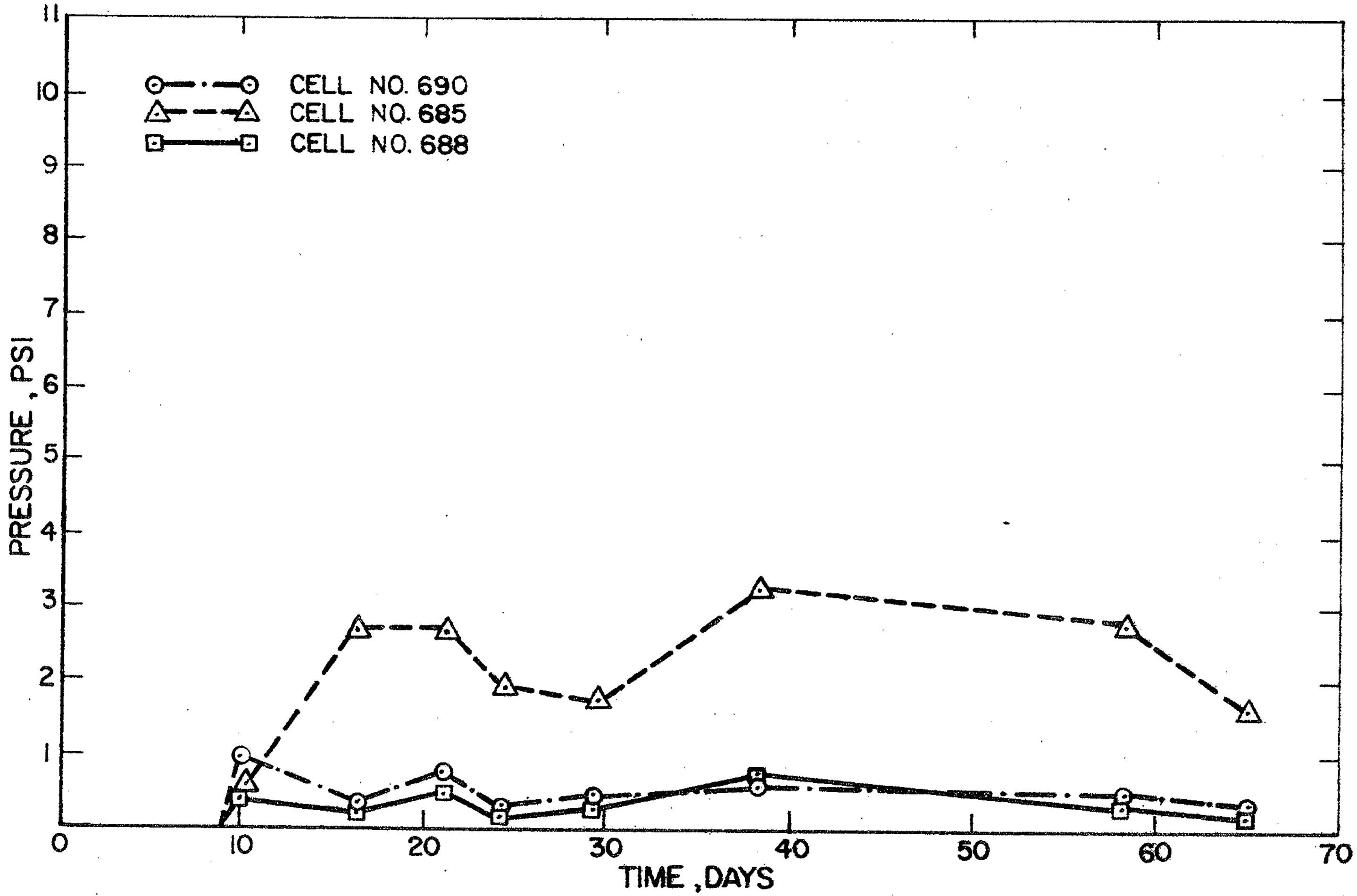

FIG. 7—MEASURED PRESSURE VERSUS TIME, UPPER ROW OF CELLS

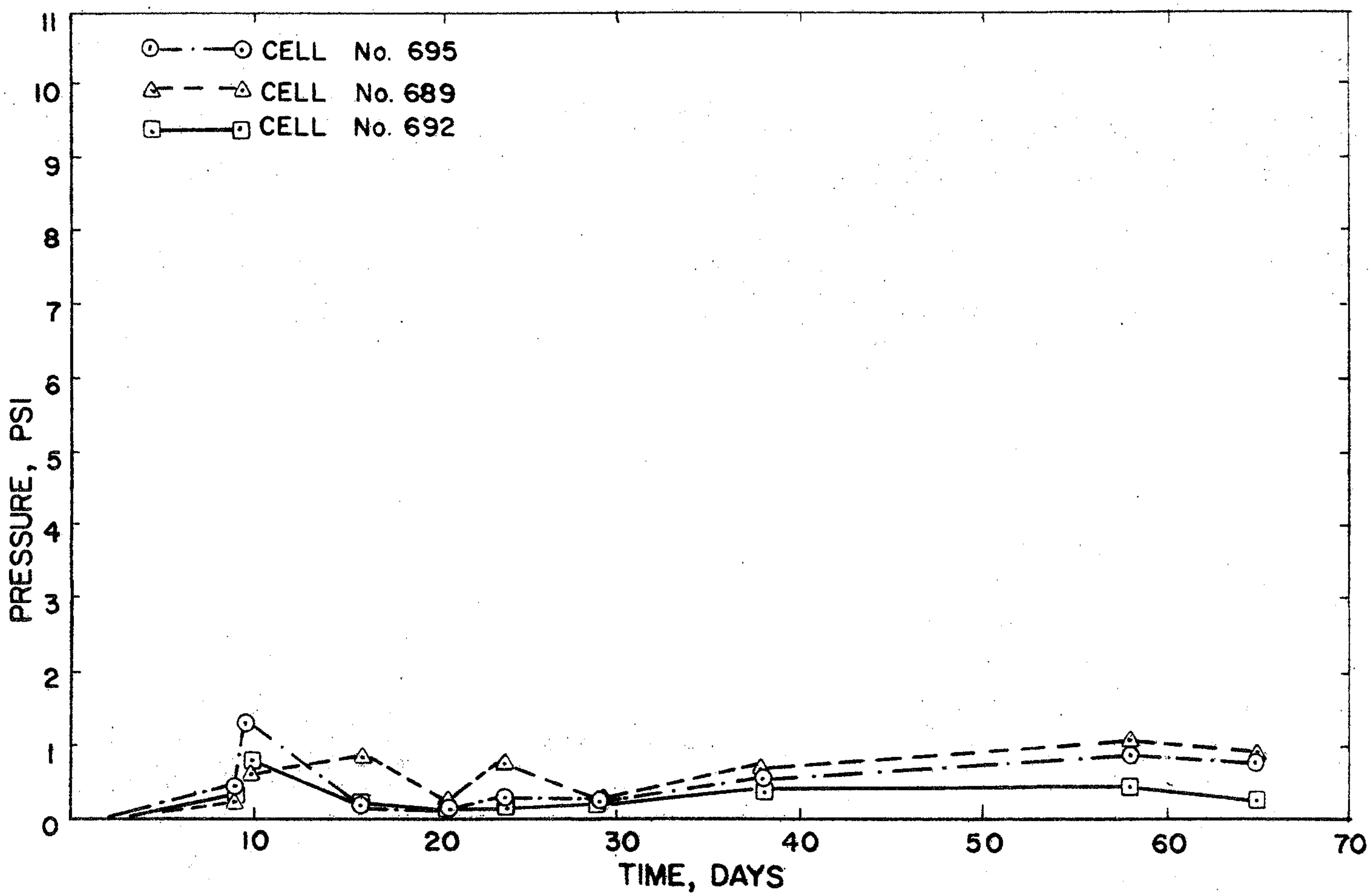

FIG. 8—MEASURED PRESSURE VERSUS TIME, MIDDLE ROW OF CELLS

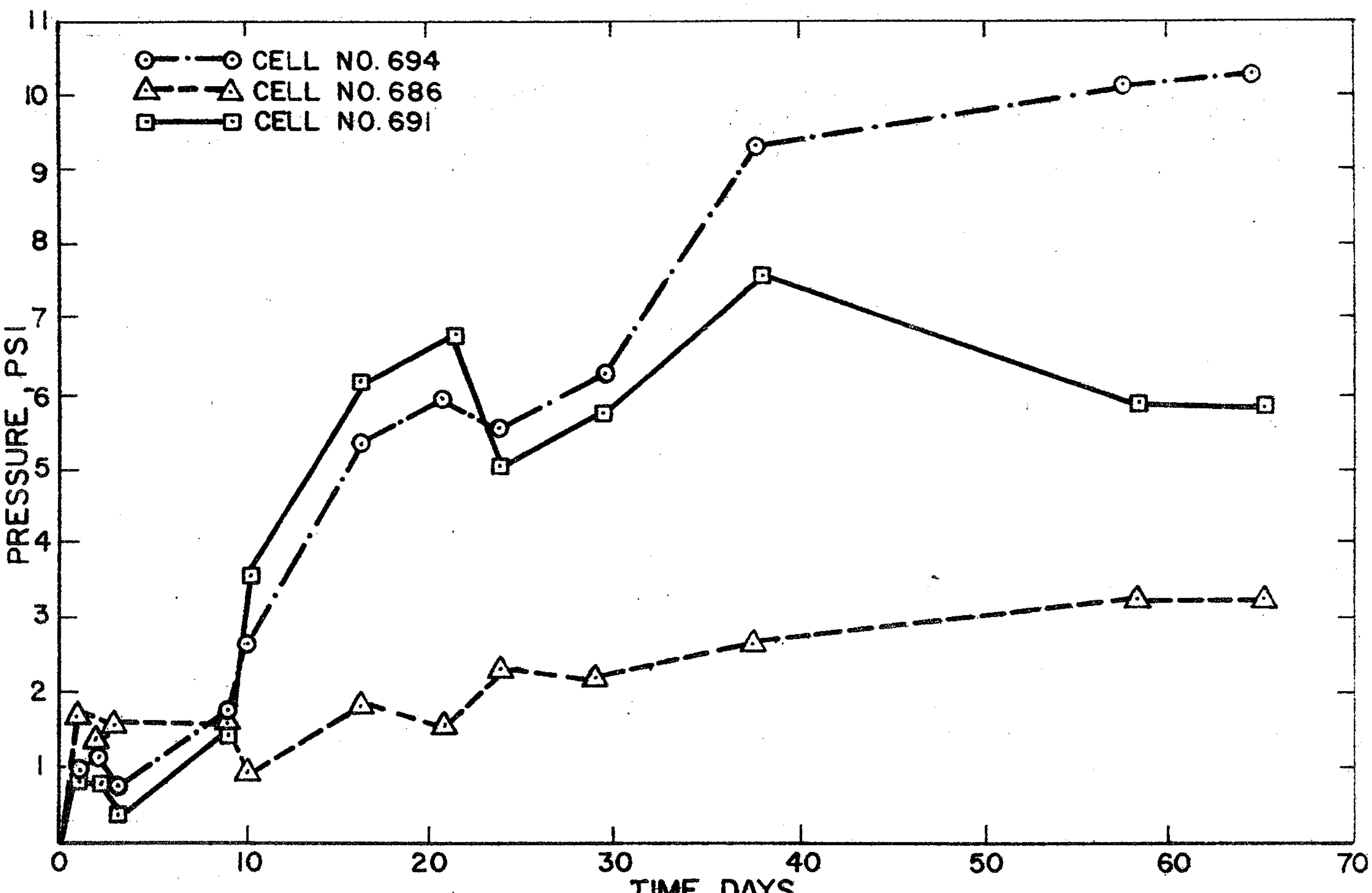

FIG. 9—MEASURED PRESSURE VERSUS TIME, LOWER ROW OF CELLS

There are several sources of error in the pressure cell measurements. These include non-linearity, hysteresis, read-out resolution, and zero stress reading stability with temperature change. As stated previously, during the pneumatic calibration it was observed that the cells installed in the panel had negligible errors resulting from hysteresis and non-linearity. The read-out unit has a resolution of 0.05 psi. The calibration factor seems to be independent of temperature change (3).

The zero stress reading stability with temperature change is ± 0.4 psi. This value is the average of the maximum deviations from the zero gage reading versus temperature curve for each cell. This maximum deviation for each cell is given in Table 3.

TABLE 3. - MAXIMUM DEVIATION FROM ZERO GAGE READING AND TEMPERATURE RELATIONSHIP

Cell No.	Max. Deviation (psi)	Cell No.	Max. Deviation (psi)
685	0.49	691	0.20
686	0.16	692	0.37
688	0.53	694	0.22
689	0.34	695	0.47
690	0.87	Average	0.40

All other errors are negligible by comparison. Therefore, the average error associated with the pressure cell measurements is ± 0.4 psi for each cell.

Force Transducer Measurements. - Calibration of the force transducers revealed negligible errors due to non-linearity, hysteresis, and read-out resolution. A typical calibration curve is shown in Fig. 10. The zero force reading versus temperature relationship was established in a manner similar to that used for the earth pressure cells. This relationship for force transducer No. 4 is shown in Fig. 11. Deviations from this relationship had negligible effects on the measured forces.

The force indicated by a particular transducer is found by recording the field reading and the temperature. The zero force reading corresponding to that temperature is subtracted from the field reading. This difference is then multiplied by the transducer's calibration factor to arrive at the actual force indicated by the transducer. Table 4 gives the forces measured by each transducer through 65 days. These forces are plotted versus time in Fig. 12.

Panel Movement Measurements. - It was necessary to know both the lateral translation and tilting or rotation of the panel. Lateral translations of the panel were measured from a horizontal reference point which was established in front of the wall with an engineers tape. This point was referenced to several permanent locations so it could be reestablished in the event of disturbance. The tape was attached to a small hook rigidly fixed to the front of the panel and readings were taken on the reference point. The reference point and the hook are shown in Fig. 13.

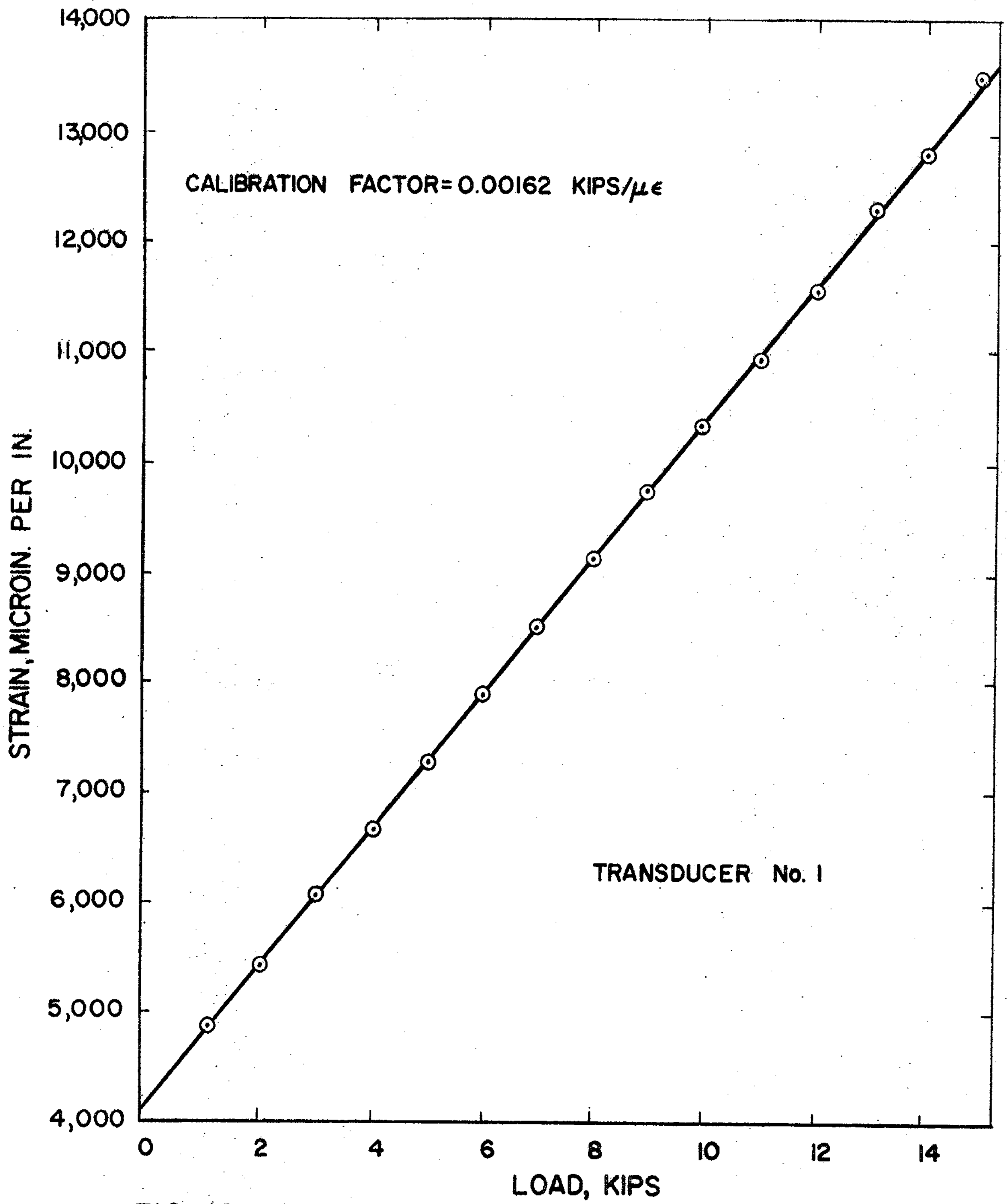

FIG. 10 – TYPICAL CALIBRATION CURVE FOR A FORCE TRANSDUCER

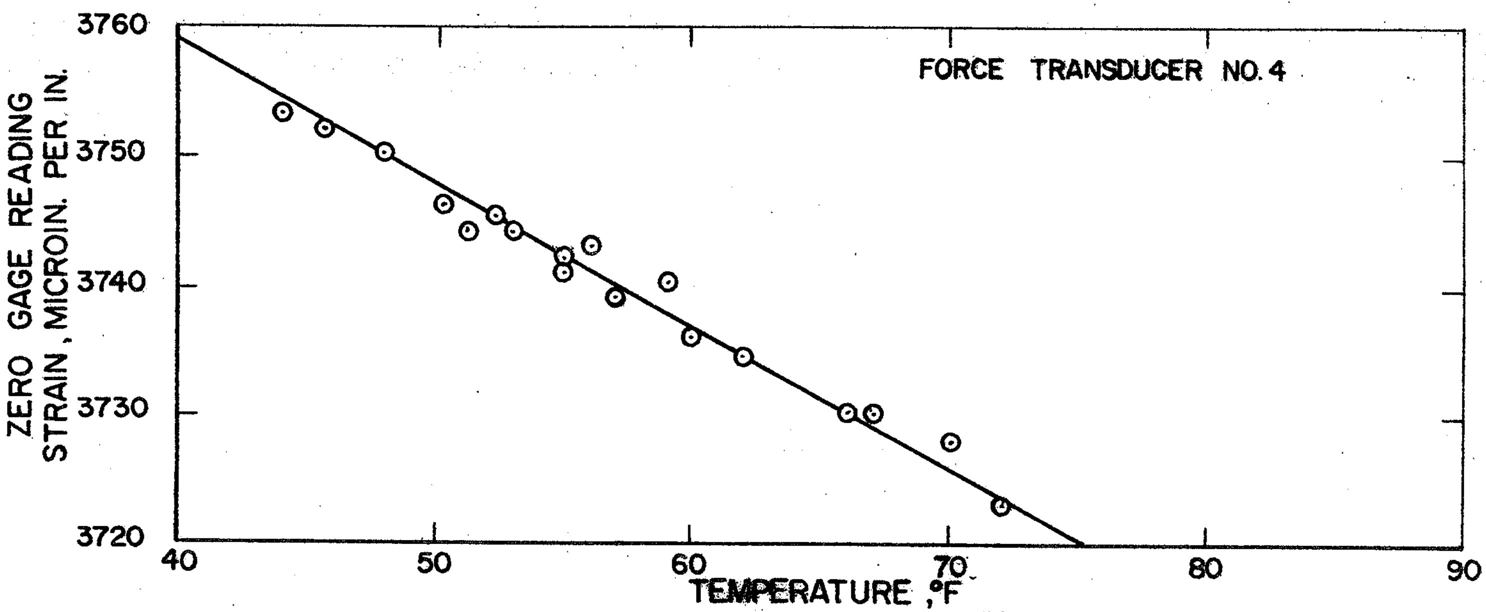

FIG. 11— TYPICAL FIELD RELATIONSHIP— ZERO FORCE READING VERSUS TEMPERATURE FOR FORCE TRANSDUCER

TABLE 4. - FORCES MEASURED BY FORCE TRANSDUCERS (KIPS)

	TRANSDUCER NUMBER			
DAY	1	2	3	4
1	0.01	0.03	0.35	0.78
2	0.01	0.03	0.47	0.88
3	0.01	0.03	1.08	1.46
9	0.01	0.11	1.97	2.42
10	0.02	2.76	2.26	4.10
16	0.21	4.82	1.69	5.11
21	0.18	4.54	1.69	4.98
24	0.24	4.56	2.16	5.81
29	0.24	4.26	1.93	5.47
38	1.02	6.42	2.92	7.99
58	1.04	5.89	3.34	9.10
65	1.01	5.64	3.42	9.02

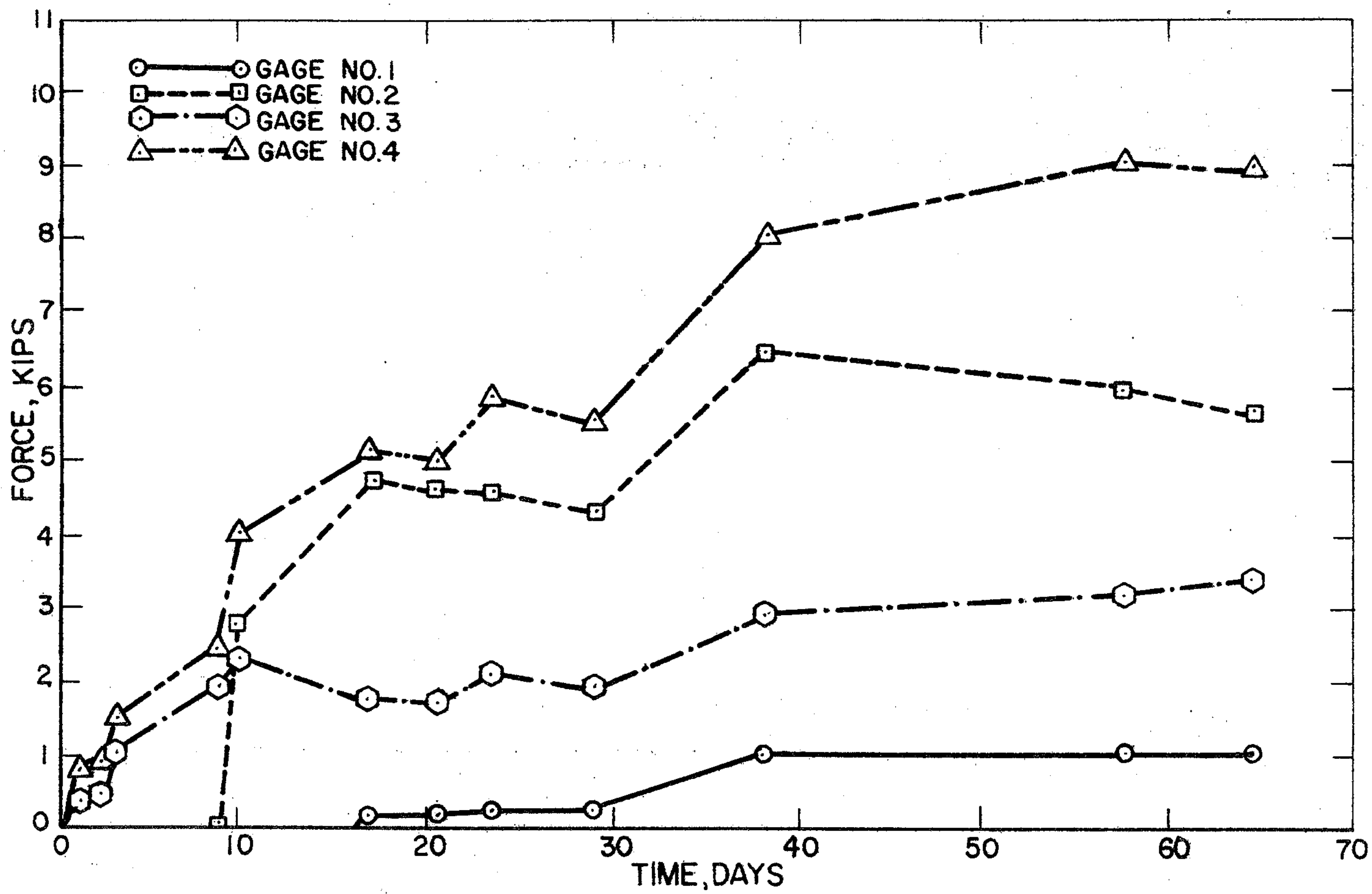

FIG. 12—FORCES MEASURED BY TRANSDUCERS VERSUS TIME

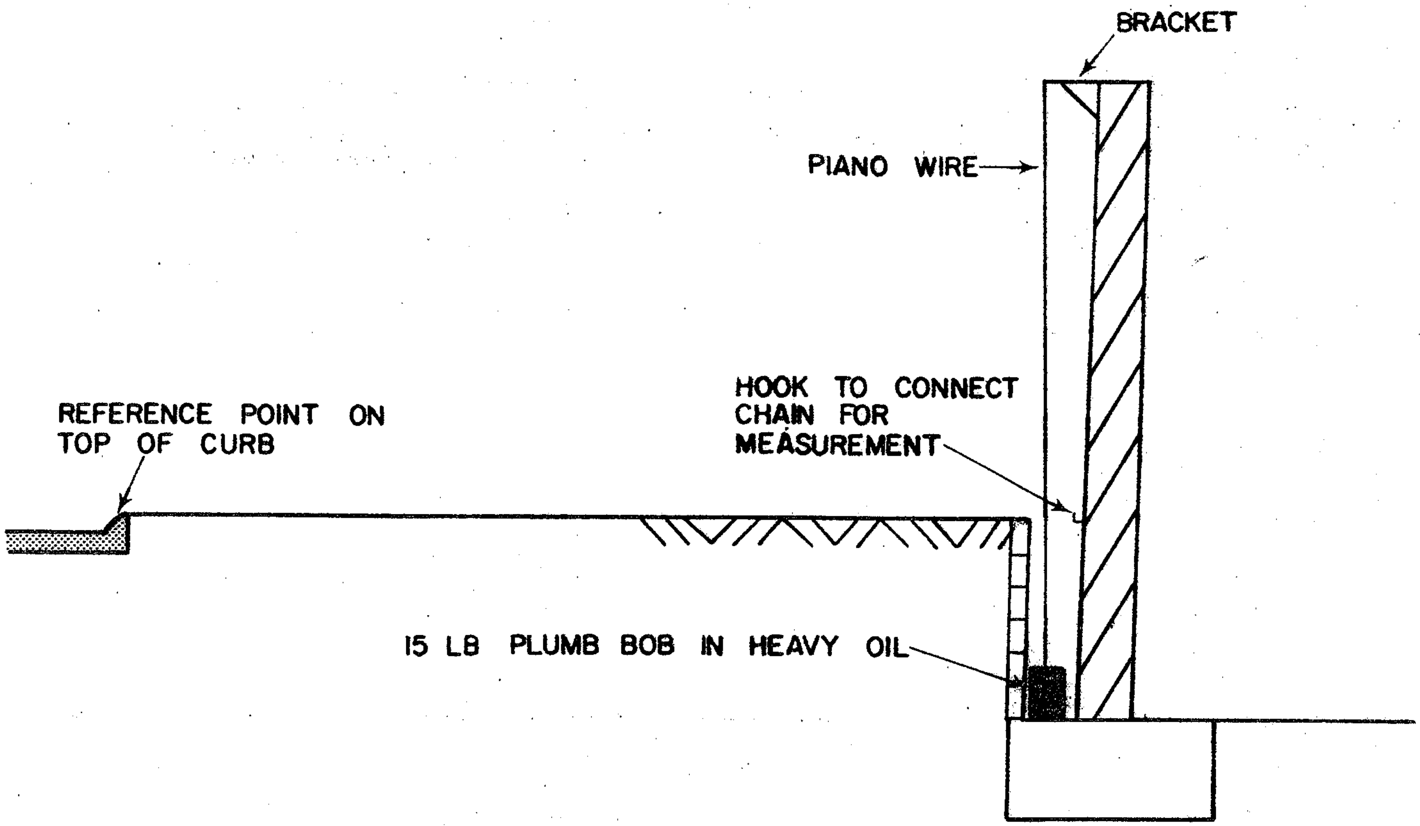

FIG. 13—CROSS SECTION OF PANEL MOVEMENT MEASURING SYSTEM

A 25 lb pull was maintained with a spring scale while measuring. The tape was supported throughout its entire length with the exception of approximately 1 ft at the face of the wall.

Fig. 13 also shows the plumb bob apparatus that was used to establish a vertical reference line from which tilting or rotation of the wall was measured. The plumb bob was hung from a metal bracket permanently fixed to the top of the wall. The plumb bob weighed 15 lbs and was suspended by a piano wire into heavy oil to reduce oscillations. Measurements were made from the piano wire to points on the wall using a metal scale with a level bubble attached. These measurements were made to the nearest 1/32 in.

Fig. 14 shows the relative movements of the panel for the first 65 days. It should be noted that all measured movements are for the panel--not the pilaster. No provisions were made for measuring the pilaster deflections. It is believed that the pilasters experienced some deflection although significantly smaller than the panel for the following reasons:

1. Initially, there was a gap between the panel and the force transducers (approximately 1/8 in.) so that the zero force versus temperature relationship for the force transducers could be established.

2. There was a 1/4 in. thick neoprene rubber pad between the force transducers and the panel to help distribute the force over the face of the transducers.

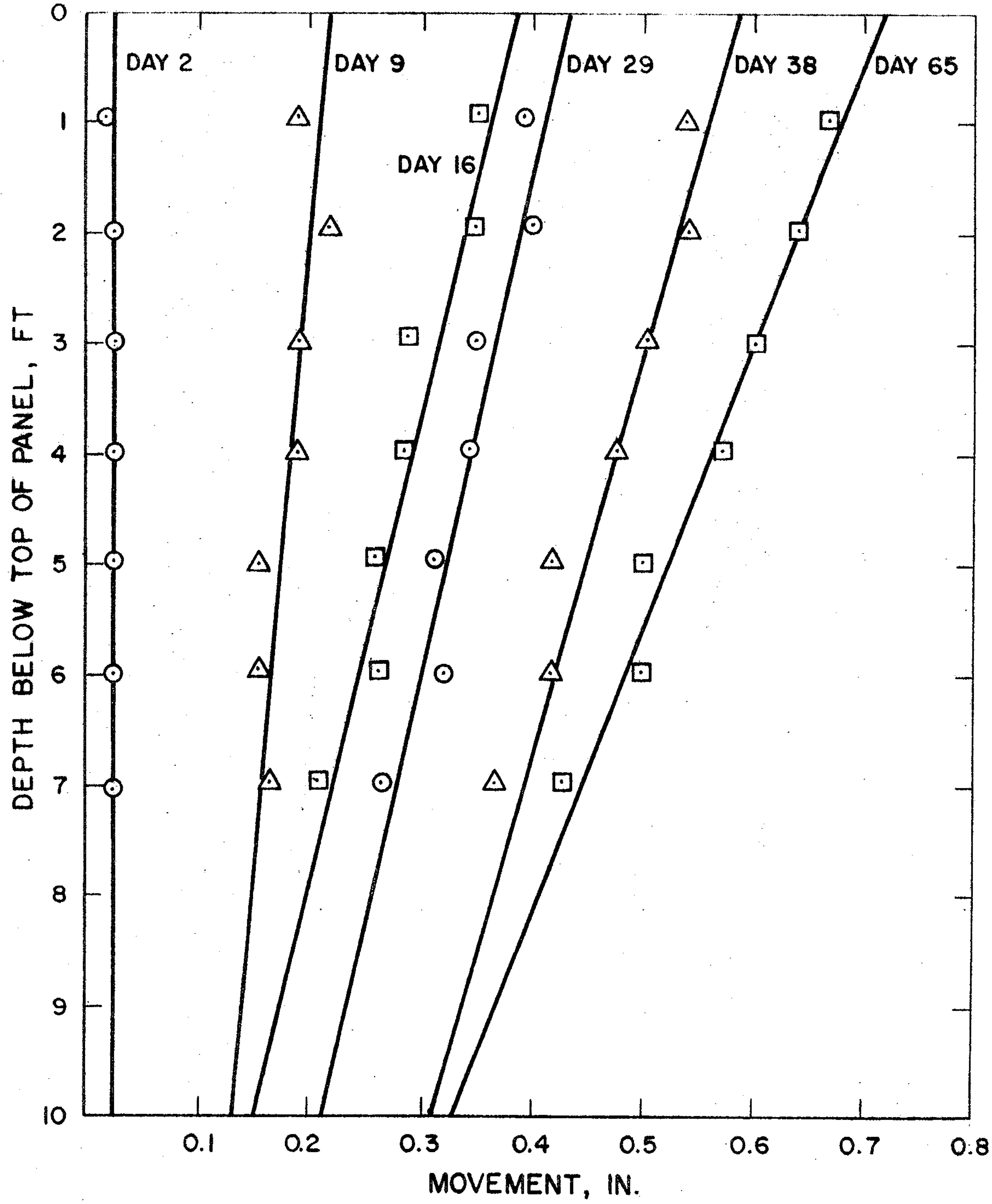

FIG. 14 – RELATIVE PANEL MOVEMENTS SINCE BEGINNING OF BACKFILL

ANALYSIS OF RESULTS

Cell Pressures versus Transducer Forces. - The total force on the panel calculated from the pressure cell measurements is given in Table 5 and plotted in Fig. 15. Each vertical column of pressure cells was considered independently from the other columns of cells when calculating the total force on the panel. Appendix III contains an example calculation of this total force on the panel for the 65th day. It should be noted that this method of calculation gives approximately the same results as averaging the horizontal rows of pressure cells.

Fig. 15 also shows the error band associated with the total force calculated to be acting on the panel according to the pressure cell measurements. This error band was calculated by multiplying the average error for all the cells times the total area of the panel (0.4 psi times 15,151 sq in.). The error band is 6 kips on either side of the measured total force. This error is a constant and has a smaller effect on the relative accuracy of the total force measurement as the pressure on the wall increases. The effect of this error was minimized by instrumenting one of the tallest panels at the test site.

The total force on the pilasters is calculated by adding the four transducer readings together. Table 6 gives the total

TABLE 5. - TOTAL FORCE ON PANEL - PRESSURE CELLS

DAY	FORCE (KIPS)	DAY	FORCE (KIPS)
1	4.38	21	24.23
2	4.07	24	21.57
3	3.35	29	22.31
9	7.46	38	33.31
10	15.53	58	32.62
16	23.46	65	27.29

TABLE 6. - TOTAL FORCE ON PANEL - FORCE TRANSDUCERS

DAY	FORCE (KIPS)	DAY	FORCE (KIPS)
1	1.18	21	11.38
2	1.39	24	12.76
3	2.58	29	11.90
9	4.51	38	18.34
10	9.13	58	19.37
16	11.84	65	19.09

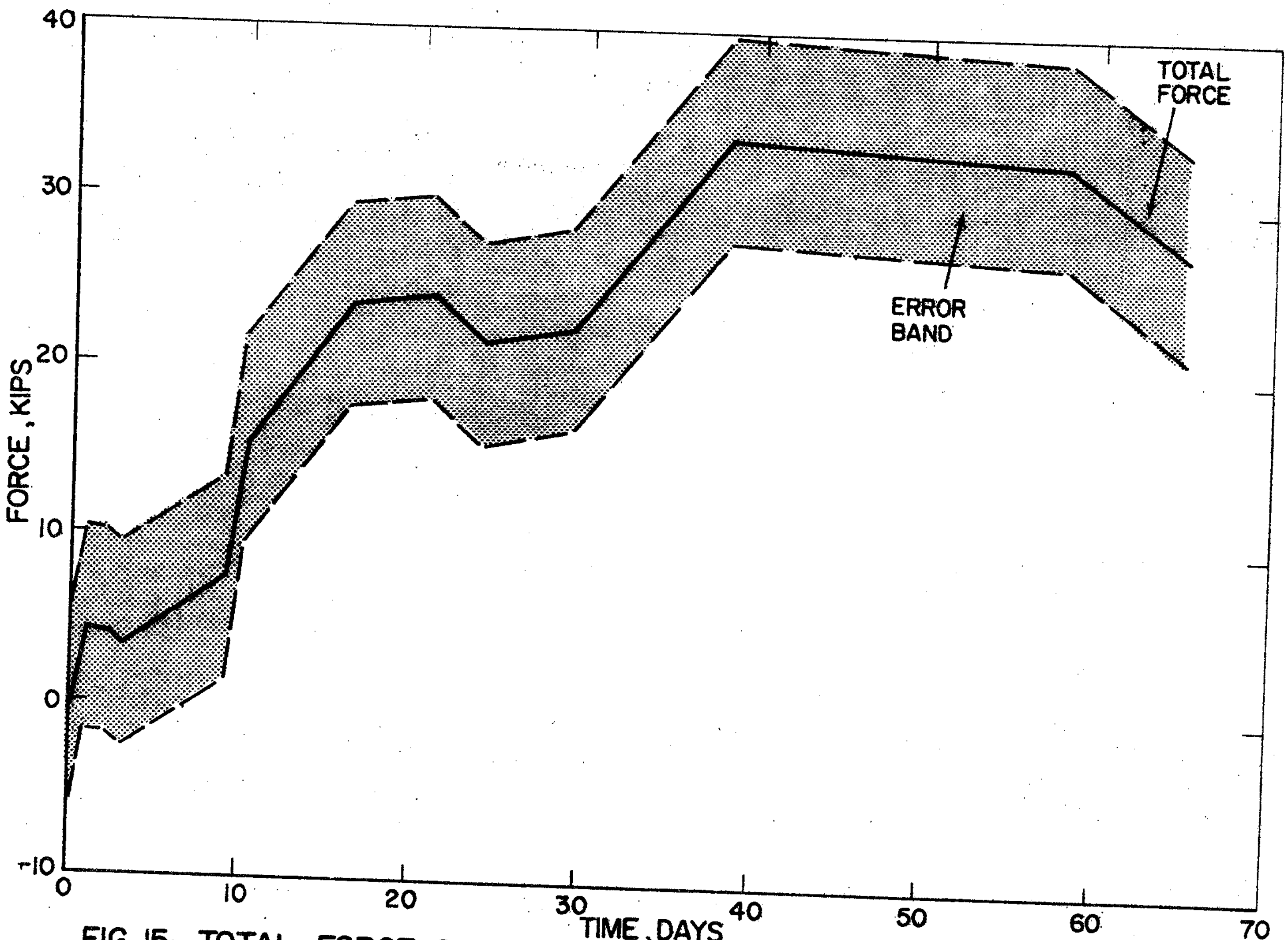

FIG 15—TOTAL FORCE ON PANEL WITH ERROR BAND—PRESSURE CELLS

force acting on the transducers and the forces are plotted in Fig. 16.

As the data were being reduced and analyzed it became apparent there was a significant difference in the total force on the panel computed from the pressure cell measurements and the total force measured by the four force transducers. It was noted that the panel bears on neoprene rubber pads as shown in Figs. 1 and 3. It was believed that these pads may be carrying a significant portion of the total force exerted by the backfill material. Since the movement at the bottom of the panel was known, the force carried by the neoprene rubber pads could be determined if the shear force versus deflection relationship for the pads could be established.

Three tests were performed on a neoprene rubber pad to establish this relationship. In each test the pad was loaded vertically with 7,500 lbs or approximately half the panel's weight. The testing apparatus is shown in Fig. 17. In the first test the pad was simply sheared in increments of 0.01 in. movement while measuring the force required to reach that deflection. In the second test the pad was loaded for approximately 24 hours and then was again sheared in increments of 0.01 in. movement. The object of this test was to determine if being loaded vertically for an extended period of time had any effect on the amount of force required to shear the pad. In the last test a side

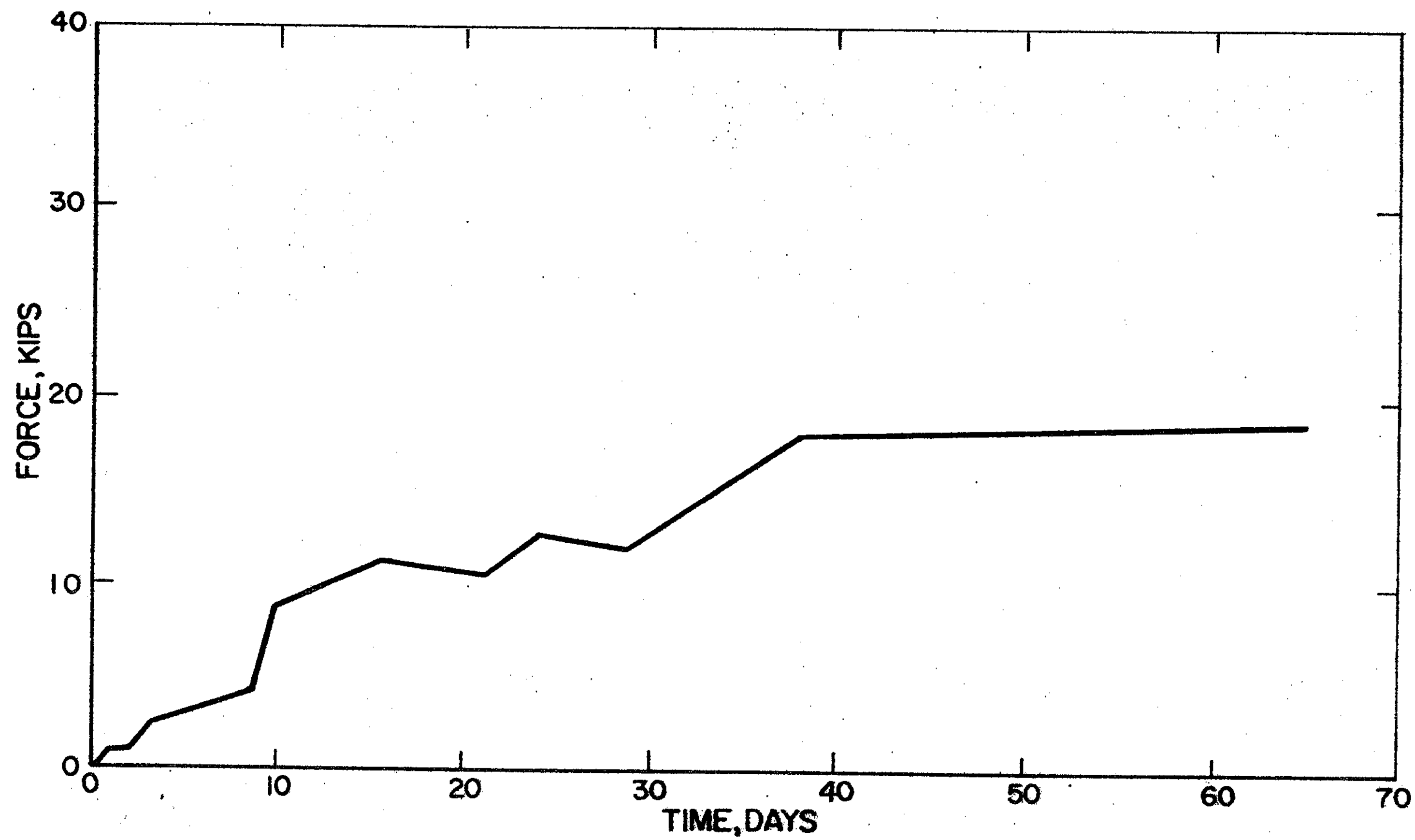

FIG. 16—TOTAL FORCE ON PANEL-FORCE TRANSDUCERS

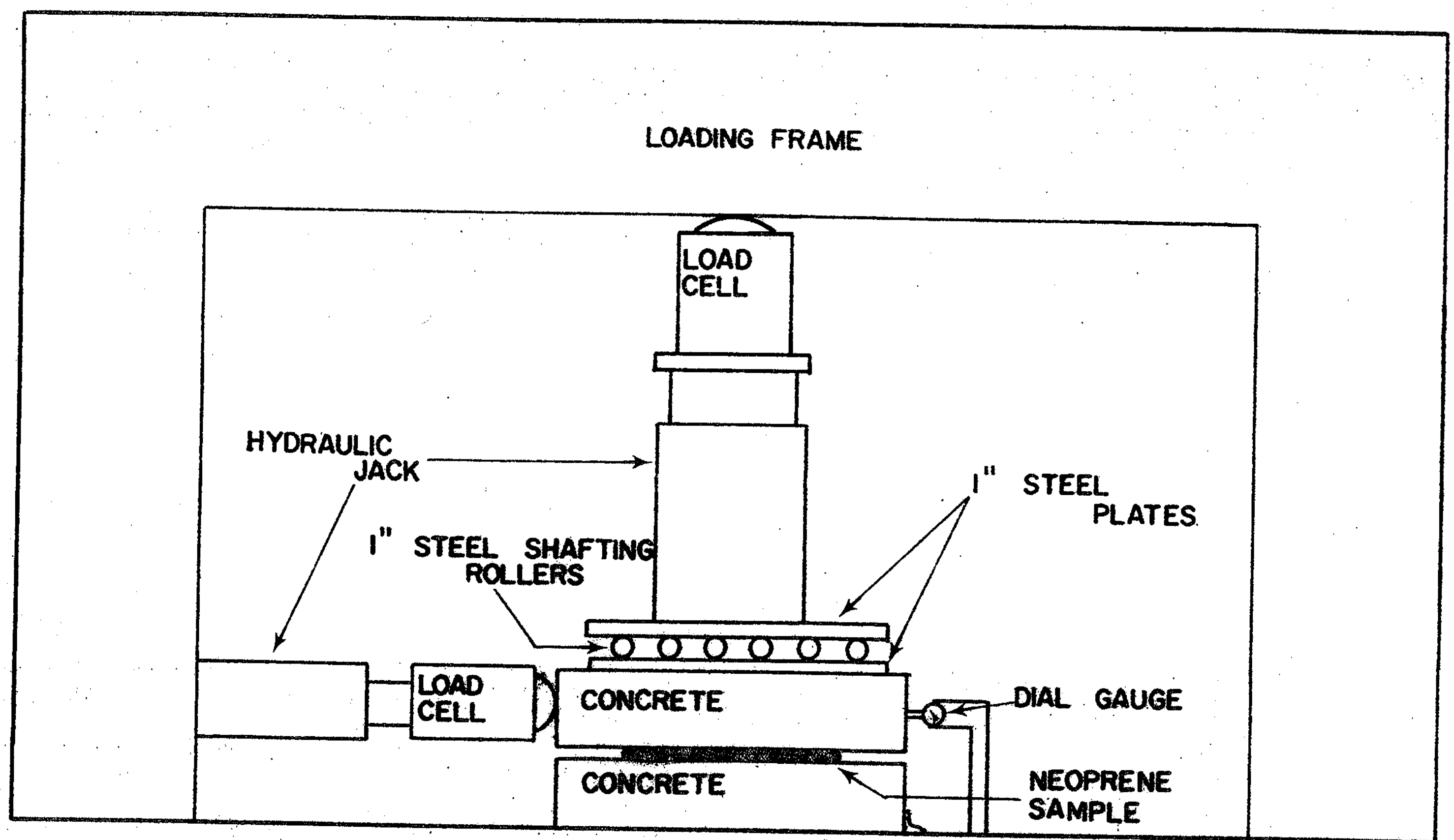

FIG. 17—TESTING APPARATUS FOR NEOPRENE RUBBER PAD

load was applied and held constant while measuring the resulting deflections. This test was used to determine if being loaded horizontally for an extended period of time would affect the resulting movements. Table 7 gives a summary of the results of these tests. Note that the different loadings produced nearly the same results. Fig. 18 shows the average displacement and force required to attain that displacement.

During the design stages of this project the possible problem of shearing force in the rubber pads was discussed but it was not expected to be significant. The wall movements were not expected to be as large as those measured and the pads were much stronger in shear than had been anticipated.

Table 8 gives the total force on the panel measured by the force transducers plus the shear force in the rubber pad at the appropriate measured wall movement. These forces are also plotted in Fig. 19. Table 9 compares the total force on the panel computed from the pressure cells measurements and the total force from the force transducers measurements plus the neoprene rubber pads correction. Fig. 20 shows the plotted results.

Also presented in Table 9 is the difference in the total force determined by the two measuring systems. The maximum difference is 8.47 kips on day 38. This would appear to be a significantly large error. However, if this difference is converted to a pressure difference and the pressure difference is assumed to be uniform over the entire surface of the panel, the

TABLE 7. - SHEAR FORCE IN A NEOPRENE RUBBER PAD (KIPS)

Displacement (in.)	Simple Shear	Sustained Vertical Load Simple Shear	Sustained Horizontal Load Resulting Shear	Average
0.05	1.15	1.25	1.50	1.30
0.10	1.85	1.85	1.80	1.83
0.15	2.30	2.35	2.00	2.22
0.20	2.70	2.80	2.30	2.60
0.25	3.00	3.10	2.60	2.90
0.30	3.30	3.30	2.90	3.17
0.35	3.50	3.55	3.20	3.42
0.40	3.65	3.65	3.35	3.55

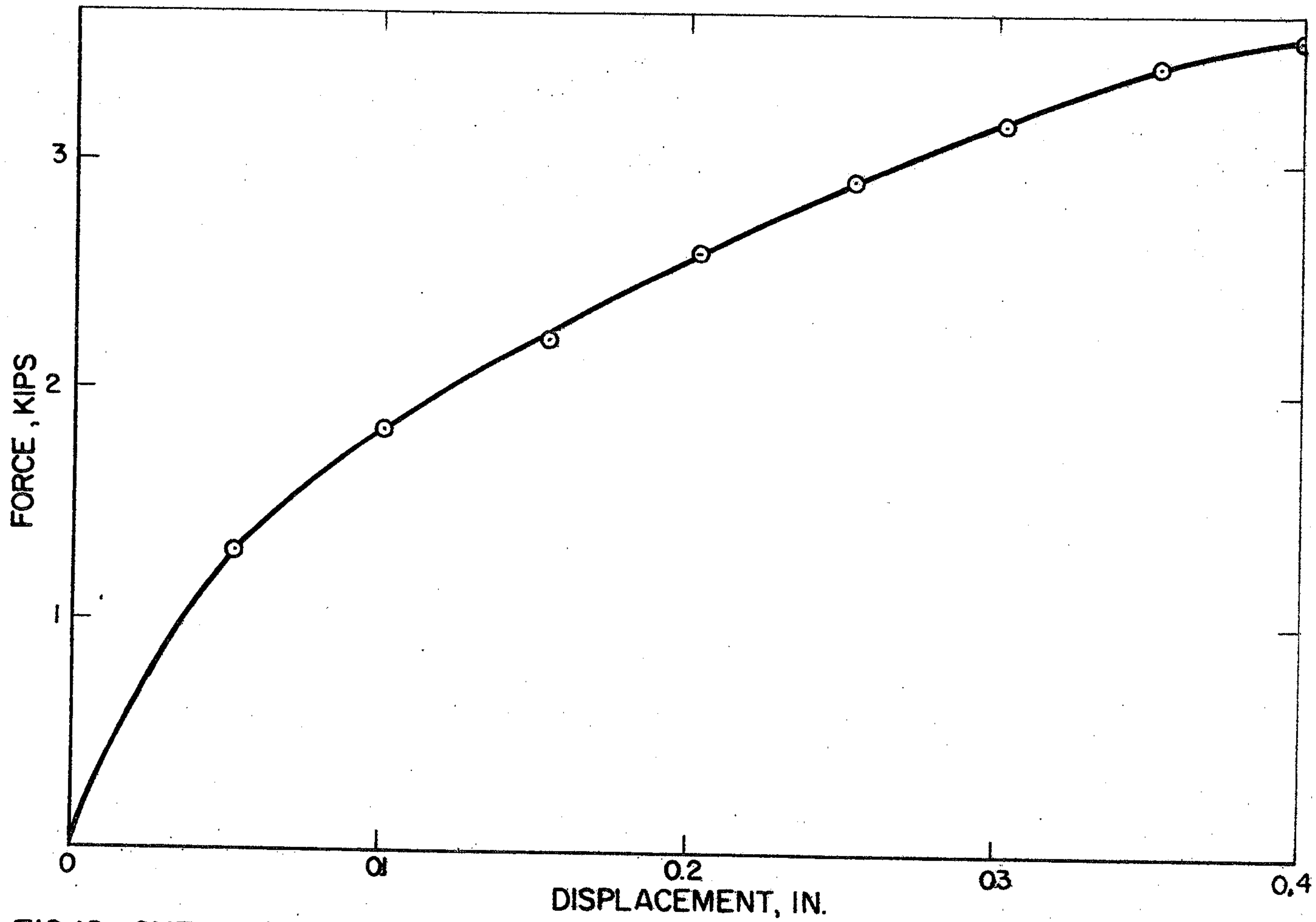

FIG. 18—SHEAR FORCE VERSUS DISPLACEMENT IN NEOPRENE RUBBER SAMPLE

TABLE 8. - TOTAL FORCE ON PANEL - TRANSDUCERS + PADS (KIPS)

Day	Wall Movement @ Bottom (in.)	Force in One Pad	Force in Both Pads	Total Transducer Force	Total Force on Panel Transducers + Pads
1	0.11	1.90	3.80	1.18	4.98
2	0.02	0.80	1.60	1.39	2.98
3	0.09	1.75	3.50	2.58	6.08
9	0.13	2.10	4.20	4.51	8.71
10	0.21	2.65	5.30	9.13	14.43
16	0.15	2.20	4.40	11.84	16.24
21	0.23	2.95	5.90	11.38	17.28
24	0.23	2.95	5.90	12.76	18.66
29	0.21	2.65	5.30	11.90	17.20
38	0.31	3.25	6.50	18.34	24.84
58	0.27	3.00	6.00	19.37	25.37
65	0.33	3.30	6.60	19.09	25.69

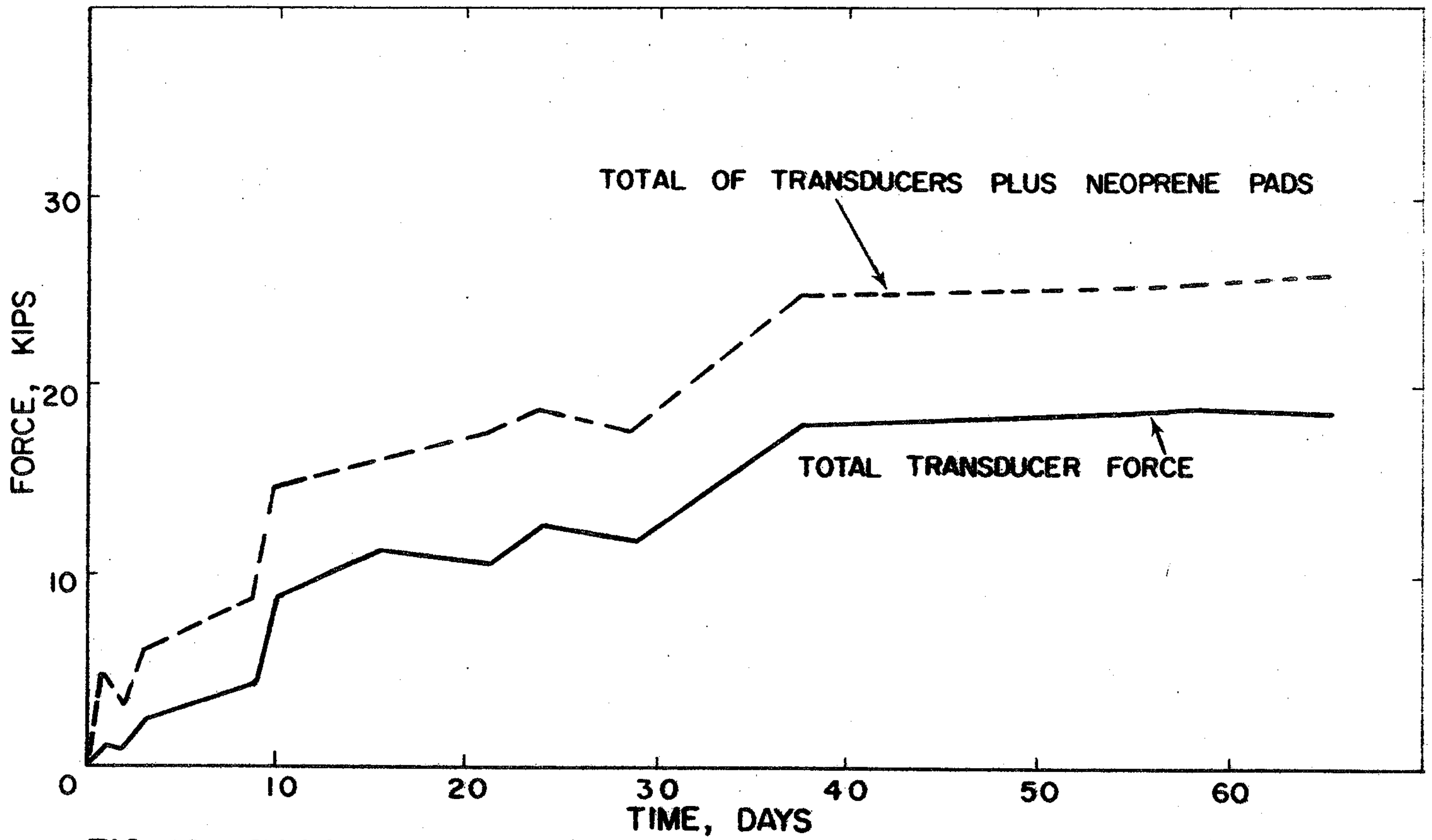

FIG. 19—TOTAL FORCE ON PANEL—TRANSDUCERS AND TRANSDUCERS PLUS NEOPRENE RUBBER SHEAR FORCE

TABLE 9. - COMPARISON OF TOTAL FORCE ON PANEL DETERMINED BY PRESSURE CELLS AND FORCE TRANSDUCERS PLUS RUBBER PADS

Day	Pressure Cells (Kips)	Force Transducers + Neoprene Pads (Kips)	Difference (Kips)	Equivalent Pressure Error (Psi)
1	4.38	4.98	0.60	0.04
2	4.07	2.99	1.08	0.07
3	3.35	6.08	2.73	0.18
9	7.46	8.71	1.25	0.08
10	15.53	14.43	1.40	0.09
16	23.46	16.24	7.22	0.48
21	24.23	17.28	6.95	0.46
24	21.59	18.66	2.93	0.19
29	22.31	17.20	5.11	0.34
38	33.31	24.84	8.47	0.54
58	32.62	25.37	7.25	0.48
65	27.29	25.69	1.60	0.11

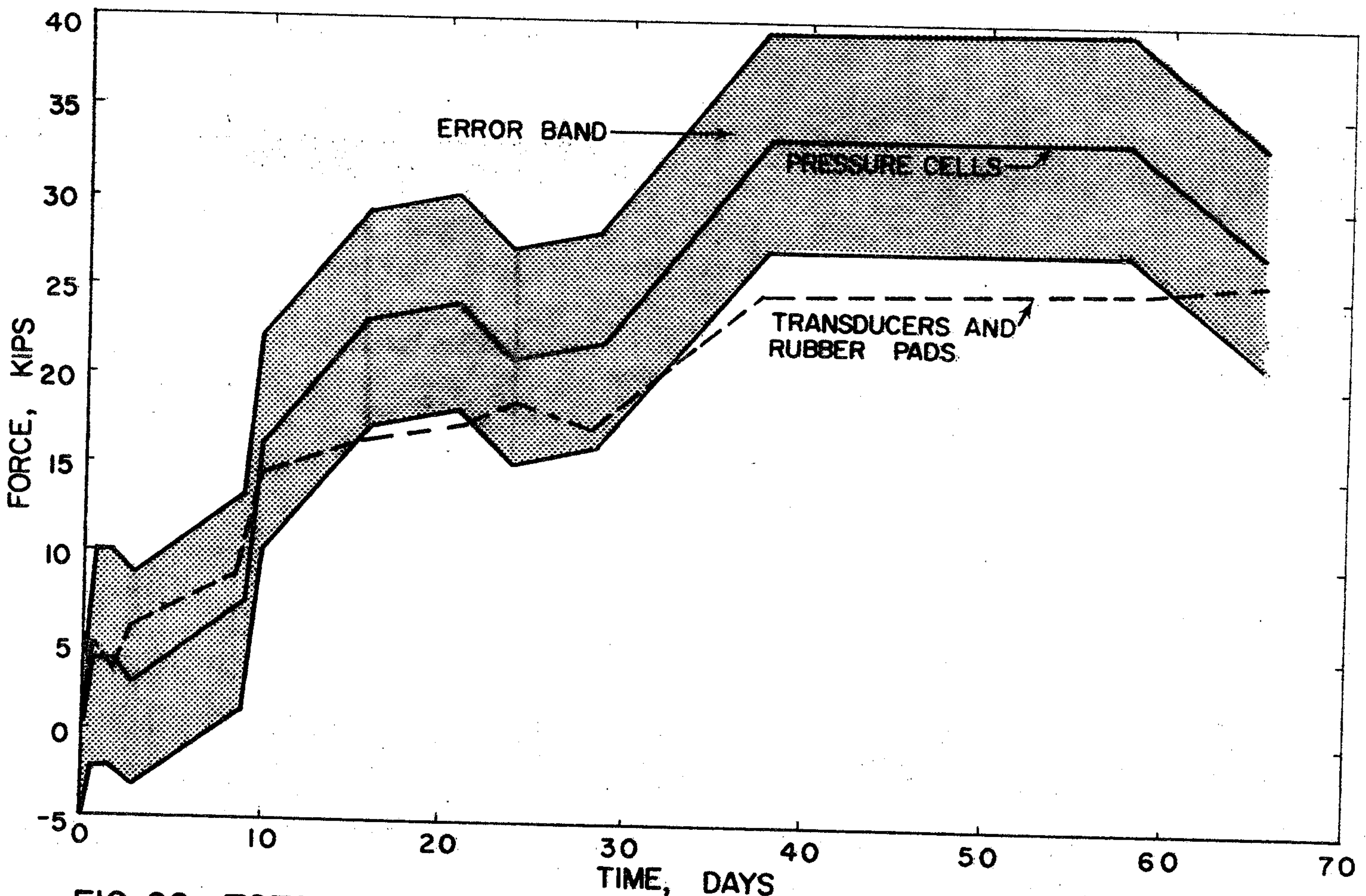

FIG. 20—TOTAL FORCE ON PANEL—PRESSURE CELLS AND TRANSDUCERS PLUS NEOPRENE RUBBER SHEAR FORCE

difference will be consistent with the stated accuracy of the pressure cells. By way of illustration, if the 8,470 lb difference is divided by the area of the panel (15,151 sq in.), an equivalent pressure error of 0.54 psi is obtained. This is only slightly in excess of the 0.4 psi stated accuracy. Also, the majority of the cell pressure errors presented in Table 9 are well within the 0.4 psi accuracy, the average error being 0.25 psi. This is a reasonably good correlation between the two measuring systems.

A center of pressure can be calculated for both methods of measurement. This center of pressure is the single point at which all the measured forces could be concentrated. As a matter of interest these points were calculated by taking moments about the edge of the panel, and considering first the pressure cells and then the transducers plus the rubber pads. The calculated points were always close to each other. For example the centers of pressure differed by only 0.67 ft in the horizontal direction and 0.1 ft in the vertical direction for day 65.

The significance of reasonably close correlation between total force and centers of pressure calculated from the two methods of measurements tends to indicate pneumatic calibration of earth pressure cells being used in this research is adequate. Previously it was not known if the cells would react to soil the same way they react to air pressure, or if the soil was arching across the cell preventing accurate measurements. Either of these would have caused poor agreement between the forces measured by the pressure cells and the force transducers plus the rubber pads. Also, arching in the soil would have caused reduced pressures on the face of the cells and the cells would have measured a lower force than the transducers.

Measured Pressures versus Theoretical Pressures. - As stated earlier in this report, pressures on a retaining wall have been shown to be a function of wall movement. Pressures drop when the wall moves away from the backfill. This is known as the active case. At rest pressures are higher since it assumes that no movement has taken place. Passive pressures, which are the highest, result from the wall moving toward the backfill (8).

The pressure distributions predicted to be acting on the panel after completion of the clay backfill by the Coulomb and Rankine theories are shown in Fig. 21. The parameters used to calculate the Coulomb and Rankine distributions are:

$\bar{\phi}$ = effective angle of internal friction of sand backfill = 32°;

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

α = angle of back of retaining wall panel with respect to horizontal = 88°;

δ = friction angle between wall and backfill = 20°.

The clay backfill was considered to be a surcharge load (1).

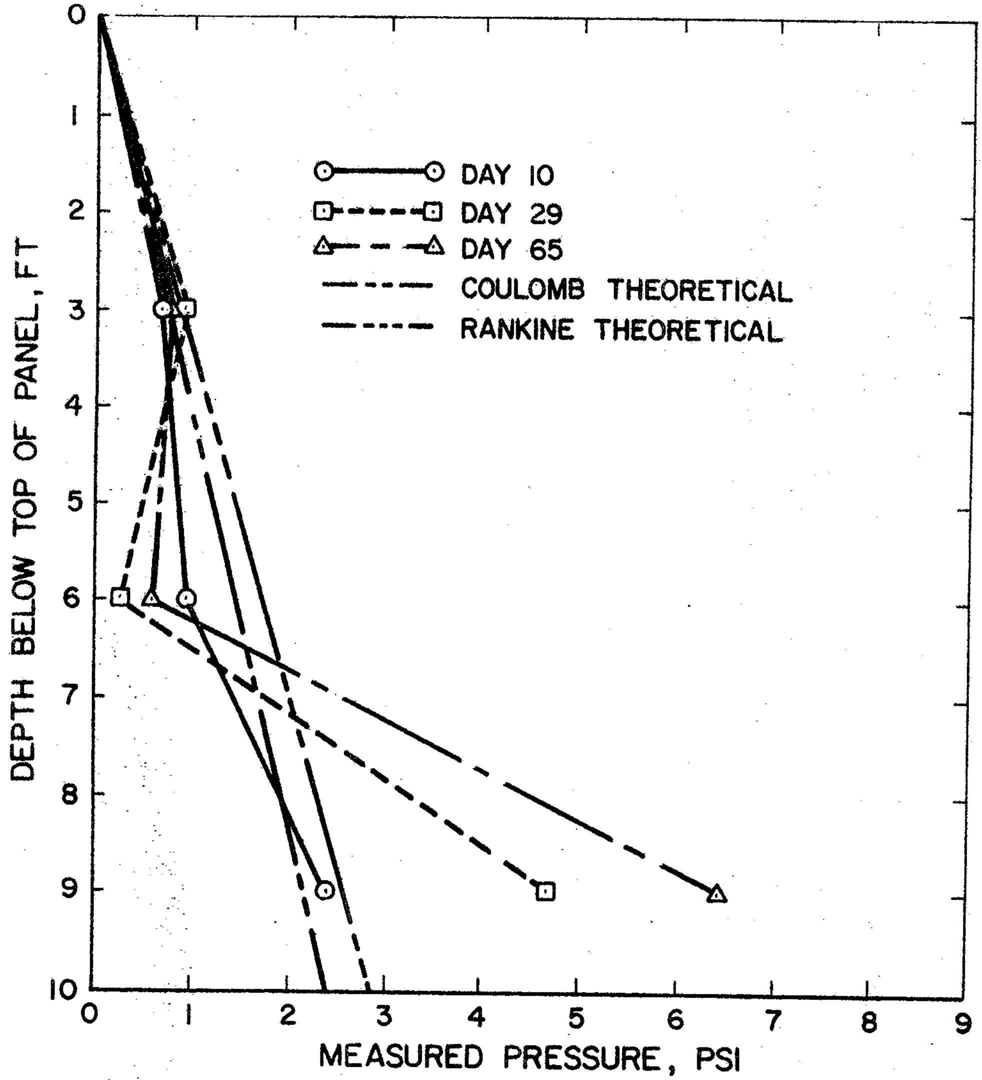

FIG. 21 — COMPARISON OF AVERAGE MEASURED PRESSURES WITH THEORETICAL PRESSURES

The wall friction angle δ is a difficult parameter to evaluate. Sowers (6) states that for smooth concrete δ is often 1/2 to 2/3 $\bar{\phi}$. Terzaghi and Peck (9) suggest that the coefficient of wall friction, tan δ, can be assumed as 2/3 tan ϕ for fairly permeable soils. Potyondy (5) found the ratio of δ to ϕ for sand to vary from 0.76 to 0.88 in shear box tests performed on various construction materials. However, this wide range of possible values for δ has little influence on the value of the coefficient of lateral earth pressure, K_a. Coulomb's value for K_a is 0.290 and Rankine's value is 0.307.

The average pressure measured by each row of cells is given in Table 10. This average pressure distribution for days 10, 29, and 65 is shown in Fig. 21. The sand backfill had been completed by day 10. The measured pressure distribution agreed fairly well with the theoretical distributions up to that time. However by day 29, just prior to addition of the clay backfill, the measured pressure on the upper row of cells had remained about the same, dropped slightly on the middle row of cells, and approximately doubled on the lower row of cells. On day 65, after completion of the clay backfill, the pressure on the upper row was still constant, the pressure on the middle row had increased slightly, and the lower row of cells was measuring more than 2 1/2 times the theoretical pressure.

There are several possible explanations for the lack of agreement between the measured and theoretical pressure distributions.

TABLE 10. - AVERAGE PRESSURE MEASURED BY EACH ROW OF PRESSURE CELLS (PSI)

DAY	UPPER ROW	MIDDLE ROW	LOWER ROW
1	0	0	1.13
2	0	0	1.07
3	0	0	0.85
9	0	0.25	1.63
10	0.63	0.92	2.38
16	1.07	0.43	4.43
21	1.30	0.18	4.72
24	0.82	0.40	4.28
29	0.82	0.27	4.70
38	1.52	0.55	6.45
58	1.18	0.80	6.35
65	0.73	0.60	6.43

First, supported as it is on neoprene rubber pads and by force transducers, the panel could deflect or bow in either the horizontal or vertical direction or both. Any bending or bowing could cause deviations in measured pressures from the theoretical because very small deflection can cause large pressure changes (8). Second, the drain for the sand backfill is directly in front of the lower row of pressure cells. The filter material and remaining sand backfill are not homogeneous. The filter material was not compacted in the same manner as the remaining backfill. Third, construction was continuing in the area. Vibrations from heavy machinery, especially while compacting the clay backfill, could have caused the material to move with the panel instead of allowing the active case to develop.

Pressures more than twice those predicted by the Coulomb and Rankine theories were also measured in the lower elevations of the cantilever retaining wall instrumented during the second year of this study (3). Measured wall movements in the lower elevations were so small as to be negligible and it was postulated that at rest pressures were acting on the wall. Since high pressures were measured in both cases, there is an indication that pressures approaching at rest values act on retaining walls under certain conditions. For at rest cases the appropriate coefficient of lateral earth pressure is between 0.8 and 1.0.

SUMMARY AND RECOMMENDATIONS

Summary. - The broad objective of this research study was to verify or modify the lateral earth pressure coefficients predicted by the Rankine and Coulomb theories through the use of field measurements on full-scale retaining walls. The specific objectives accomplished in this year of study are as follows:

1. Terra Tec earth pressure cells were used to measure the lateral earth pressures on a pre-cast panel in a full-scale retaining wall. The total force on the panel according to the pressure cell measurements was realistic. Individual pressure measurements were usually within the permissible errors of the cells.

2. Force transducers were used between the panel and its supporting pilasters to measure the force of the lateral earth pressure transmitted through the panel. These measurements were consistently lower than expected. It was shown that the measurements were low because neoprene rubber pads supporting the panel were carrying a significant amount of load. The force transducer measurements plus the forces carried by the rubber pads gave a reasonably good correlation with the pressure cell measurements.

3. Both lateral translation and tilting or rotation of the

panel was measured accurately. Sufficient movement was measured to have attained the fully active case.

4. The engineering properties of the backfill material were determined. The backfill was clean sand with an average total unit weight of approximately 105 pcf. Its gradation was such that it was classified SP by the Unified Soil Classification System. Its effective angle of internal friction was 32°.

5. One of the major objectives of this study was to verify the calibration of the pressure cells. It was concluded that the pneumatic calibration of the cells is adequate. This conclusion was based on the reasonably good correlation between the total force on the panel calculated from pressure cell measurements and the total force measured by the transducers plus the rubber pads. This correlation also showed that soil arching across the face of the pressure cells was probably not a significant factor.

6. Another major objective of this study was to compare the measured pressure distribution with that predicted by the Coulomb and Rankine theories. In the upper elevation of the panel there was reasonably good correlation. In the lower elevations the measured pressures were over twice those predicted. Since this was also the case in the cantilever retaining wall instrumented during the second year of this study, there is an indication that at rest lateral earth pressures may be exerted in the lower elevations of retaining walls.

Recommendations. - The following recommendations are made concerning the results of research accomplished thus far and continued research in this program:

1. Continue measuring pressures, forces, and movements of the pre-cast panel. Designs of retaining walls must be based on long term as well as short term conditions. Future construction at the test site may also influence the lateral earth pressures and movements.

2. Continue to develop improved calibration procedures for the pressure cells used in this research. This effort should be directed at further verifying the adequacy of a simple pneumatic calibration to establish cell calibration factors, and validating and improving the techniques for establishing the relationship between the zero stress reading and such factors as time and temperature. Errors resulting from deviations in the zero stress reading versus temperature relationship are the largest ones known to exist with these cells. Reducing these errors would greatly improve the accuracy of the earth pressure cells.

3. Continue to compare field measurements with theoretical pressures so that the overall objective of verifying or modifying the existing earth pressure theories can be accomplished.

APPENDIX I. - REFERENCES

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APPENDIX II. - NOTATION

$°F$ = degrees Farenheit

ft = feet

in. = inch

K_a = active earth pressure coefficient

lb = pound

micro in. = 1×10^{-6} inches

no. = number

% = percent

psi = pounds per square inch

sq = square

α = angle of back of retaining wall from horizontal, in degrees

β = angle of slope to horizontal, in degrees

$\overline{\phi}$ = effective angle of internal friction, in degrees

$\mu\varepsilon$ = strain, in micro inches per inch

δ = angle of wall friction, in degrees

ϕ = angle of internal friction, in degrees

APPENDIX III. - PROCEDURE FOR CALCULATING TOTAL FORCE ON PANEL

Procedure. - The following is the method used for calculating the total force exerted on the pre-cast panel by the backfill. Those calculations are based on the pressures measured by the earth pressure cells on the 65th day:

For a unit width (see Fig. 22)

$$P_4 = P_3 + \frac{P_3 - P_2}{h_3} h_4$$

$$F = \frac{1}{2} P_1 h_1 + \frac{1}{2}(P_1 + P_2) h_2 + \frac{1}{2}(P_2 + P_3) h_3 + \frac{1}{2}\left[P_3 + \left(P_3 + \frac{P_3 - P_2}{h_3} h_4\right)\right] h_4$$

$$F = \frac{3}{2} P_1 + \frac{3}{2}(P_1 + P_2) + \frac{3}{2}(P_2 + P_3) + \frac{3}{2}\left[2P_3 + \frac{P_3 - P_2}{h_3} h_4\right] \frac{h_4}{3}$$

$$F = \frac{3}{2}(2P_1 + 2P_2 + P_3) + \frac{3}{2}\left[2P_3 + (P_3 - P_2)\frac{5}{18}\right]\frac{5}{18}$$

$$F = \frac{3}{2}\left(2P_1 + 2P_2 + P_3 + \frac{10}{18} P_3 + \frac{25}{324} P_3 - \frac{25}{324} P_2\right)$$

$$F = \frac{3}{2}\left(2P_1 + \frac{623}{324} P_2 + \frac{529}{324} P_3\right)$$

$$F = 3P_1 + \frac{623}{216} P_2 + \frac{529}{216} P_3$$

$$F = 3P_1 + 2.884\, P_2 + 2.449\, P_3$$

Figure 23 shows the width of the panel associated with each column of pressure cells.

$F_{left} = [3P_1 + 2.884P_2 + 2.449P_3][W] = [3\text{ ft }(0.35\text{ psi}) + 2.884\text{ ft}$

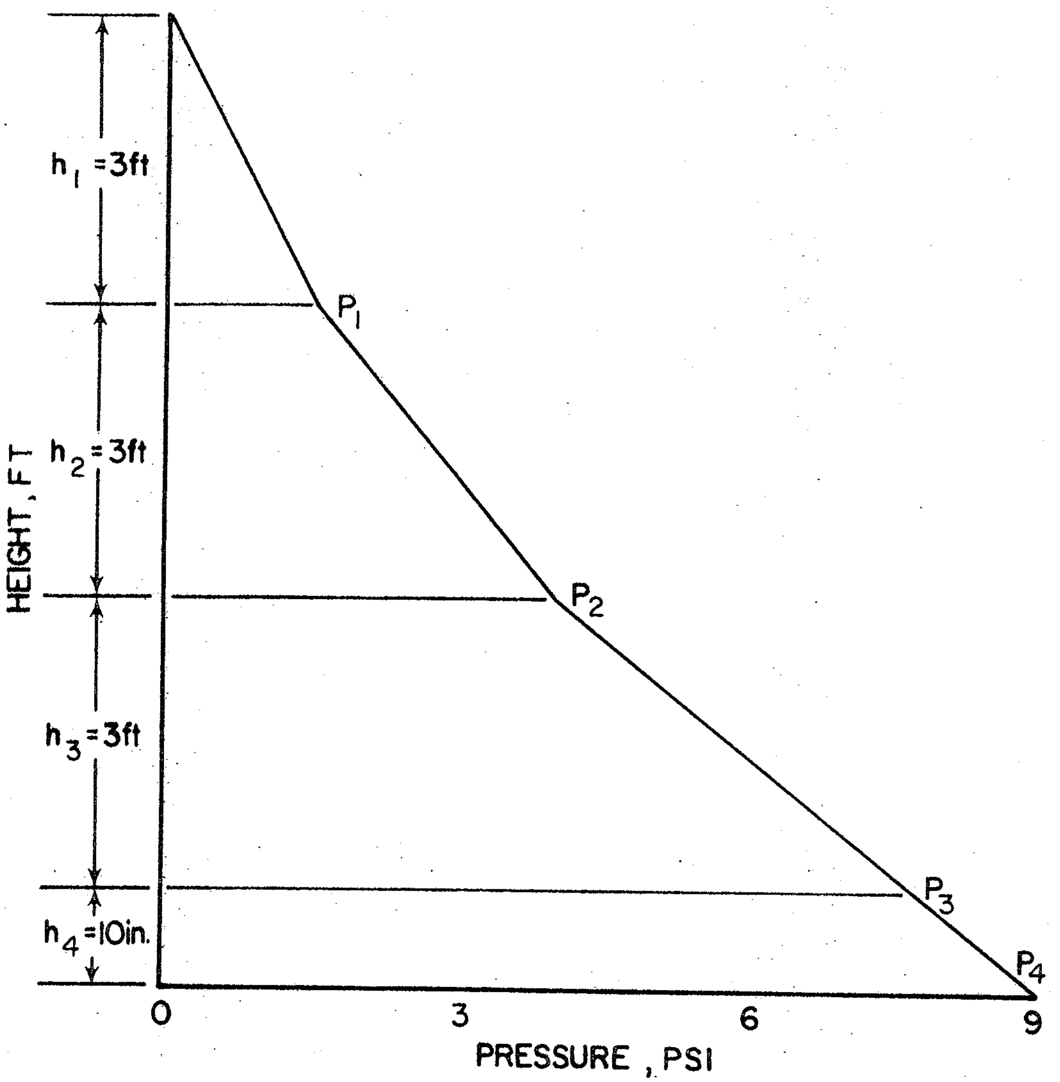

FIG.22 – HEIGHT VERSUS PRESSURE FOR A UNIT WIDTH

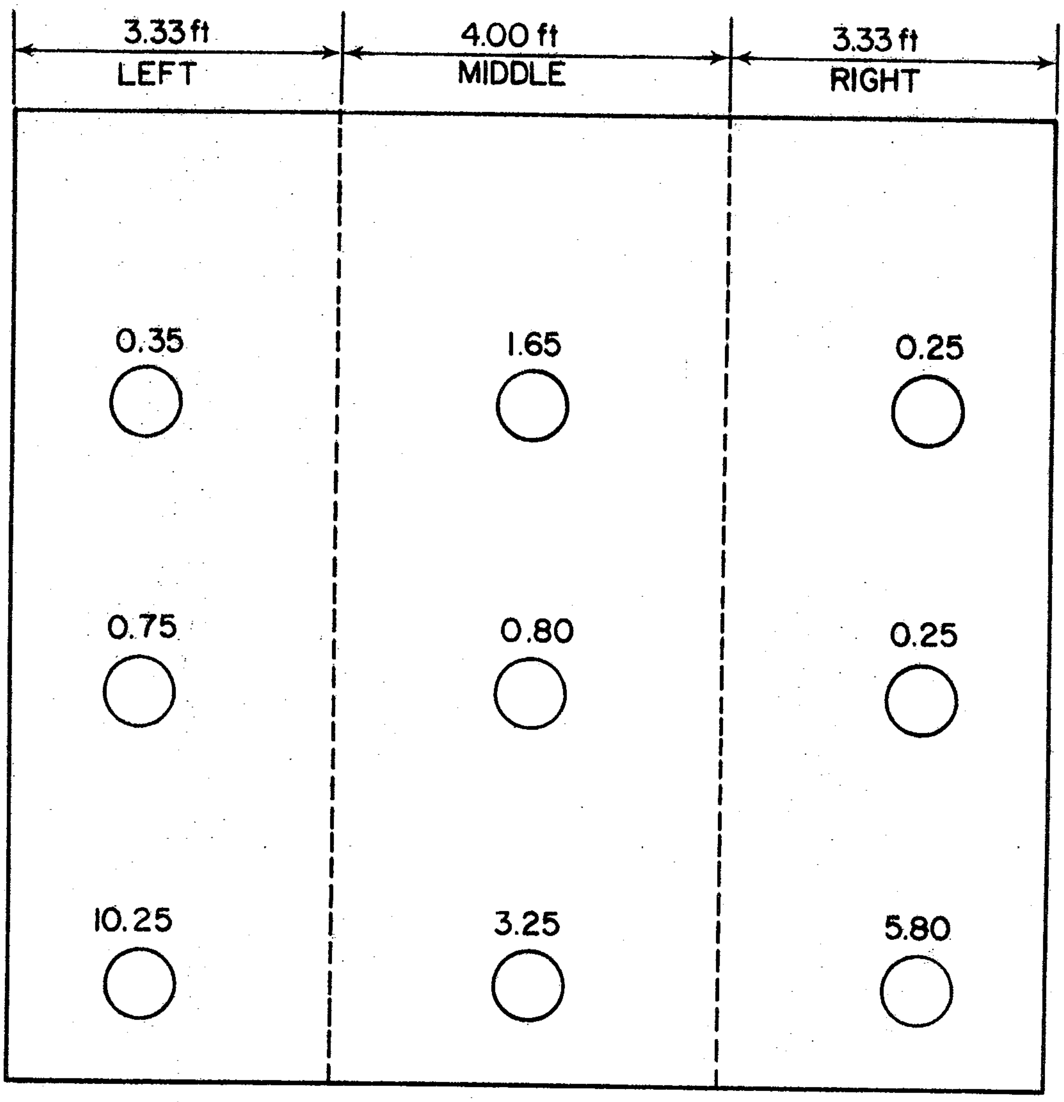

FIG. 23 – PRESSURE (PSI) AND WIDTHS USED FOR CALCULATING TOTAL FORCE ON PANEL

$$(0.75\ \text{psi}) + 2.449\ \text{ft}\ (10.25\ \text{psi})]\ [3.33\ \text{ft}] \left[\frac{144\ \text{in.}^2}{\text{ft}^2}\right]$$

$$\left[\frac{1}{1000\ \text{lb/kip}}\right]$$

$$F_{left} = 13.55\ \text{kips}$$

$$F_{mid} = [3(1.65) + 2.884(0.80) + 2.449(3.25)]\ [4\ \text{ft}]$$

$$F_{mid} = 6.21\ \text{kips}$$

$$F_{left} = [3(0.25) + 2.884(0.25) + 2.449(5.80)]\ [3.33\ \text{ft}]$$

$$F_{left} = 7.35\ \text{kips}$$

$$F_{total} = 13.55 + 6.21 + 7.53 = 27.29\ \text{kips}$$