NEW RETAINING WALL DESIGN CRITERIA
BASED ON
LATERAL EARTH PRESSURE MEASUREMENTS

by

William V. Wright
Research Assistant

Harry M. Coyle
Research Engineer

Richard E. Bartoskewitz
Engineering Research Associate

and

Lionel J. Milberger
Research Associate

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ABSTRACT

A procedure for determination of the lateral earth pressure distribution to be used for computation of forces and moments acting on retaining walls which are fixed at their base and backfilled with cohesionless sand are developed in this study. The procedure is based on the analysis of data collected from two instrumented full scale retaining walls. Data are presented covering a period of 1156 days for a cantilever wall founded on H-piles and 769 days for a panel wall supported by pilasters founded on drilled shafts. The data consist of pressure cell and movement measurements for both walls. In addition, the force transmitted from the panel wall to its supporting pilasters was measured with force transducers. A discussion of structural design considerations and some recommended construction practices are included.

Earth pressure distributions and wall movement data are compared with the results of Terzaghi's large scale retaining wall test. This comparison indicates that the foundation of the wall will prohibit the wall from tilting by an amount sufficient to reduce the earth pressures below the at rest value near the base of the wall. Thus for design purposes at-rest pressures are considered to act in this region of the wall.

Earth pressure changes with time show a seasonal variation in pressure for both walls. The pressure on the panel wall increased as the panel moved outward after backfill. Significant changes in pressure appear to result from the movement of construction equipment during backfill and afterward. However, vehicular traffic after construction did not produce measurable changes in pressure during the time periods covered by this study.

KEY WORDS: Cantilever Retaining Wall, Precast Panel Retaining Wall, Earth Pressure Cells, Force Transducers, Wall Movement Measurements

SUMMARY

The information presented in this report was developed during a five-year study on "Determination of Lateral Earth Pressure for Use in Retaining Wall Design." The objective of the study was to verify or modify existing lateral earth pressure design criteria through the use of long term field measurements of lateral earth pressures on full scale retaining walls.

Pressure cells were used to measure the lateral earth pressure acting on a cantilever retaining wall and a precast panel retaining wall. Force transducers were used to measure total force acting on the precast panel wall. Measurements of wall movement were made during and after backfilling on both walls. Data were collected covering a period of 1156 days for the cantilever wall and 769 days for the precast panel wall. Measured pressures on the lower portion of both walls were higher than the active pressures predicted by Coulomb or Rankine theories.

New retaining wall design criteria have been developed based on the results of this study. The resulting recommended pressure distribution is developed considering active pressure on the upper half of the wall and at-rest pressure at the base of the wall. This pressure distribution corresponds with the measured pressure distribution on both test walls.

IMPLEMENTATION STATEMENT

Research Report 169-4F is the final report covering the work accomplished under Research Study 2-5-71-169 entitled "Determination of Lateral Earth Pressure for Use In Retaining Wall Design." New retaining wall design criteria were developed using long term field measurements of lateral earth pressures on two full scale retaining walls. Active pressures measured at the the base of both walls were higher than would be obtained by presently used design criteria. The current design method involves the use of an equivalent fluid pressure which results in a simple triangular pressure distribution. The new design criteria consist of a recommended method and an alternate method for design. Both methods are based on a compound triangular pressure distribution with the linear increase in pressure with depth being larger on the lower half of the wall. The recommended method is to be used when the engineering properties of the backfill soil are known or specified before construction. The alternate method is for use when the backfill properties are not known or specified before construction, and if used, would result in a move conservative design.

The greater-than- theoretical active pressures measured on the lower half of the cantilever wall and the panel wall were about equal to the theoretical at-rest pressures that are computed on the basis of an at-rest earth pressure coefficient equal to 0.8. Compared to the current design method, the effect of the larger pressures on the lower half of the wall is to increase the overturning moment and resultant force while lowering the point of application of the resultant force. These facts are incorporated in the new design criteria, and the adoption of the new design criteria is recommended.

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INTRODUCTION

Earth Pressure Theories -- The principles of limiting equilibrium mechanics are used to design earth retaining structures. In this approach the pressures that would exist at a failure condition are predicted from Coulomb or Rankine (13)* theories and suitable safety factors are applied. Earth pressure computations for both theories are the same:

$$p = K \gamma' h + u \tag{1}$$

where p is the lateral earth pressure, γ' is the effective unit weight of the backfill material, h is the depth of the backfill and u is the pore water pressure in the backfill. K is the coefficient of lateral earth pressure and is equal to the ratio of the horizontal effective stress to the vertical effective stress in a soil mass. Since the value of h is dependent on wall geometry and the value of γ' is dependent on properties of the available backfill material, the design is greatly affected by the choice of K values. When soil has been deposited and there are no lateral strains within the ground, the coefficient is called the coefficient of lateral earth pressure at rest, K_0. Values of K greater than K_0 are termed passive coefficients, and values of K less than K_0 are termed active coefficients. For the purposes of this study an important difference between the Rankine and Coulomb theories is the boundary conditions which are applied to the retaining wall problem. Rankine (10) described the stress conditions which can be developed simultaneously throughout a semi-infinite mass of soil acted on by no force other than gravity. When applied to most real retaining walls, movements in the soil involve displacements between the sand and the surface of the wall. If the contact surfaces are rough shear forces are developed. These are not accounted for in the Rankine theory.

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

In contrast to Rankine, Coulomb (10) never attempted to investigate the state of stress within the backfill. He recognized that the lateral yield of a wall produces a strictly localized transition from the natural state into a state of complete mobilization of the internal friction. Thus Coulomb's theory is not restricted to a semi-infinite mass and his method can be adapted to any boundary condition. Also, the effects of wall friction can be included. Terzaghi (10) has pointed out that, "the fundamental assumptions of Rankine's earth pressure theory are incompatible with the known relation between stress and strain in soils."

There is one case in which Rankine's method can be applied, and the assumption of a smooth vertical wall is almost strictly correct (12). This case is illustrated in Fig. 1 for a cantilever wall of the same dimensions as the one analyzed in this report. If such a wall yields under the influence of the earth pressure, the sand fails by shear along two planes rising from the heel of the wall at angles of 45° + $\phi/2$ with the horizontal.

If the distance between the back face of the stem, point A, and the heel at the end of the spread footing, point B, is sufficient in length the shear plane BC' will not intersect the wall. Thus no wall friction will be involved. For the cantilever wall shown a small part of the wall intersects the shear plane, and shear will occur along the wall from C to D. The error involved in neglecting this friction is small for this wall.

Within the wedge shaped zone located between these two planes, the sand is in the active Rankine state and no shearing stresses act along the vertical plane BE. The earth pressure against this plane is identical with that against a smooth vertical wall. The Coulomb method should be used to determine lateral earth pressures on other types of retaining walls such as the precast panel wall discussed herein.

<u>Present Status of the Question</u> -- Since the publication in 1934 of earth pressure tests on large-scale retaining wall models by Terzaghi (11), designers have accepted Terzaghi's conclusion that a small yield of the structure will cause shear resistance to develop

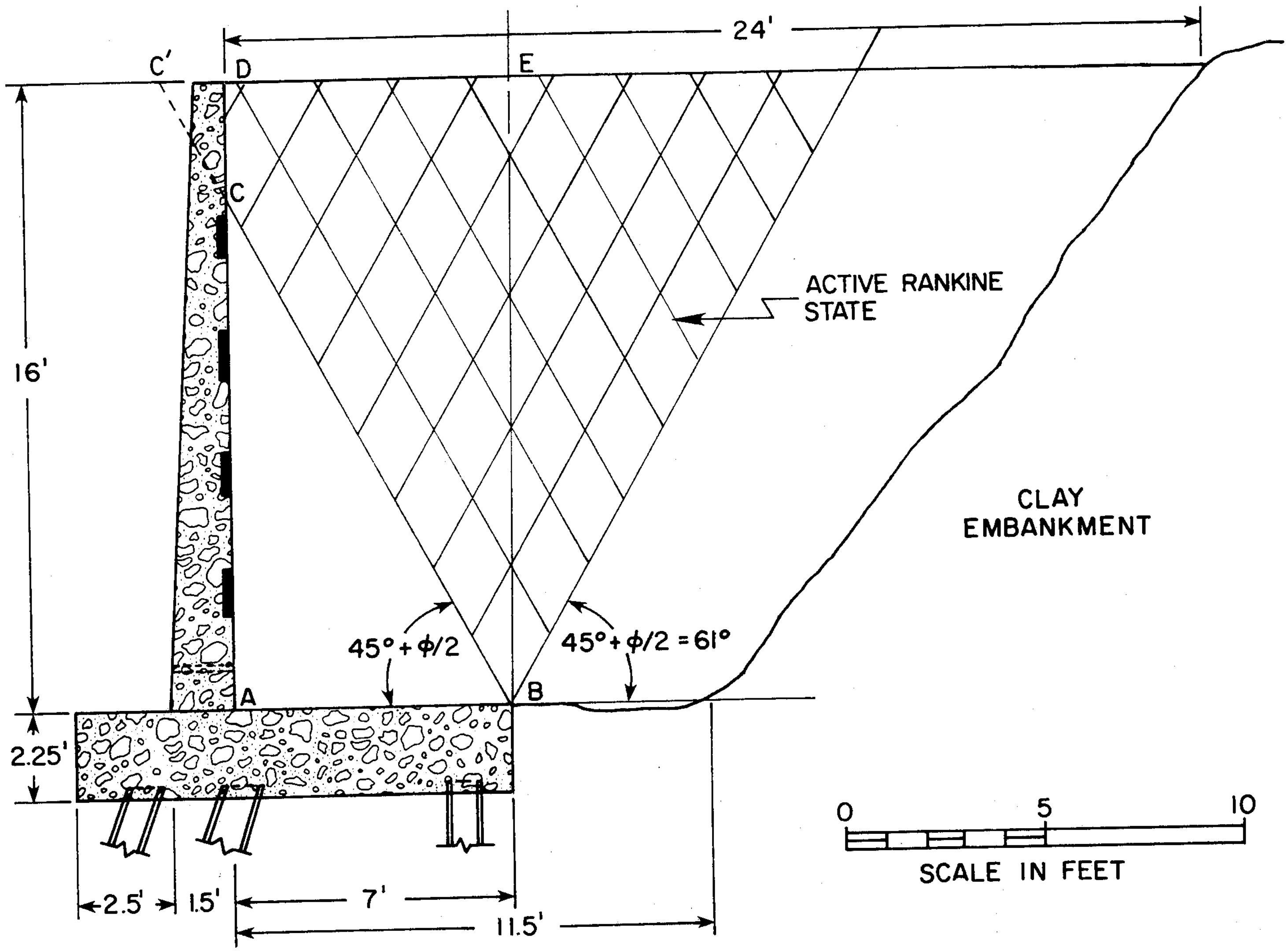


FIG. 1 - CONDITION OF ACTIVE RANKINE STATE, CANTILEVER WALL
(1 ft = 0.305 m)

in a sand backfill. When sufficient movement has occurred the developed shear stress reduces the earth pressure on the wall to the active state.

Using the principles of limiting equilibrium, the design is based not on an analysis to determine the expected forces but analysis of the forces that would exist if the wall started to fail by overturning or sliding outward (6). Terzaghi observed during his large scale model tests (11) that the lateral earth pressure existing after backfill and prior to yielding of the wall, "undoubtedly depends to a considerable extent on the method of compaction." Terzaghi and Peck (12) have observed that for rigid structures the magnitude of earth pressure depends to a large extent on the methods of placing the fill. Casagrande (2) cites the results of field measurement which revealed that even light compaction could result in the development of greater than active earth pressures. Lambe and Whitman (6) have pointed out that, "if the thrust against a retaining wall were greater than the active value it would not mean that potentially the wall was in trouble. On the contrary it would mean that the soil underlying the wall is much stronger than it need be". They further observed that, "Long before a wall can fail, it must move enough to mobilize the shear strength of the soil and to drop the thrust to its active value." The term "failure" refers to foundation failures, i.e. to overturning or sliding outwards. The structure of the wall is assumed unyielding.

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

A five-year research study was begun at Texas A&M University in 1970 to measure lateral earth pressures in the field on full scale retaining walls. The first year (3) was devoted to selecting earth pressure cells which would provide both accuracy and long term reliability. Nine cell types were considered. Four types were field tested. Two types, Terra Tec and Geonor, were selected for installation in the cantilever test wall during the second year (4) of the study. Terra Tec cells were selected for installation in the precast panel wall during the third year (7) of the study. The instrumentation of the panel wall consisted of nine Terra Tec cells, three rows of three cells, embedded with thermocouples in the concrete panel. In addition, force transducers were placed between the panel and the supports to measure total load transmitted by the panel. During the fourth and fifth years of the study field data were collected and analyzed for both the cantilever and the precast panel walls.

Purpose of the Study -- The purpose of this research study on retaining walls is to verify or modify the existing lateral earth pressure design criteria through the use of long term field measurements of lateral earth pressures on the full scale retaining walls. Analysis of the data obtained from both walls and new design considerations and recommendations are presented in the main body of this report. Theoretical earth pressure computations are presented in Appendix III and the procedure for computing forces and moments are presented in Appendix IV. The results of a separate laboratory calibration study are presented in Appendix V. The purpose of the calibration study was to investigate the cause of seasonal variations in pressure cell readings. The results of another separate study on measurement of passive earth pressure on a drilled shaft are presented in Appendix VI. The purpose of the drilled shaft study was to determine the feasibility of using earth pressure cells to measure passive pressures. The calibration and drilled shaft studies were beyond the scope of the original research study objectives.

CANTILEVER RETAINING WALL

Test Wall

Test Wall Description -- The instrumented cantilever retaining wall is located near the intersection of U.S. Highway 59 and Interstate 45 in Houston, Texas. A total of seven cantilever retaining walls were constructed at this site. One panel in a retaining wall supporting an access road was selected for instrumentation.

The test wall represents a typical cantilever retaining wall design with the exception that it has been founded on steel H-piles. A cross section of the cantilever test wall is shown in Fig. 2. The test panel is approximately 16 ft (4.9 m) high and 30 ft (9.2 m) long. The significant dimensions of the cantilever wall and the location of the pressure cells are shown in Fig. 3. The groundwater table is located below the footing of the wall. Weep holes are provided to allow drainage and thus prevent hydrostatic forces from building up behind the wall.

The wall was instrumented in March 1972 and the backfilling operation was completed in April 1972. Paving of the access road began in May 1973. Vehicular traffic began in October 1974.

Backfilling Procedure -- The backfill material was obtained at the construction site. Heavy scrapers excavated, transported, and dumped the material in a single operation. Due to wet conditions, the backfilling required seven days. The scrapers spread the borrow, and a bulldozer completed spreading and compaction. The backfill material was nearly saturated when placed and compaction was wetter than optimum moisture content. Eight-inch lifts were used and approximately three passes were made on each lift. The width of the bulldozer blade prevented the bulldozer from compacting near the wall. As the backfill was raised the bulldozer compacted farther from the wall to prevent overstressing the panel.

Properties of Backfill Material -- The backfill soil was a uniformly graded tan fine sand with approximately nine percent fines. Sieve analysis results are shown in Table 1. Atterburg limits test

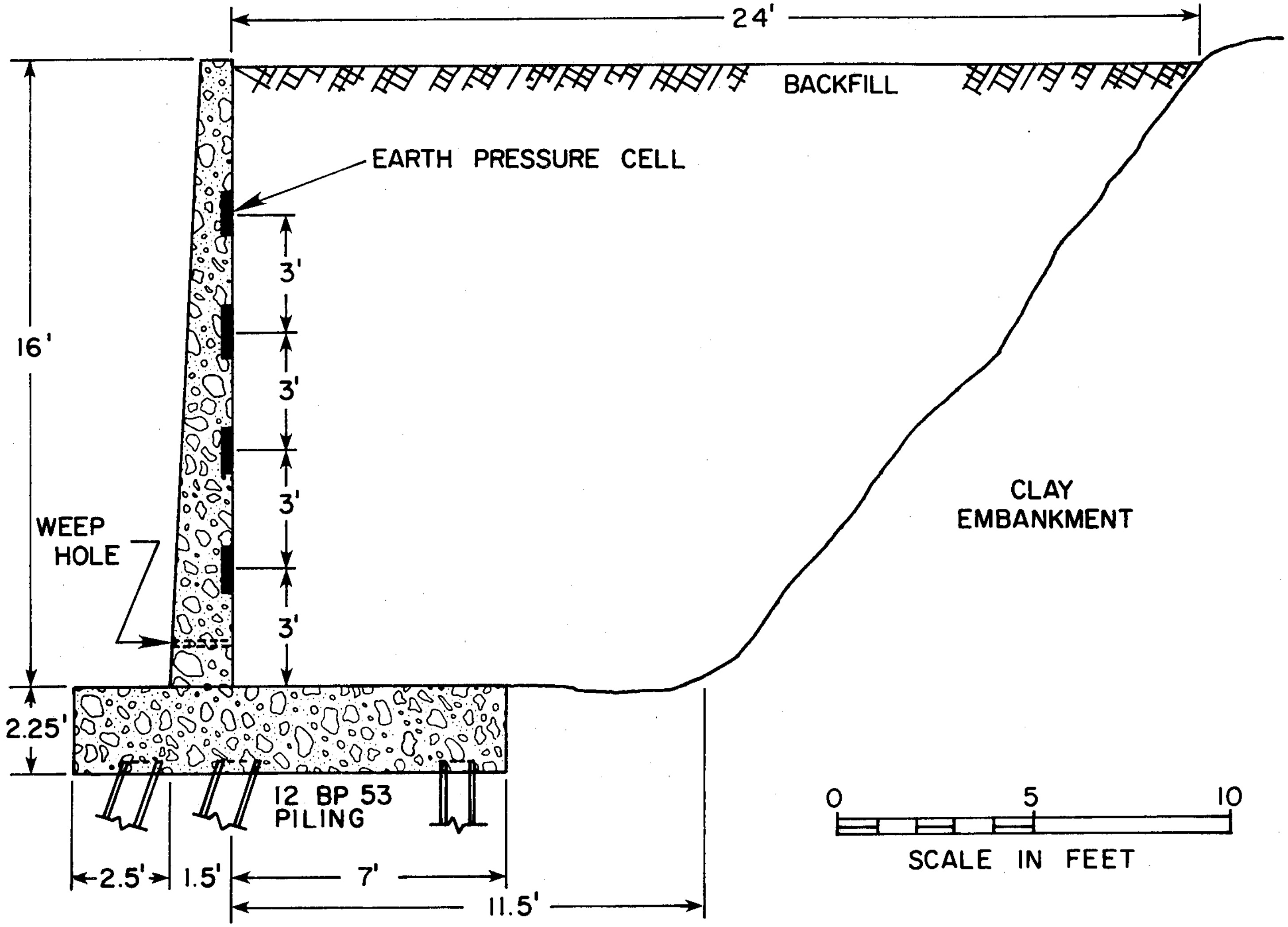


FIG. 2 — CROSS SECTION OF CANTILEVER WALL
(1 ft = 0.305 m)

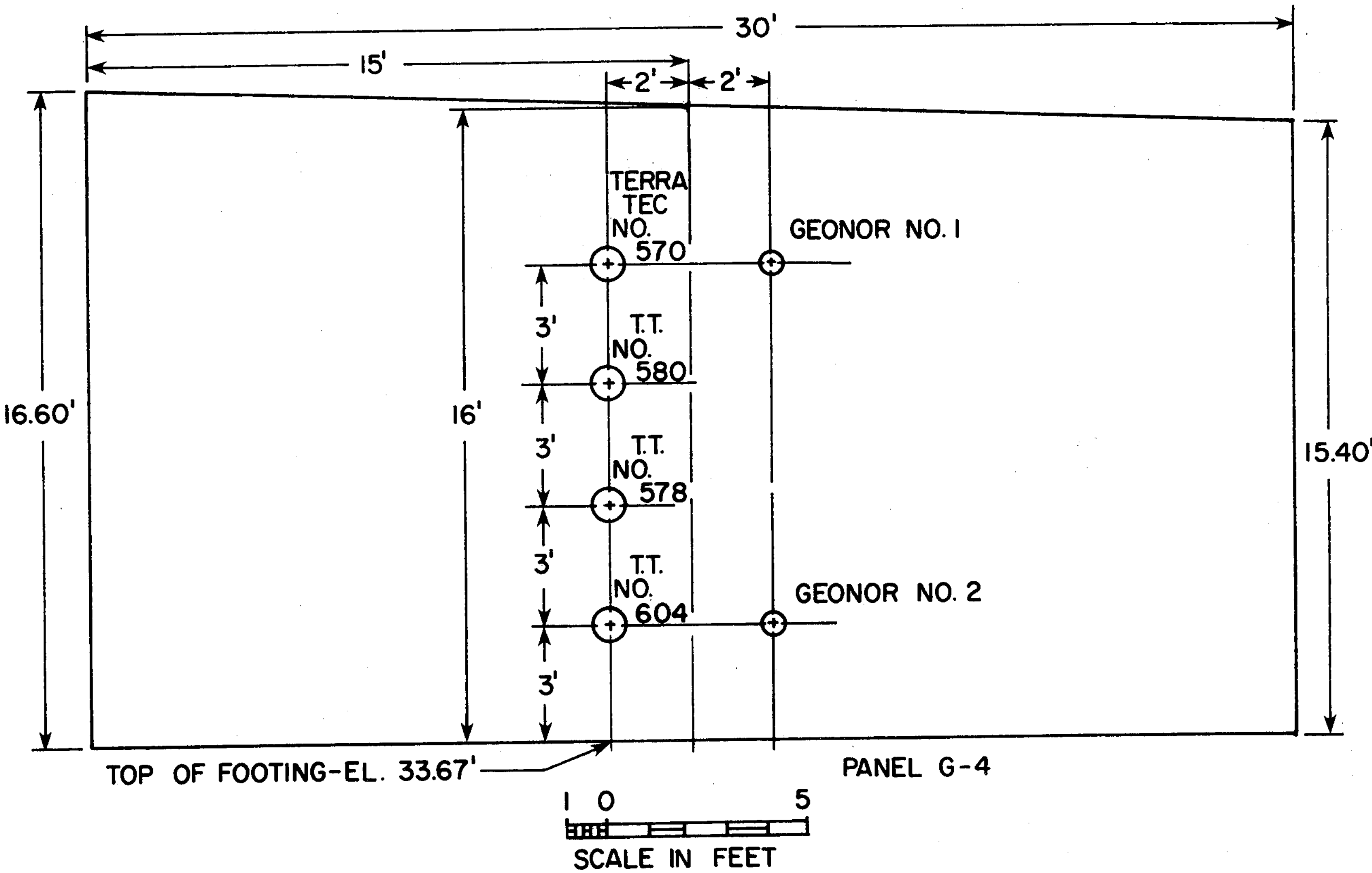


FIG. 3—LOCATION OF EARTH PRESSURE CELLS, CANTILEVER WALL
(1 ft = 0.305 m)

data plotted below the A line on the Unified Plasticity Chart. A dual classification of SP-SM was assigned in accordance with the Unified Classification System.

TABLE 1. SIEVE ANALYSIS OF BACKFILL MATERIAL, CANTILEVER WALL

Sieve Number	% Finer by Weight
4	99.2
10	97.4
20	93.9
40	92.9
80	50.8
200	8.8

The backfilling procedure resulted in high moisture contents and low unit weights particularly near the wall. Soil samples were collected during backfill and eighteen months after construction. The results of unit weight and moisture content tests are shown in Table 2. The following observations are made:

1. Moisture content decreased about 10 percent during the eighteen-month period after backfilling. The decrease in moisture content was slightly larger at a distance of 2 ft from the back face of the wall as compared to the decrease which occured next to the wall.
2. During the backfilling period the average unit weight of the soil at the center of the backfill was about 10 percent greater than the unit weight of the soil near the wall.
3. Eighteen months after completion of the backfilling operation the soil unit weight 1 ft from the wall appeared to be significantly higher than the soil unit weight 3 ft from the wall.

A unit weight of 101.3 pcf (1623 kg/m^3) was used for theoretical calculations. An angle of internal friction of 32° was determined from direct shear tests (4).

Instrumentation

Lateral Earth Pressure -- The cantilever wall was instrumented with four Terra Tec and two Geonor cells. The cell locations are

TABLE 2 - UNIT WEIGHT AND MOISTURE CONTENT OF BACKFILL MATERIAL
CANTILEVER WALL

DURING PLACEMENT APRIL 12-18, 1972

	TOTAL UNIT WEIGHT (PCF)		MOISTURE CONTENT (PERCENT)	
	NEXT TO WALL	CENTER OF FILL	NEXT TO WALL	CENTER OF FILL
AVERAGE	91.6	101.3	18.3	21.4
RANGE	78-116	85-122	15 - 23	
NO. SAMPLES	4	5	16	
SAMPLING METHOD — SOIL TEST BALLOON VOLUMETER				

NOVEMBER 1973 (18 MONTHS AFTER CONSTRUCTION)

	TOTAL UNIT WEIGHT (PCF)		MOISTURE CONTENT (PERCENT)	
	1 FOOT FROM WALL	3 FEET FROM WALL	1 FOOT FROM WALL	2 FEET FROM WALL
AVERAGE	101.3	98.9	11.3	10.8
RANGE	99-104	92-110	10-13	9-12
NO. SAMPLES	6	6	6	6
SAMPLING METHOD — DRIVEN SAMPLE TUBE				

NOTE: 1 ft = 0.305 m; 1 pcf = 16.0 kg per m^3

shown in Fig. 3. The four Terra Tec cells were placed in a vertical row to measure pressure distribution behind the wall. The Geonor cells were located adjacent to the upper and lower Terra Tec cells.

Since the wall was constructed prior to installation of the cells it was necessary to cut cavities in the wall to install the pressure cells. The cells were grouted flush with the back of the wall. A thermocouple was installed at each pressure cell location. Connecting cables and wires were secured with a strip of raw tread rubber and a steel box on top of the wall protected the cable ends.

Results of pressure cell calibration revealed that with no pressure applied, the initial zero cell readings vary with temperature. These calibration studies are described in detail in TTI Research Reports No. 169-1 (3) and No. 169-2 (4). Calibration tests were performed at the test site after the wall was instrumented and prior to backfilling. The pressure cell variations over a range of temperatures from 70°F (21°C) to 90°F (32°C) were observed. Temperature correction curves were developed for each cell and these were used to correct measured pressures (4).

<u>Wall Movement</u> -- Wall movement was determined by two measurements. These measurements included lateral translation and offset from a vertical line. The measurement scheme is presented in Fig. 4. Lateral translation was determined by measuring the change in distance from a fixed point on a bridge bent column to a reference point on top of the wall. The change in distance was measured to the nearest 0.0017 ft (0.00051 m) by using a 50 div-per-in. engineer's scale and a 100 ft (30.5 m) steel tape. The steel tape was always pulled with the same tension and a correction was made for variation of tape temperature.

Offset measurements from a vertical reference line were used to determine relative movements of six points aligned in a vertical row. The reference line was established by suspending a plumb-bob from a permanent frame at the top of the wall. Offsets were measured horizontally from the reference line to each of the wall points. Initial offsets were obtained before backfill. Subsequent offset measurements were made at regular intervals. These were subtracted from the initial offset measurements to obtain the movement of each reference point since backfill. These movements will subsequently be referred to as deflections.

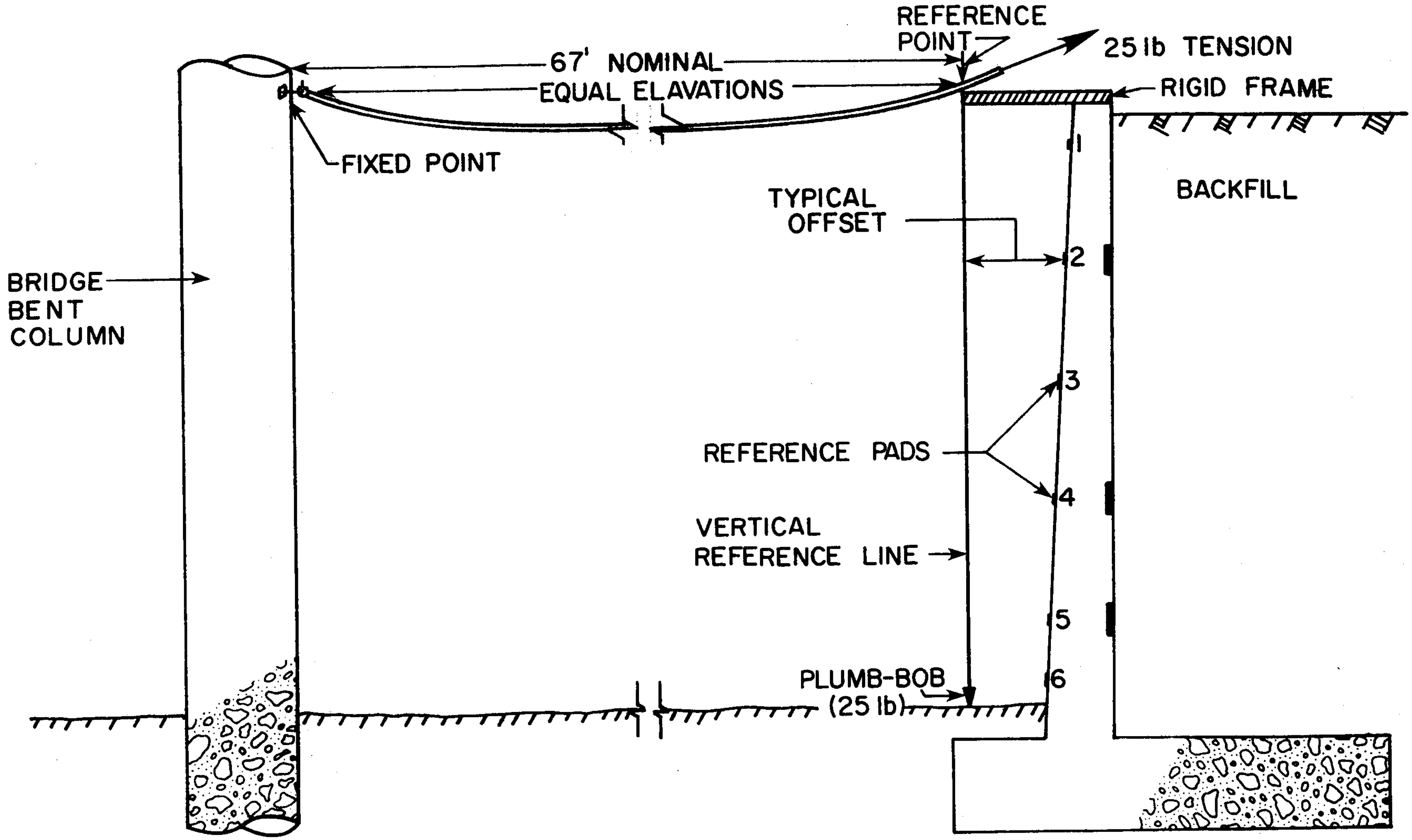


FIG. 4 - MOVEMENT MEASUREMENT SCHEME, CANTILEVER WALL
(1 lb_m = 0.453 kg; 1 lb_f = 4.45 N; 1 ft = 0.305 m)

Data Collection

Pressure Cell Data -- Pressure measurements were made approximately once a month by Texas Transportation Institute technicians. The field data included both cell pressure and temperature from the adjacent thermocouple. A correction was applied for the variation in cell reading with temperature. Corrected pressure measurements are given in Table 3.

Pressure Cell Accuracy -- Sources of measurement error include nonlinearity, hysteresis, read-out resolution, and reading stability with temperature change. Initial calibration indicated that the cell response, i.e., pressure change measured in accordance with pressure applied, was linear within one percent (4). The effect of installation by grouting into a wall was investigated and no effect on pressure cell response was indicated (4). Hysteresis was also found to be negligible. Read-out resolution of the Terra Tec cells was improved by replacing the 250 psi (1730 kN/m^2) gauge on the readout device with a more sensitive 35 psi (242 kN/m^2) gauge. Read-out resolution error was 0.05 psi (0.346 kN/m^2).

Although the cell response was linear, the gauge reading with no pressure applied was not zero. This pressure reading was termed "ZERO OFFSET" and was a function of cell temperature. Both laboratory and field calibration tests were conducted. Laboratory calibration indicated that over the temperature range encountered, 44°F (6.7°C) to 95°F (35°C), zero offset variation for all cells averaged 0.71 psi (4.91 kN/m^2). Field calibration indicated a larger variation, averaging 1.48 psi (10.2 kN/m^2). Thus, the cell readings could vary this amount if not corrected. An important difference between these calibration tests is that the laboratory measurements were made after the cell temperature had stabilized. This was not possible in the field. The field calibration was used for correction of the data presented in this study. The scatter of the field calibration data was small, less than 0.15 psi (1.04 kN/m^2) at any temperature. Based on these calibration tests the estimated maximum error of the pressure cell data with zero offset correction applied was plus or minus 0.5 psi (3.45 kN/m^2).

TABLE 3 - CORRECTED PRESSURE MEASUREMENTS, CANTILEVER WALL

DATE	ELAPSED TIME IN DAYS	PRESSURES, (PSI)					
		TERRA TEC				GEONOR	
		570	580	578	604	1	2
12 Apr. 72	1	0	0	0	0.64	0	0.46
13 Apr. 72	2	0	0	0	1.97	0	1.79
14 Apr. 72	3	0	0	0	1.20	0	1.19
17 Apr. 72	6	0	1.65	4.00	4.55	0	4.23
18 Apr. 72	7	1.74	2.93	6.93	8.05	2.92	7.89
BACKFILLING OPERATION COMPLETED							
20 Apr. 72	9	1.66	2.87	6.65	8.59	2.40	8.27
25 Apr. 72	14	1.10	2.48	6.20	8.49	1.80	8.64
2 May 72	21	1.24	2.54	5.97	8.30	2.64	8.23
10 May 72	29	1.70	2.98	6.78	8.97	2.89	8.71
17 May 72	36	0.40	2.60	6.03	8.20	2.31	8.34
1 Jun. 72	51	1.08	2.27	6.27	8.40	2.40	8.35
15 Jun. 72	65	2.18	2.68	6.56	9.13	3.22	8.35
18 Jul. 72	98	1.42	2.24	6.00	8.35	2.30	8.52
6 Sept.72	148	2.16	2.51	6.43	9.24	2.30	8.52
10 Oct. 72	182	1.70	1.76	6.06	8.60	2.38	8.45
FIVE FEET OF BACKFILL REMOVED							
10 Oct. 72	182	0	1.96	5.86	8.40	0	8.13
19 Oct. 72	191	0	2.56	6.52	9.05	0	8.73
BACKFILL REPLACED							
19 Oct. 72	191	0	2.46	6.42	8.95	0.31	8.69
19 Dec. 72	252	0	1.20	4.50	6.35	0.74	7.70
8 Jan. 73	272	0	0.40	4.30	6.20	0.63	8.12
26 Feb. 73	321	0	2.00	5.40	7.95	0.35	a
5 Apr. 73	359	0	1.65	5.10	8.05	0.43	a
9 May 73	393	0	2.20	6.00	9.40	a	a

a - Gage inoperative

Note: 1 psi = 6.9 KN/m^2

TABLE 3 (Cont.) - CORRECTED PRESSURE MEASUREMENTS, CANTILEVER WALL

DATE	ELAPSED TIME IN DAYS	PRESSURES (PSI)					
		TERRA TEC				GEONOR	
		570	580	578	604	1	2
		SURCHARGE LOAD ADDED					
31 May 73	415	0.35	1.75	5.80	9.30	a	a
15 Aug. 73	491	0.40	1.30	5.50	9.25	a	a
14 Sept.73	521	0.55	1.35	5.70	9.15	a	a
24 Oct. 73	561	0.40	0.85	5.15	7.95	a	a
19 Nov. 73	587	0.40	1.10	5.50	8.15	a	a
13 Dec. 73	611	0.20	0.55	5.15	7.20	a	a
16 Jan. 74	645	0.35	0.60	5.35	7.30	a	a
13 Feb. 74	673	0.30	0.65	5.10	7.15	a	a
20 Mar. 74	708	0.65	1.30	6.25	9.05	a	a
30 Apr. 74	749	0.75	1.50	6.85	10.10	a	a
20 Jun. 74	800	1.15	1.35	7.30	10.90	a	a
16 Jul. 74	826	0.60	0.90	6.30	9.50	a	a
19 Aug. 74	860	0.63	1.20	6.80	10.06	a	a
18 Sept.74	890	0.55	0.50	5.80	8.60	a	a
15 Oct. 74	917	0.70	0.55	5.55	7.85	a	a
13 Nov. 74	946	0.50	0.00	5.20	6.40	a	a
11 Dec. 74	974	0.70	0.00	4.80	5.85	a	a
16 Jan. 75	1040	0.80	0.15	4.80	5.70	a	a
27 Feb. 75	1082	0.65	0.70	6.10	6.80	a	a
27 Mar. 75	1110	0.70	1.10	6.95	7.90	a	a
10 Apr. 75	1124	0.70	0.87	7.00	8.10	a	a
12 May 75	1156	0.76	0.70	7.17	9.22	a	a

Wall Movement Data -- Lateral translation and deflection data are compiled in Table 4. Lateral translation measurements were discontinued after September 1974 because of traffic flow between the drilled shaft and the panel. It should be noted that the lower reference point, number 6, was covered in September 1973 by construction of a concrete drain. Point number 5 was inaccessible due to construction activities after June 1974.

Movement Accuracy -- Accuracy was limited by the restrictions of the test site. Continuous construction required the establishment of the fixed reference point above ground level on the bridge bent column This resulted in possible error in establishing the horizontal movement of the wall. The relatively high flexibility of the wall reduced the accuracy of the offset measurements. The combination of these factors undoubtedly affected the accuracy of the horizontal movement computation. Thus, the long term relationship between horizontal movement and time is of questionable accuracy. The only conclusions that can be drawn concern the amount of movement occurring during backfill because these movements were relatively large. The offsets were measured to 1/32 of an inch (0.079 cm).

Presentation of Results

Pressure Cell Variation with Time -- The pressure cell measurements corrected for temperature are plotted versus time in Fig. 5. Although the backfill operation required six days, the upper three cells were not covered until day 5 and 6. As shown in Fig. 6, cell pressures increased rapidly on day 6 and 7. At the end of backfill the two middle cells, 578 and 580, attained pressures near the maximum measured during the entire study. The upper cell, number 570, reached a pressure within 0.5 psi of its maximum. The lower cell, number 604 was 8.6 psi (59.5 kN/m^2) at the completion of backfill. This value has been exceeded seasonally.

Obvious seasonal variations of cell 604 and cell 578 are shown in Fig. 5. These cell pressures were lower in the winter and reach peak values during the warm months of June, July and August. Sharp drops began in September or October. Lowest readings were recorded

TABLE 4

WALL MOVEMENT DATA, CANTILEVERED DATA

DATE	DAY	LATERAL TRANSLATION (INCHES)	DEFLECTION (1/32 INCH)						REMARKS
			1	2	3	4	5	6	
10 Apr. 72			17-25/32	16-16/32	15-12/32	14-4/32	12-15/32	11-23/32	INITIAL OFFSETS
12 Apr.	0	0	0	0	0	0	0	0	1740 HRS
13 Apr.	1	0.30	4	2	3	2	3	4	1130 HRS
13 Apr.	1	0.19	-1	-1	0	-1	-1	-2	1730 HRS
14 Apr.	2	--	-1	2	2	2	2	2	0735 HRS
14 Apr.	2	0.39	-1	2	3	3	3	2	1100 HRS
17 Apr.	5	--	-1	4	4	4	4	4	0815 HRS
17 Apr.	5	0.41	-1	3	4	4	4	4	1000 HRS
17 Apr.	5	0.25	-1	2	2	1	2	2	1400 HRS
17 Apr.	5	0.20	-1	0	-1	0	0	0	1645 HRS
18 Apr.	6	0.39	0	4	5	6	6	6	0730 HRS
18 Apr.	6	0.41	0	4	5	6	7	7	0940 HRS
18 Apr.	6	0.48	0	4	5	7	8	8	1150 HRS
18 Apr.	6	0.53	0	3	6	7	9	9	1320 HRS
18 Apr.	6	0.61	0	5	8	9	12	12	1530 HRS
20 Apr.	8	0.73	2	8	10	13	15	15	
25 Apr.	13	0.82	0	7	9	13	16	16	
12 May	20	0.78	—	—	—	—	—	—	NO READINGS MADE DUE TO MUDDY SITE CONDITIONS

TABLE 4 (Cont.) - WALL MOVEMENT DATA, CANTILEVERED DATA

DATE	DAY	LATERAL TRANSLATION (INCHES)	1	2	3	4	5	6	REMARKS
10 May	28	0.90	0	7	11	14	17	18	
17 May	35	--	-1	6	10	13	16	17	
1 Jun.	50	--	0	7	12	15	17	18	
15 Jun.	64	--	-	-	-	-	-	-	NO READINGS MADE DUE TO MUDDY SITE CONDITIONS
18 Jul.	97	0.92	3	8	11	15	17	17	
6 Sep.	147	0.91	1	10	14	15	18	18	
10 Oct.	181	0.91	0	8	12	15	17	17	1145 HRS
10 Oct.	181	0.88	1	7	11	15	17	18	1430 HRS
11 Oct.	182	0.94	0	8	12	15	17	18	
19 Oct.	190	0.89	0	7	12	15	17	18	1115 HRS
19 Oct.	190	0.89	0	8	11	15	17	18	1240 HRS
19 Dec.	251	0.81	6	11	14	13	16	19	
8 Jan. 73	271	0.81	1	7	11	15	17	18	
26 Feb.	320	0.87	0	6	11	14	16	17	
5 Apr.	358	0.78	0	7	11	14	17	18	
9 May	392	0.88	1	7	12	15	18	19	
31 May	415	0.98	-	9	14	17	21	22	
15 Aug.	491	0.95	-	10	15	19	23	23	
14 Sep.	521	0.94	1	9	14	18	22	22	

TABLE 4 (Cont.) - WALL MOVEMENT DATA, CANTILEVERED DATA

DATE	DAY	LATERAL TRANSLATION (INCHES)	1	2	3	4	5	6	REMARKS
24 Oct.	561	0.91	1	9	14	18	21	-	
19 Nov.	587	0.95	1	9	14	18	21	-	
13 Dec.	611	0.95	0	8	13	17	21	-	
16 Jan.	645	0.95	0	8	14	18	21	-	
13 Feb.	673	0.96	0	8	13	17	20	-	
20 Mar.	708	0.82	1	9	15	19	23	-	
30 Apr.	749	0.76	1	10	15	19	-	-	
11 Jun.	791	0.83	3	11	17	23	25	-	
20 Jun.	800	0.73	3	11	17	21	25	-	
16 Jul.	826	0.74	2	10	16	20	-	-	
19 Aug.	860	0.70	1	10	14	20	-	-	
18 Sep.	890	0.74	1	9	14	19	-	-	
15 Oct.	917	--	1	9	14	19	-	-	
13 Nov.	946	--	1	8	14	19	-	-	
11 Dec.	974	--	1	9	14	19	-	-	

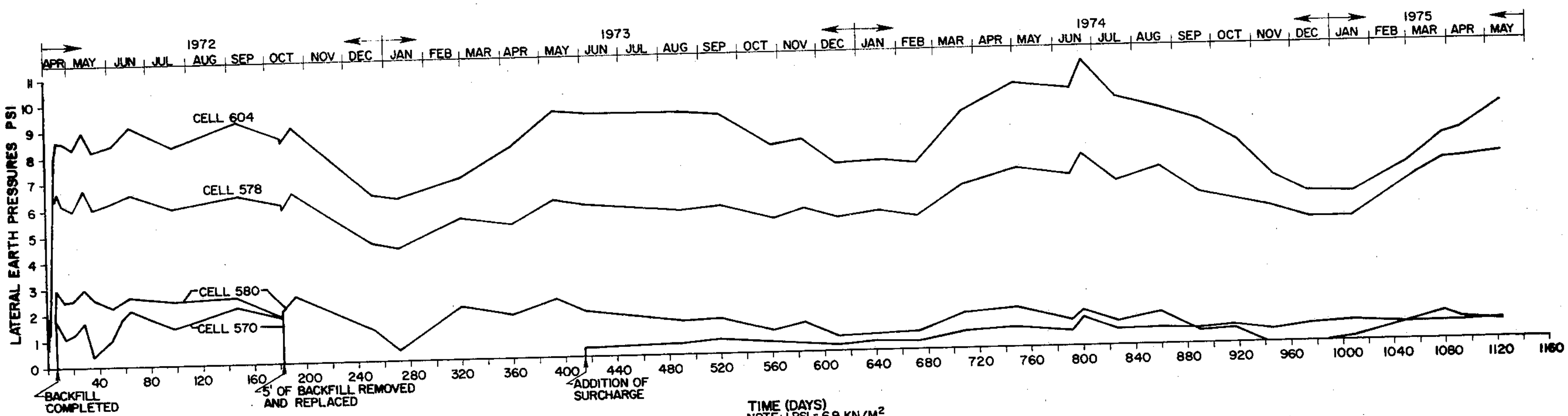


Fig. 5 MEASURED LATERAL EARTH PRESSURES FOR TEST CANTILEVER WALL G

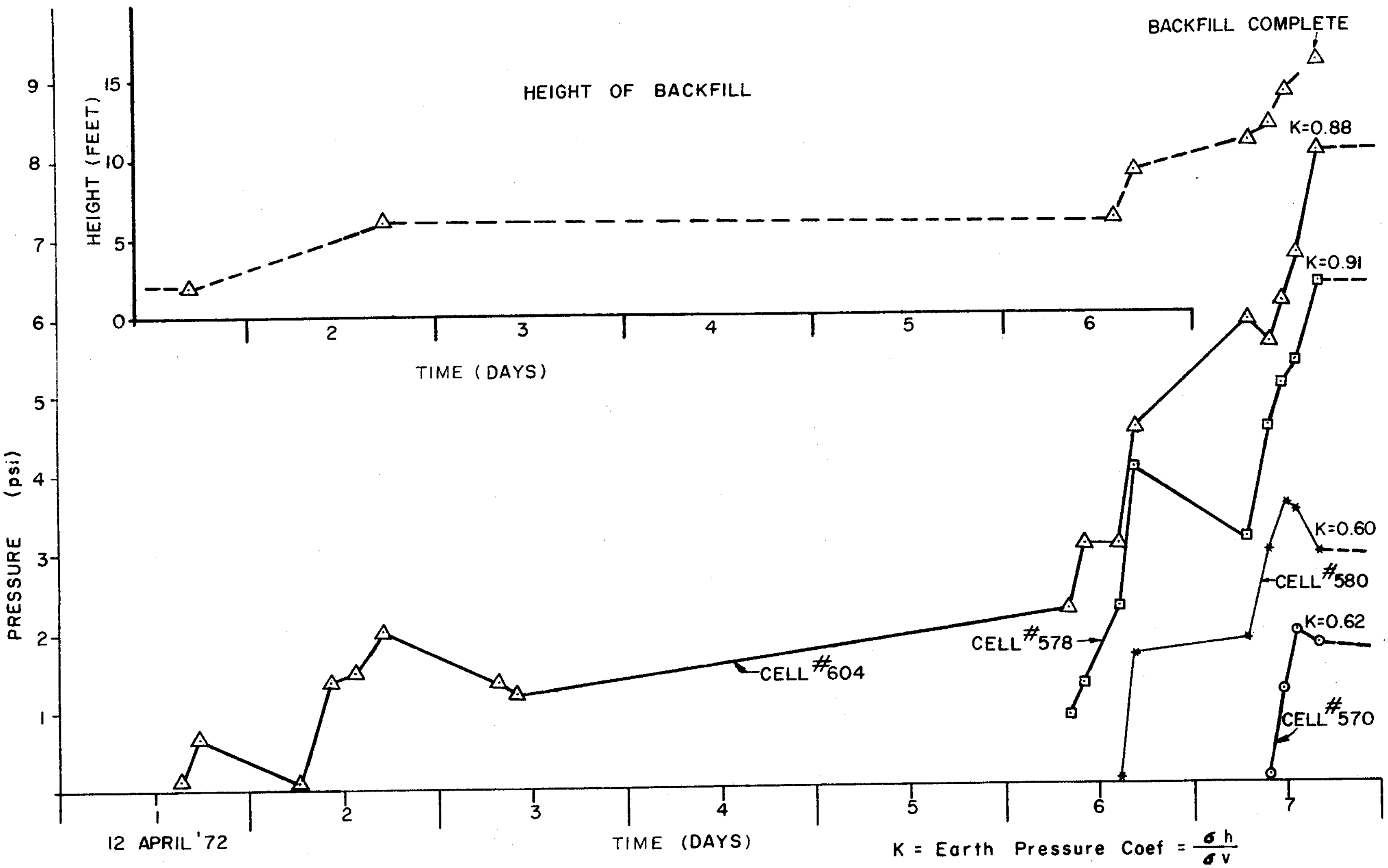


FIG. 6 - PRESSURE CELL CHANGES DURING BACKFILL (1 psi = 6.9 kN/m²)

in December or January, and recovery occurred in early spring. The range of the seasonal variation of cell 604 was approximately 3.5 psi (24.2 kN/m^2) which corresponds to 40 percent of the mean pressure. The mean pressure is about that established at the end of the backfill.

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

Wall Movement with Time -- As mentioned previously, the wall movement instrumentation system was limited by the physical constraints of the site. The movement associated with each cell is not precisely known. Analyses of these data were limited to characterizing and quantifying the movements.

The movement data for each day have been resolved into tilt and lateral translation. Tilt was computed directly from the deflection data for each of the four middle measurement points on the wall. Tilt was expressed as the ratio of deflection (d) divided by height from the base to measuring point (h). The four ratios were averaged and are plotted on Fig. 7. The upper point on the wall, number 1, was omitted because of data scatter due to the flexibility of wall at the tapered end. The lower point, number 6, was omitted because as noted previously, this point was covered about 500 days after backfill. After day 800, point number 5 was unreadable due to construction. Loss of point number 5 reduced the number of points averaged to three. As a result, accuracy was lost and the computation was discontinued after day 800.

The following observations concerning tilt are made: (See Fig. 7)

1. Seventy to eighty percent of the tilt occurred during backfill.
2. A least square fit of the data from after backfill to day 800 reveals a continuing small increase in tilt.
3. A slight cyclic trend roughly corresponding to seasonal pressure variations is evident.

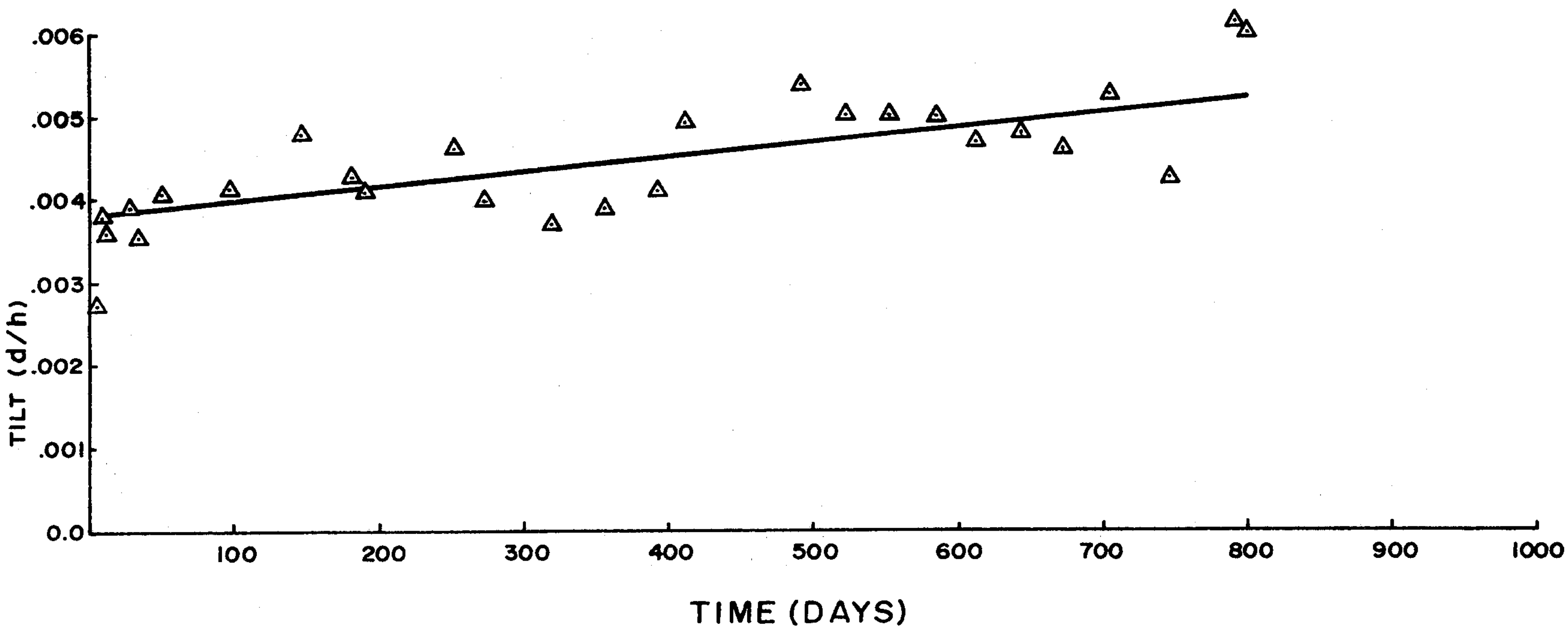


FIG. 7 - WALL TILT , CANTILEVER WALL

Tilt computations are limited to the indication of trends and the approximation of the magnitude of tilting. The accuracy of this computation is estimated to be 0.001 $\frac{d}{H}$.

Typical displacements of the wall are pictured in Fig. 8. The large deflections and horizontal movements during backfill as well as the high flexibility near the top of the wall are quite evident.

Lateral Force and Moment Changes -- Lateral force per unit length of wall and corresponding moment were calculated from the pressure cell data. These calculations are plotted as a function of time in Fig. 9. The method of computation is similar to that shown for the panel wall in Appendix IV. The lateral force data reflect the cyclic variations in the pressure cell readings. The moment data have less seasonal change. This results from a reduction in moment arm when lower cell pressures are high. Since the lower cells exhibit a large seasonal change, the center of pressure for the wall is usually reduced when these pressures are highest.

Lateral force and moment were also computed using an equivalent fluid pressure of 40 lb/ft^3 (641 kg/m^3) and the Rankine active earth pressure. The equivalent fluid pressure is presently used by the Texas Highway Department. The lateral forces and corresponding moments for both the equivalent fluid pressure and Rankine active earth pressure are plotted in Fig. 9. The measured lateral force was at times twice the fluid pressure design value. The design value was more comparable for moments but usually lower than the measured. Forces and moments increased rapidly at the completion of backfill. Except for moderate reductions during winter months, lateral force remained near the level reached at the end of backfill. The overturning moment tended to decrease with time. Thus for this wall, the lateral forces and moments computed from the pressures acting at the end of backfill are approximately equal to maximum lateral force and overturning moments that have existed.

Analysis of Results

Earth Pressures After Backfill -- The saturated condition of the fill and the lack of compaction near the wall resulted in a zone

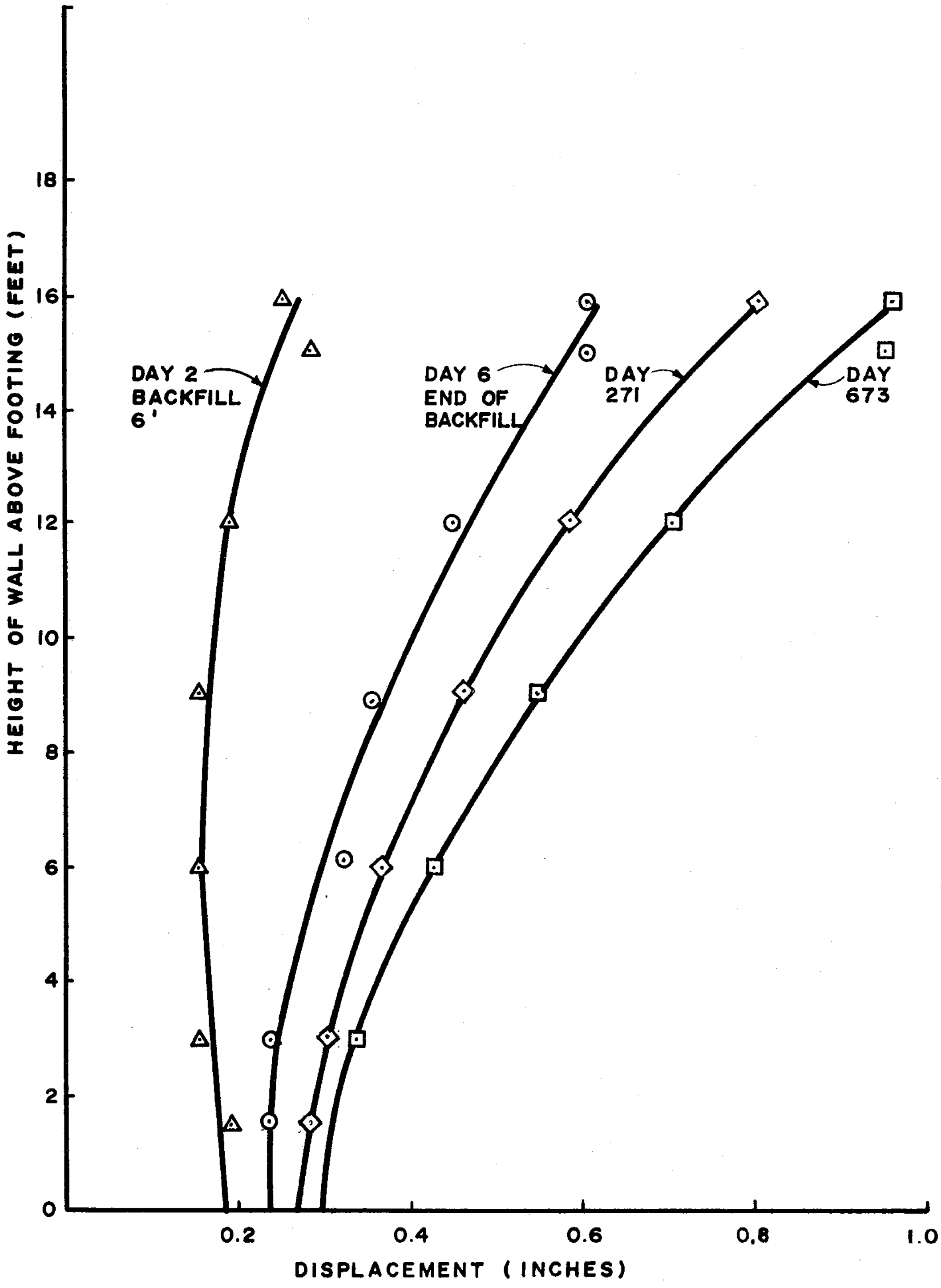


FIG. 8 - TYPICAL DISPLACEMENTS, CANTILEVER WALL.
(1ft. = 0.305m, 1in. = 25.4mm)

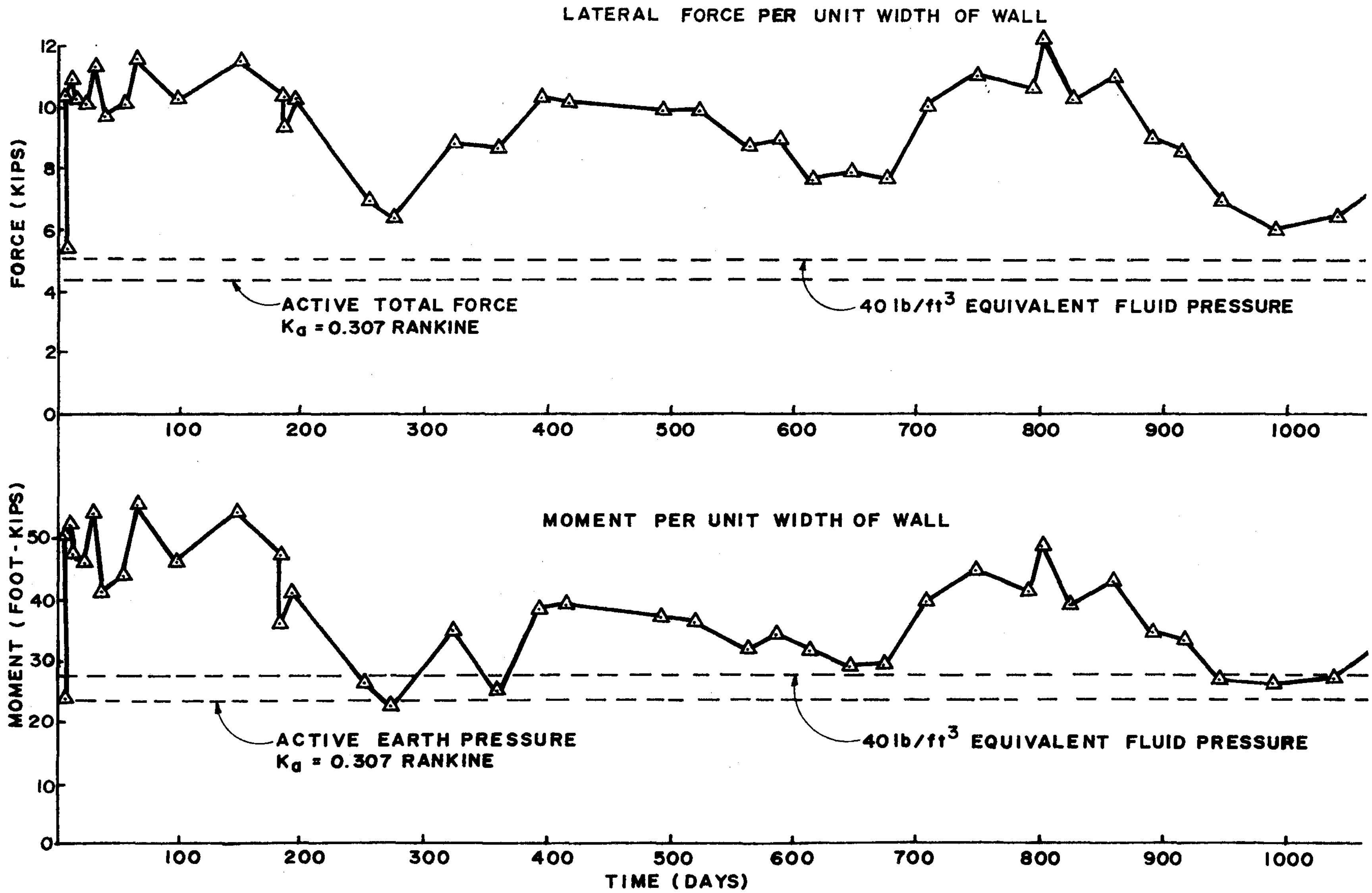


FIG. 9 - FORCES AND MOMENTS, CANTILEVER WALL.
(1 kip = 4.45 kN; 1 ft = 0.305 m; 1 psf = 47.9 N/m^2)

of loose soil along the wall. The average total unit weight of 101.3 pcf (1623 kg/m^3) when compared with typical unit weights of fine sands (6) indicated that the state of density was loose to medium.

The coefficients of earth pressure at rest, K_0, at the end of backfill were computed and are shown in Table 5. Terzaghi and Peck (12) have pointed out that if the backfilling involves no artificial compaction by tamping the value of K_0 ranges from about 0.40 for dense sand to 0.50 for loose sand.

TABLE 5. EARTH PRESSURE COEFFICIENTS AT THE END OF BACKFILL

CELL NUMBER	DEPTH (FEET)	$K_0 = \sigma_h / \sigma_v$ (γ_m=101.3 PCF) 1623 kg/m^3
570	4'(1.22 m)	0.62
580	7'(2.14 m)	0.60
578	10'(3.05 m)	0.91
604	13'(3.96 m)	0.88

They suggest that tamping in layers may increase K_0 to about 0.8. K_0 for the lower two cells, numbers 578 and 604 are somewhat higher than 0.80. The soil at this level of backfill was allowed to drain between day 2 and 6 and was probably denser than at cells 580 and 570 where the measured K_0 was slightly lower than 0.80.

Terzaghi (9) has pointed out that at the end of construction the coefficient of lateral earth pressure depends on the relative density of backfill material, method of compaction and wall movements during backfill. As stated previously, the measurement scheme used in this study was not sufficiently accurate to allow correlation of individual pressure cell readings with movements. Movement occurred as the backfill was being placed. The backfill material was saturated when placed. As a result the compacted soil had a soft, plastic consistency, and could have moved with the wall as compaction continued. Movements slowed abruptly when the backfill was completed.

Earth Pressure Changes After Backfill -- The seasonal variations in pressure readings probably result from temperature changes in the backfill. As shown in Fig. 10, these variations correlate with the seasonal changes in temperature. Pressure cell calibration

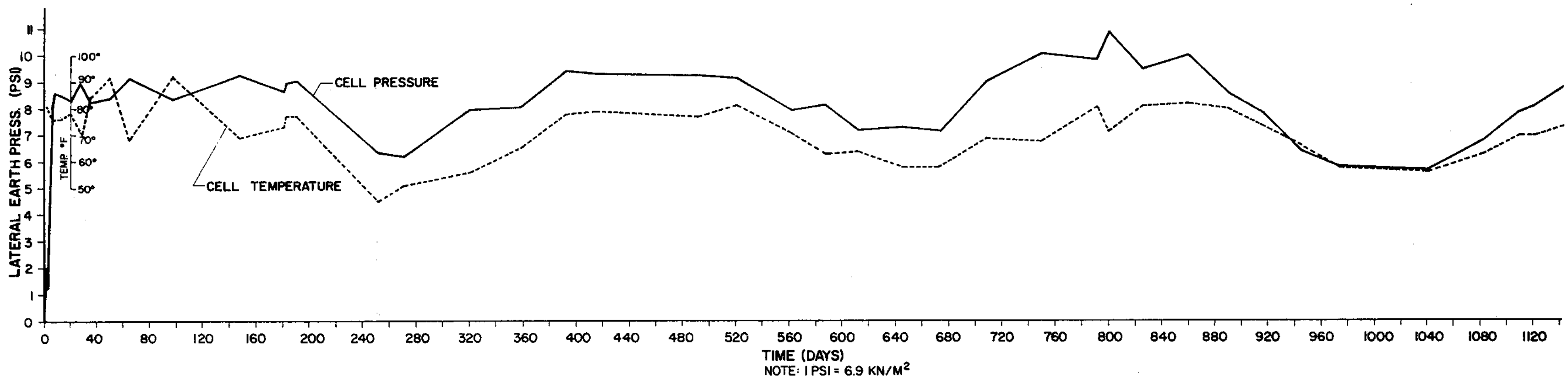


FIG. 10—TEMPERATURE AND PRESSURE RELATIONSHIP CELL 604, CANTILEVER WALL

tests indicated that the variations are not the result of instrument error. Field tests before backfill and laboratory tests with and without pressure applied indicate that over the temperature range encountered the cell variation is only about one-half pound per square inch. Seasonal variations of cell 604 were much greater, averaging 3.5 psi (24.2 kN/m^2). Pore water pressure build up was not likely because the cells were located above weep holes at the base. The weep holes have been observed draining frequently. Also maximum pressures occurred during the summer months when rainfall was lowest.

Wall Movements After Backfill -- The wall tilt calculations are considered reliable up to day 800. Wall tilt increased about 0.0015 d/h as shown in Fig. 7, between backfill and day 800. This corresponds to 0.29 inches (0.74 cm) of movement at the top. Horizontal movement at the top was estimated directly from translation measurements. This estimated movement, 0.33 inches (0.84 cm), corresponded to a tilt of 0.0017 $\frac{d}{h}$. Thus there was good agreement with the tilt computed from offset measurements. The horizontal position of the base was assumed unchanged since backfill.

Comparison of Wall Movements and Pressures -- In the introduction it was pointed out that the state of stress of the sand behind the cantilever retaining wall corresponded to the deformation conditions for active Rankine state. The wall tilt required to obtain the Rankine pressure distribution was determined by Terzaghi (10) to be 0.005 times the wall height. For movements less than this the coefficient of earth pressure lies between the at rest coefficient, K_o, and the active coefficient, K_a. The pressure distribution for an interim state is unknown, but depends on the wall movements.

The measured wall movement of approximately 0.3 inches (.76 cm) at the top of the wall was not sufficient to obtain the Rankine active pressure distribution over the entire height of the wall. However, pressure reductions to the active Rankine values have occurred in the upper cells. These pressure reductions probably resulted from movements associated with the higher flexibility of the wall in that region. The lower two cells are showing seasonal variations but on the average are maintaining at rest pressures.

PRECAST PANEL RETAINING WALL

Test Wall

Wall Description -- The test site for this wall 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 panel selected for instrumentation is part of the southwest wall.

The design of these retaining walls is different from the cantilever wall design. The wall was founded on a series of drilled shafts placed at regular intervals. Footings were constructed on the drilled shafts and T-shaped pilasters were formed on the footings. Pre-cast panels were then placed between the pilasters. The panels rested on neoprenebearing 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 (91.4 cm) in diameter, 20 ft (6.1 m) deep, and were spaced at 12 ft (3.66 m) intervals. The wall was 10 ft (3.05 m) high and the footings were 3 ft 2 in. (96.5 cm) square and 16 in. (40.6 cm) high. Figs. 11 and 12 show the retaining wall and its construction elements.

There are several items of interest shown in Figs. 11 and 12 which should be noted. Fill was placed against the front of all walls except the instrumented panel to a height of three feet. A timber barrier was placed against the pilasters retaining the instrumented panel. This prevented the development of earth pressure on the front face of the instrumented panel. All panels except the instrumented one were grouted to the pilasters. A concrete gutter was placed on the backfill behind the wall. Two months after completion of the sand backfill a clay surcharge was placed above the sand. The clay surcharge was placed at a 3 to 1 slope and varied in thickness from 6 in. (15.2 cm) near the wall to 30 in (76.2 cm) near the top at the embankment. A drain for the backfill was placed directly behind the lower row of pressure cells.

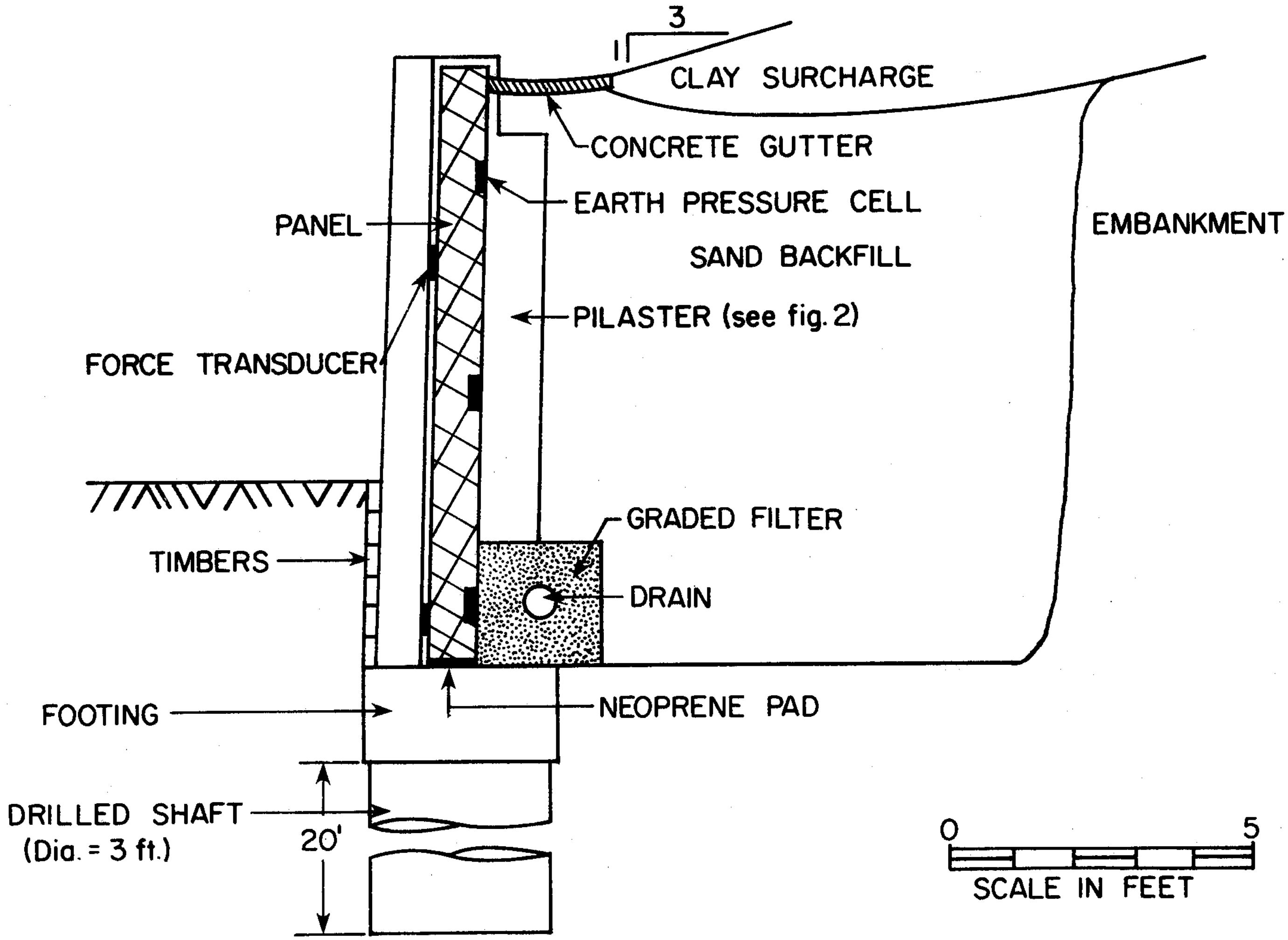


FIG. 11 - CROSS SECTION OF PANEL WALL
(1 ft = 0.305 m)

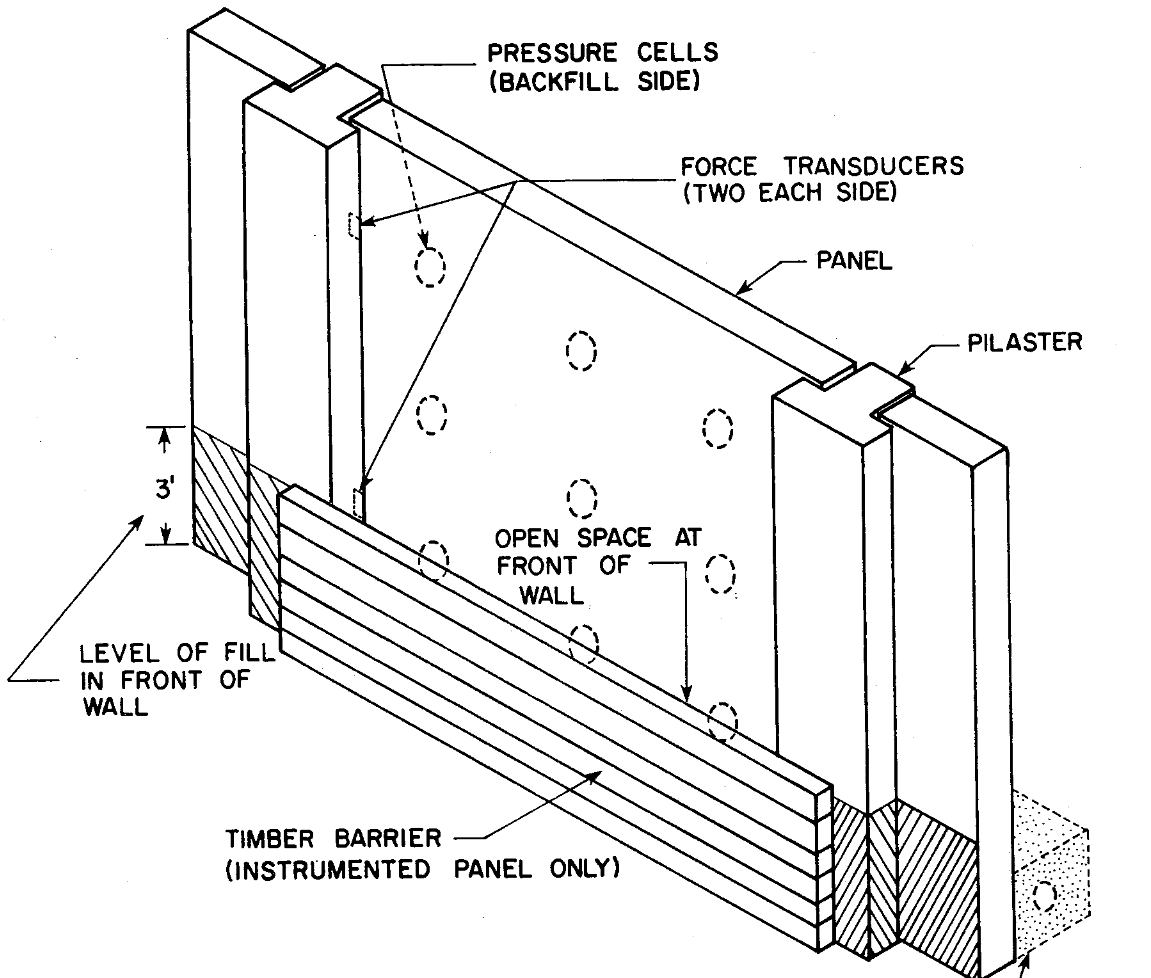


FIG. 12 – FRONT VIEW OF PANEL WALL
(1 ft = 0.305 m)

The instrumented panel was supported at six points. Vertical support was provided by the footings through the neoprene pads. The neoprene pads measured 5 x 10 inches (12.7 x 25.4 cm) and were 3/8 inch (.95 cm) thick. Lateral support was provided at four points on the front face of the panel. Two force transducers were installed between the pilasters and the panel on each side. The location of the force transducers and the neoprene pads is shown in Figs. 13 and 14.

Backfilling Procedure -- The backfill was compacted in six-inch lifts using vibratory rollers. Moisture content and unit weight were carefully controlled and each lift was carefully compacted near the wall. The sand drain was installed after the backfill was approximately two feet high. A two-foot wide strip of backfill was removed and a six inch perforated drain pipe running the length of the wall was placed in the trench. The drain pipe was surrounded with lightly compacted coarse sand. After the installation of the sand drain was completed the backfilling was continued. Backfilling was begun April 4, 1973 and the last cell was covered on April 13, 1973.

Properties of the Backfill Material -- The backfill material was a uniformly graded fine sand. Atterberg Limits plotted below the A-line on the Unified plasticity charts. A classification of SP-SM was established based on the Unified classification system. The results of grain size analysis are shown in Table 6.

TABLE 6 - SIEVE ANALYSIS OF BACKFILL MATERIAL, PANEL WALL

SIEVE NUMBER	PERCENT PASSING
4	100
10	99.7
20	99.0
40	96.9
80	26.9
200	8.2

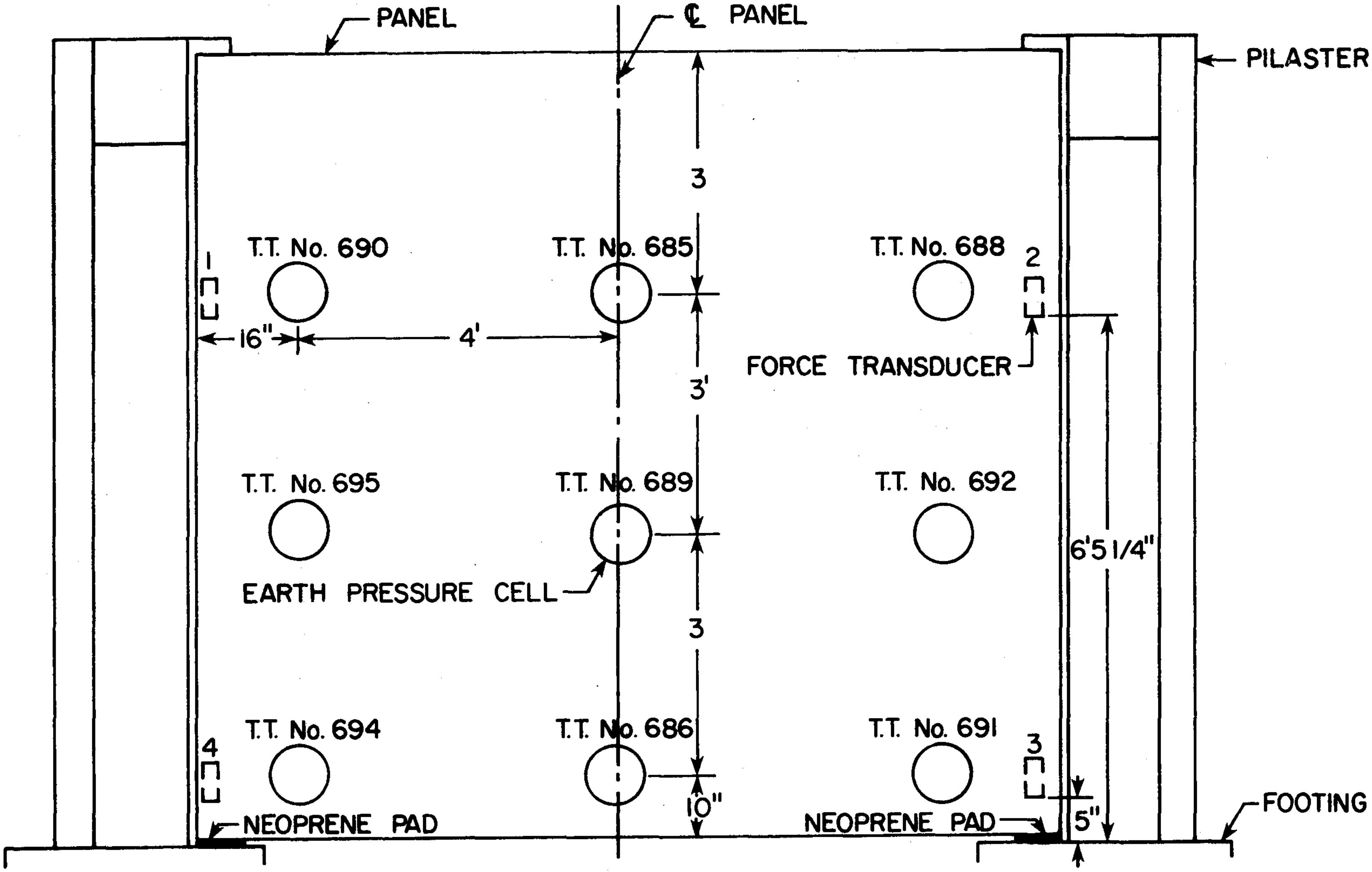


FIG. 13—LOCATION OF EARTH PRESSURE CELLS AND FORCE TRANSDUCERS, PANEL WALL
(1 ft = 0.305 m, 1 in = 25.4 mm)

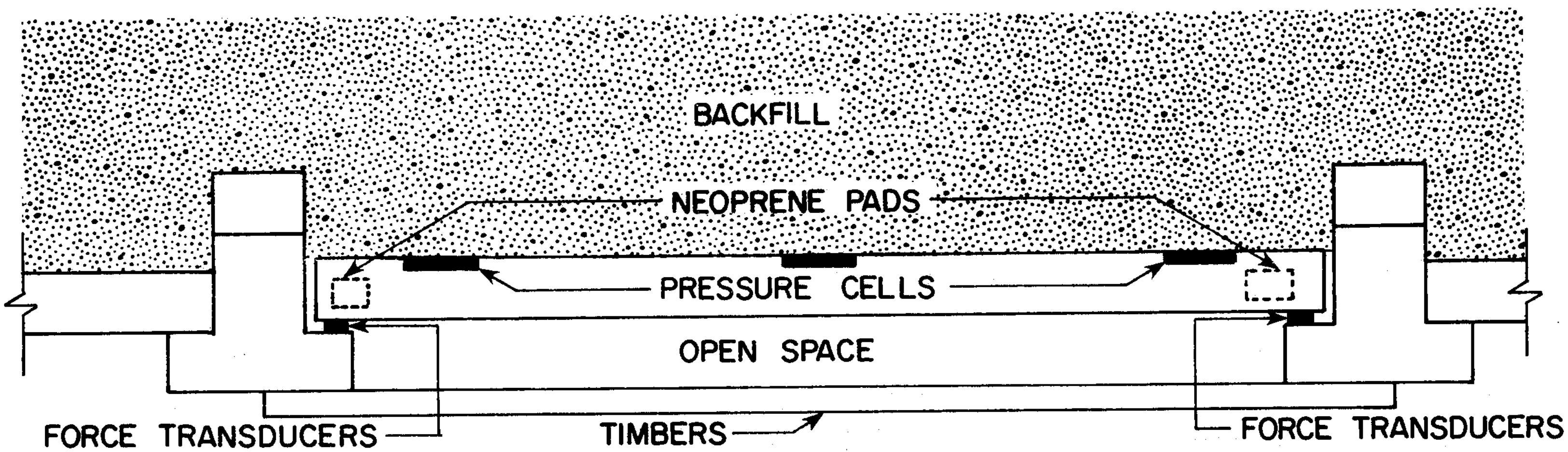


FIG. 14 - TOP VIEW OF PANEL WALL

Texas Highway Department personnel measured the unit weight of the sand backfill material during compaction. The compacted dry unit weight was 95 pcf (1522 kg/m^3). The moisture content was 10% and the total unit weight was 105 pcf (1682 kg/m^3). An effective angle of internal friction of 32^o was measured by direct shear test.

Properties of the Clay Surcharge -- As mentioned previously a 3:1 clay slope was placed on the sand backfill between day 36 and day 58. The average total unit weight of this material was 122 pcf (1954 Kg/m^3). Compaction was at a dry unit weight of 106 pcf (1698 Kg/m^3) and a moisture content of 15%.

Instrumentation

Pressure Cells and Force Transducers -- Lateral earth forces acting on the panel were measured by two methods. Nine Terra Tec pressure cells were provided to measure the lateral earth pressures on the back of the panel. The cells were placed symmetrically in three rows as shown in Fig. 13. The second measurement method used force transducers located between the panel and the supporting pilasters. The locations of the force transducers are also shown in Fig. 13. The transducers measure the force transmitted by the panel to the supporting pilasters.

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

Terra Tec cell calibration studies had shown that with no applied load the pressure readings varied with temperature. These studies are described in greater detail in TTI Research Reports Numbers 169-1 and 169-3 (7). Additional calibration tests were performed after instrumentation, and prior to backfilling. The gage readings with no force applied were recorded over a temperature range of 45^{o}F (7^{o}C) to 74^{o}F (23^{o}C). A temperature correction curve for each cell and transducer was developed from these data.

Wall Movement -- Wall movement was determined by two measurements, lateral translation and offset from a vertical line. The measurement scheme is diagrammed in Fig. 15 and was similar to that used for the cantilever wall. Only movements along a vertical line midway between the pilasters were measured.

Lateral translation was determined by measuring the distance from a fixed point on top of the curb to the reference point on the wall. This point was a small hook attached to the wall at ground level seven feet below the top of the wall. This distance was measured with a steel tape. A constant 25 lb. tension was held.

Offset measurements from a vertical reference line allowed the determination of the relative movements of seven points aligned in a vertical row at one foot intervals. The reference line was established by suspending a plumb-bob from a permanent frame at the top of the wall. Offsets were measured horizontally from the reference line to each of the wall points. Initial offsets were measured before backfill. These initial measurements were subtracted from subsequent offset measurements to obtain the wall movement since backfill. These movements will subsequently be referred to as "deflections".

Data Collection

Pressure Cell Data -- Cell pressure and temperature measurements were taken on a regular monthly basis during the course of this study. A correction for zero-offset with temperature was made. Corrected measured pressures are given in Table 7. The accuracy of the Terra Tec cells has been discussed previously. Based on calibration test resolution accuracy of these cells installed in the panel wall was estimated to be plus or minus 0.5 psi (3.45 kN/m^2).

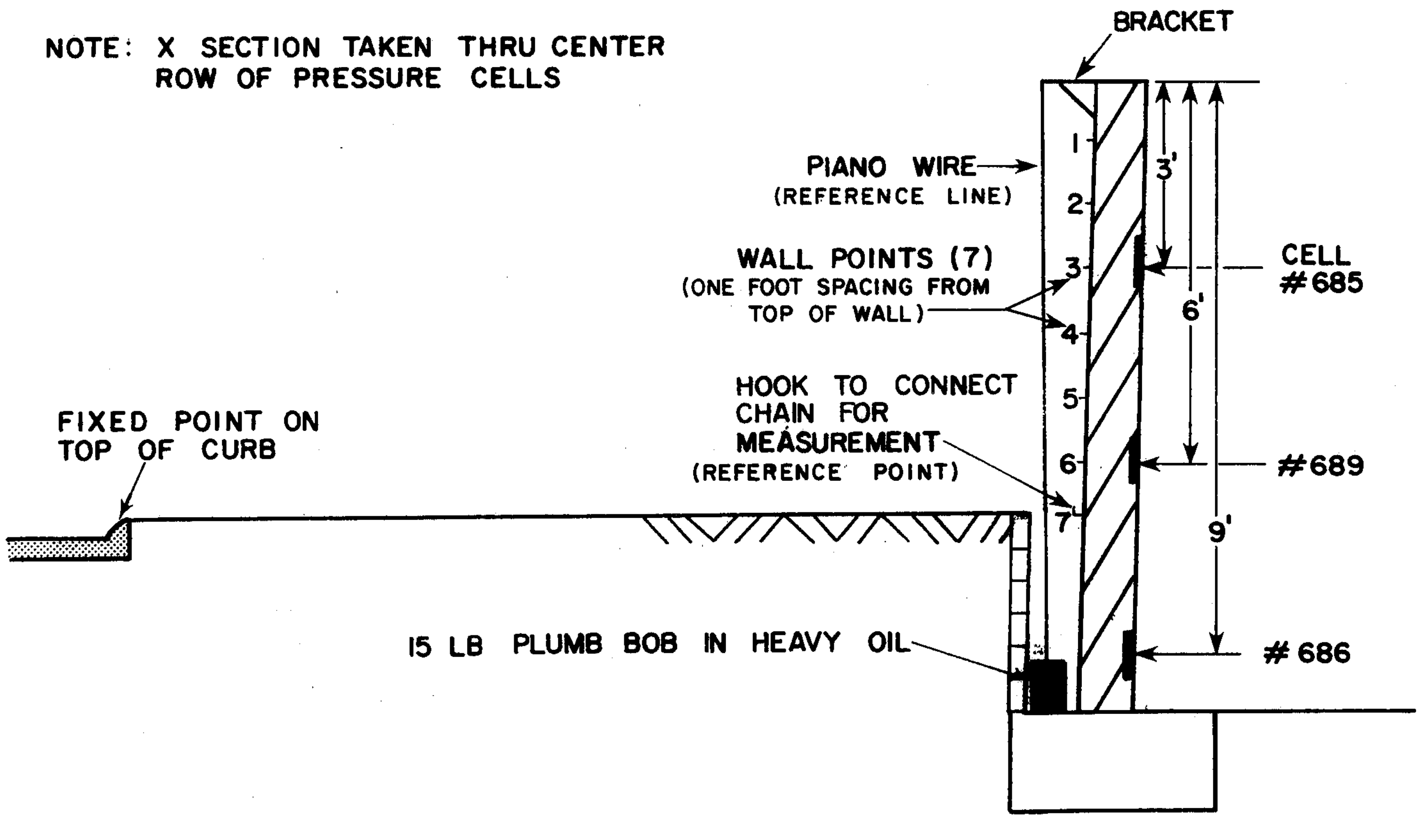


FIG. 15— MOVEMENT MEASUREMENT SCHEME, PANEL WALL
(1 lb_m = 0.453 kg; 1 ft = 0.305 m)

TABLE 7 - CORRECTED PRESSURE MEASUREMENTS, PANEL WALLS (PSI)

Date	Elapsed Time (Days)	Cell Number			Cell Number			Cell Number		
		690	685	688	695	689	692	694	686	691
4 Apr. 1973	1	0	0	0	0	0	0	0.95	1.65	0.80
5 Apr.	2	0	0	0	0	0	0	1.10	1.30	0.80
6 Apr.	3	0	0	0	0	0	0	0.70	1.50	0.88
12 Apr.	9	0	0	0	0.40	0.25	0.25	1.75	1.60	1.55
13 Apr.	10	0.95	0.55	0.40	1.30	0.70	0.75	2.65	0.95	3.55
19 Apr.	16	0.35	2.65	0.20	0.20	0.85	0.25	5.35	1.80	6.15
24 Apr.	21	0.75	2.70	0.45	0.15	0.25	0.15	5.85	1.55	6.75
27 Apr.	24	0.30	1.95	0.20	0.30	0.75	0.15	5.55	2.25	5.05
2 May	29	0.45	1.75	0.25	0.25	0.30	0.25	6.25	2.15	5.70
11 May	38	0.60	3.25	0.70	0.55	0.65	0.45	9.25	2.60	7.50
31 May	58	0.50	2.75	0.30	0.85	1.10	0.45	10.05	3.15	5.85
7 Jun.	65	0.30	1.65	0.25	0.75	0.80	0.25	10.25	3.25	5.80
5 Jul.	93	0.50	2.40	0.30	0.95	1.05	0.40	10.30	3.20	5.05
15 Aug.	134	0.30	2.15	0.45	0.50	0.20	0.10	9.95	2.95	4.85
14 Sept.	164	0.15	2.45	0.30	0.90	0.80	0.20	9.80	3.05	4.05
24 Oct.	204	0.00	2.20	0.10	0.75	1.10	0.00	8.90	2.85	2.85
19 Nov.	230	0.10	1.75	0.35	0.55	0.45	0.00	8.95	2.65	2.95
13 Dec.	254	0.00	1.40	0.05	0.44	0.30	0.00	7.80	2.55	2.20
16 Jan. 1974	288	0.00	1.90	0.40	0.30	0.70	0.00	7.45	2.45	1.75
13 Feb.	316	0.00	2.10	0.15	0.55	1.05	0.00	7.10	2.65	1.30
20 Mar.	361	0.10	2.70	0.45	1.10	1.40	0.05	8.60	2.90	1.35

NOTE: 1 psi = 6.9 kN/m^2

TABLE 7 (CONT.) - CORRECTED PRESSURE MEASUREMENTS, PANEL WALL (PSI)

Date	Elapsed Time (Days)	Cell Number			Cell Number			Cell Number		
		690	685	688	695	689	692	694	686	691
30 Apr.	392	0.30	2.15	0.30	1.25	0.85	0.00	9.25	2.95	1.45
11 Jun.	434	0.10	2.65	0.10	0.60	1.00	0.00	9.30	2.95	1.40
20 Jun.	443	0.85	3.55	0.50	1.45	2.25	0.40	9.35	2.55	1.05
16 Jul.	469	0.00	1.70	0.15	0.65	0.75	0.00	10.45	3.20	1.50
19 Aug.	503	0.00	1.90	0.15	0.95	0.95	0.00	10.70	3.45	1.50
18 Sep.	533	0.57	1.15	0.80	0.35	0.20	0.00	10.57	2.92	1.79
15 Oct.	560	0.00	0.65	0.00	0.10	1.05	0.00	8.77	3.25	0.85
13 Nov.	589	0.00	0.70	0.05	0.00	0.10	0.00	8.35	2.80	0.95
11 Dec.	617	0.00	0.50	0.05	0.00	0.00	0.00	7.50	2.60	0.90
16 Jan. 1975	653	0.00	0.90	0.30	0.00	0.10	0.00	7.40	2.67	0.93
27 Feb.	695	0.00	2.25	0.50	0.15	1.05	0.00	7.55	3.20	0.75
27 Mar.	723	0.00	2.70	0.50	0.40	1.30	0.00	8.45	3.25	0.80
10 Apr.	737	0.10	2.75	0.65	0.35	1.20	0.00	8.58	3.20	0.80
12 May	769	0.10	2.65	0.50	0.20	1.55	0.00	9.42	3.50	0.88

1 psi = 6.9 k^N/m^2

Force Transducer Data -- Force transducer measurements corrected for variations with temperature are tabulated in Table 8. Calibration of the force transducers revealed negligible errors due to non-linearity, hysteresis, and read-out resolution. The zero force reading versus temperature relationship was established in a manner similar to that used for the earth pressure cells.

The force was calculated by correcting the field reading for temperature. This difference was then multiplied by the transducer's calibration factor to obtain the actual force indicated by the transducer. Calibration tests (7) indicated that the force transducer accuracy was plus or minus 0.10 kips (44.5 N).

Wall Movement Data -- Lateral translation and deflection data are compiled in Table 9 and the measurement scheme is shown in Fig. 15. Lateral translations were adjusted to show differential movement since backfill. Lateral translation was measured to point 7 which is at ground level. The base of the wall is three feet below point 7 and was not measured directly. Offsets measured before backfill were subtracted from subsequent measurements to obtain deflections since backfill.

Movement Measurement Accuracy -- Although construction was a factor in the instrumentation set-up no interferences occurred during the panel wall program. The fixed reference point was close to the panel wall and the panel was more rigid than the cantilever wall. For these reasons the panel wall measurements were more reliable than those made on the cantilever wall.

Presentation of Results

Pressure Cell Variation with Time -- All of the pressure cell measurements corrected for temperature are presented in Fig. 16. The cells were grouped into vertical rows. This arrangement illustrates the pressure distribution on the left, center and right portions of the wall.

Cells located near the pilasters exhibit similar pressure increases

TABLE 8 - MEASURED FORCES, PANEL WALL

DATE	ELAPSED TIME (DAYS)	FORCES (KIPS) TRANSDUCER NUMBER 1	2	3	4	TOTAL FORCE
4 Apr. 1973	1	0.01	0.03	0.35	0.78	1.17
5 Apr.	2	0.01	0.03	0.47	0.88	1.39
6 Apr.	3	0.01	0.03	1.08	1.46	2.58
12 Apr.	9	0.01	0.11	1.97	2.42	4.51
13 Apr.	10	0.02	2.76	2.26	4.10	9.14
19 Apr.	16	0.02	4.82	1.69	5.11	11.83
24 Apr.	21	0.18	4.54	1.69	4.98	11.39
27 Apr.	24	0.24	4.56	2.16	5.81	12.77
2 May	29	0.24	4.26	1.93	5.47	11.90
11 May	38	1.02	6.42	2.92	7.99	18.35
31 May	58	1.04	5.89	3.34	9.10	19.37
7 Jun.	65	1.01	5.64	3.42	9.02	19.09
5 Jul.	93	1.13	5.90	3.76	9.26	20.05
15 Aug.	134	1.53	5.90	3.84	8.91	20.18
14 Sept.	164	1.80	6.52	4.30	9.84	22.46
24 Oct.	204	1.61	6.28	3.95	9.30	21.14
19 Nov.	230	1.40	5.96	3.46	8.54	19.36
13 Dec.	254	1.10	5.63	3.31	8.11	18.15
16 Jan. 1974	288	1.59	5.79	3.11	7.31	17.80
13 Feb.	316	1.78	6.30	3.34	7.81	19.23
20 Mar.	351	1.99	6.92	3.58	8.56	21.05
30 Apr.	392	1.92	6.69	3.07	8.86	20.54
11 Jun.	434	1.98	6.92	3.74	9.20	21.84
20 Jun.	443	2.04	7.58	3.88	9.42	22.93

1 KIP = 4.45kN

TABLE 8 (cont.) - MEASURED FORCE, PANEL WALL

		FORCES (KIPS)				
DATE	ELAPSED TIME (DAYS)	TRANSDUCER NUMBER				TOTAL FORCE
		1	2	3	4	
16 Jul '74	469	1.56	6.27	3.71	9.24	20.78
19 Aug.	503	1.61	6.36	3.89	9.68	21.54
18 Sep.	533	1.07	5.93	3.06	8.09	18.14
15 Oct.	560	1.19	5.50	3.88	9.30	19.86
13 Nov.	589	1.06	5.24	3.13	7.88	17.31
11 Dec.	617	0.96	5.02	2.96	6.72	15.67
16 Jan. '75	653	1.27	5.26	2.88	7.05	16.46
27 Feb.	695	1.51	6.26	3.28	7.83	18.88
27 Mar.	723	0.97	5.29	2.34	7.07	15.68
10 Apr.	737	2.06	6.27	3.48	8.16	19.98
12 May	769	2.24	6.83	3.87	9.15	22.09

TABLE 9 - WALL MOVEMENT DATA, PANEL WALL (1 inch = 2.54 cm)

DATE	DAY	LATERAL TRANSLATION (INCHES)	DEFLECTION (1/ 32 inch) 1	2	3	4	5	6	7	REMARKS
4 Apr. 73	1	14' 9.640"	9 $\frac{3}{32}$	8 $\frac{31}{32}$	8 $\frac{15}{32}$	7 $\frac{30}{32}$	7 $\frac{13}{32}$	6 $\frac{30}{32}$	5 $\frac{20}{32}$	0742 hrs
4 Apr. 73	1	0.060	0	-1	-1	-1	-1	-2	-2	1330 hrs
4 Apr. 73	1	-	0	-1	-1	-2	-1	-2	-2	1600 hrs
5 Apr. 73	2	0.060	0	-1	-1	-1	-1	-2	-1	1020 hrs
6 Apr. 73	3	0.020	0	-1	-1	-1	-1	-1	-1	1130 hrs
12 Apr. 73	9	0.140	0	-1	0	0	0	0	1	1100 hrs
12 Apr. 73	9	0.160	0	-1	0	0	1	1	1	1415 hrs
13 Apr. 73	10	0.160	0	0	1	1	2	2	3	0915 hrs
13 Apr. 73	10	0.240	0	-1	0	0	1	1	2	1325 hrs
19 Apr. 73	16	0.200	0	0	1	2	3	3	5	1510 hrs
24 Apr. 73	21	0.300	0	0	1	1	3	3	4	
27 Apr. 73	24	0.260	1	1	2	2	4	4	6	
2 May 73	29	0.260	0	0	2	2	3	3	5	
11 May 73	38	0.360	1	1	2	3	5	5	7	
31 May 73	58	0.400	1	2	3	4	6	6	7	
7 Jun. 73	65	0.420	1	2	3	4	6	6	8	
5 Jul. 73	93	0.420	1	1	3	4	6	6	8	
15 Aug. 73	134	0.440	2	2	4	5	7	7	9	
14 Sep. 73	164	0.440	1	2	4	6	7	7	9	
24 Oct. 73	204	0.480	2	2	5	6	7	8	9	
19 Nov. 73	230	0.460	1	2	4	5	7	7	9	

TABLE 9 (Cont.) - WALL MOVEMENT DATA, PANEL WALL

DATE	DAY	LATERAL TRANSLATION (INCHES)	DEFLECTION ($^1/_{32}$ INCH) 1	2	3	4	5	6	7	REMARKS
16 Jul. 74	469	0.560	1	2	4	5	6	7	8	
19 Aug. 74	503	0.580	1	2	4	4	7	7	8	
18 Sep. 74	533	0.600	1	2	5	4	6	7	8	
15 Oct. 74	560	0.560	1	2	4	5	7	8	8	
13 Nov. 74	589	0.540	1	2	4	4	6	7	8	
11 Dec. 74	617	0.480	1	2	4	4	6	7	8	
16 Jan. 75	653	0.520	1	2	4	4	6	7	8	
27 Feb. 75	695	0.500	1	2	4	4	6	7	8	
27 Mar. 75	723	0.520	1	2	3	4	6	7	8	
10 Apr. 75	737	0.560	2	2	4	5	7	8	8	
12 May 75	769	0.560	1	3	4	4	7	7	9	

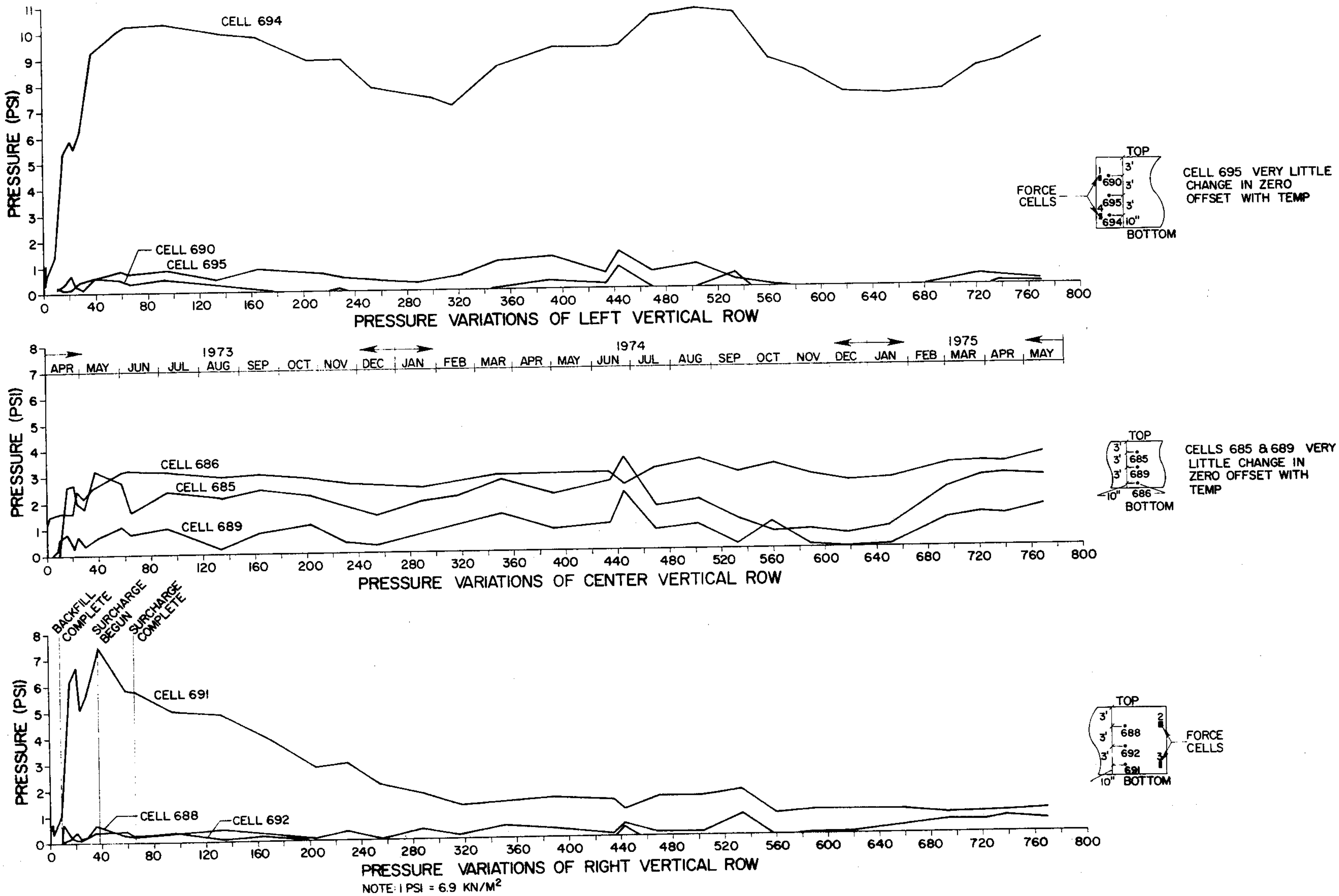


FIG. 16 – PRESSURE CELL VARIATIONS WITH TIME, PANEL WALL

after the completion of backfill. The lower cells at the panel ends Nos. 694 and 691 recorded a rapid rise in pressure up through day 38. Between day 29 and 58 the clay surcharge was added and these lower cells established different trends during this time. These changes are depicted graphically in Figs. 17 and 18. The lower right cell pressure, (No. 691) began a steady decrease dropping below the Coulomb active value about day 240. By day 560 the output of cell No. 691 became steady at about one third of the calculated active pressure. The left lower cell, No. 694, continued to increase reaching a peak about day 65. After that time it exhibited a seasonal pressure variation similar to the lower cell of the cantilever wall. The seasonal variation was about 3 psi as compared with 3.5 psi for cell 604 of the cantilever wall. The other cells at the ends of the panel have consistently measured smaller than Coulomb active pressures.

The vertical row of cells at the center of the panel showed a different pressure distribution pattern. The upper and lower cell pressures were erratic but generally increased during the first 38 days. During the surcharge period the upper cell pressure dropped below that of the lower cell pressure and has continued to remain slightly lower. Except for a brief period during the winter of 1974, the upper cell pressure has been above the Coulomb active value. The lower cell, No. 686 despite reading higher than the upper cell, has shown near active pressures since day 58. The middle cell has consistently shown the lowest pressure in the center vertical row. These pressure changes are depicted graphically for the days specified in Figs. 17 and 18.

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

The movement data given in Table 9 have been resolved into tilt and lateral translation. Tilt was computed directly from the deflection data. Tilt is equal to deflection divided by height to measuring point. This was done for all seven points in each set of data. These seven tilt computations were averaged and the average was plotted as a function of time as shown in Fig. 19.

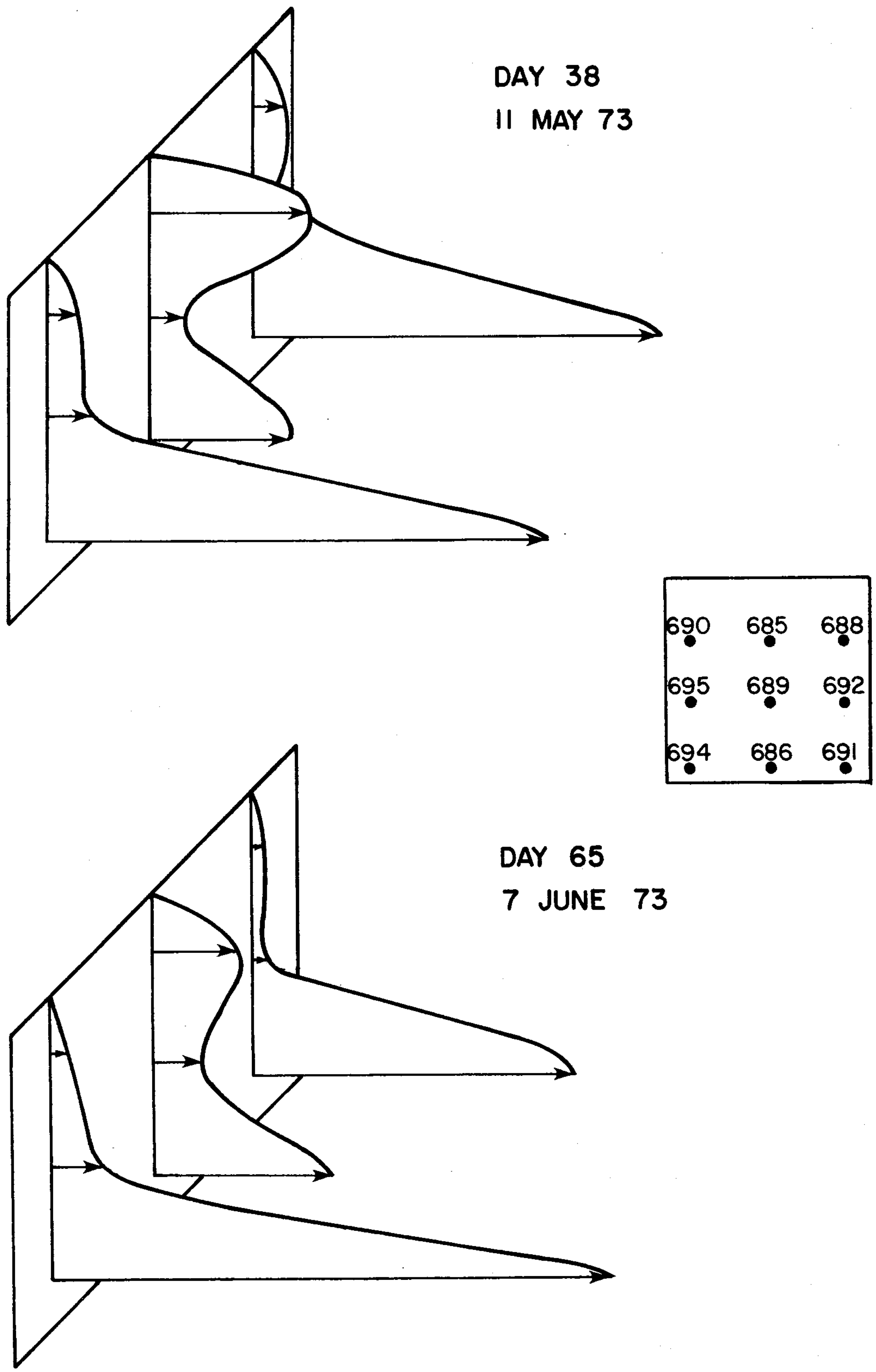


FIG. 17—PRESSURE DISTRIBUTIONS DAYS 38 & 65, PANEL WALL

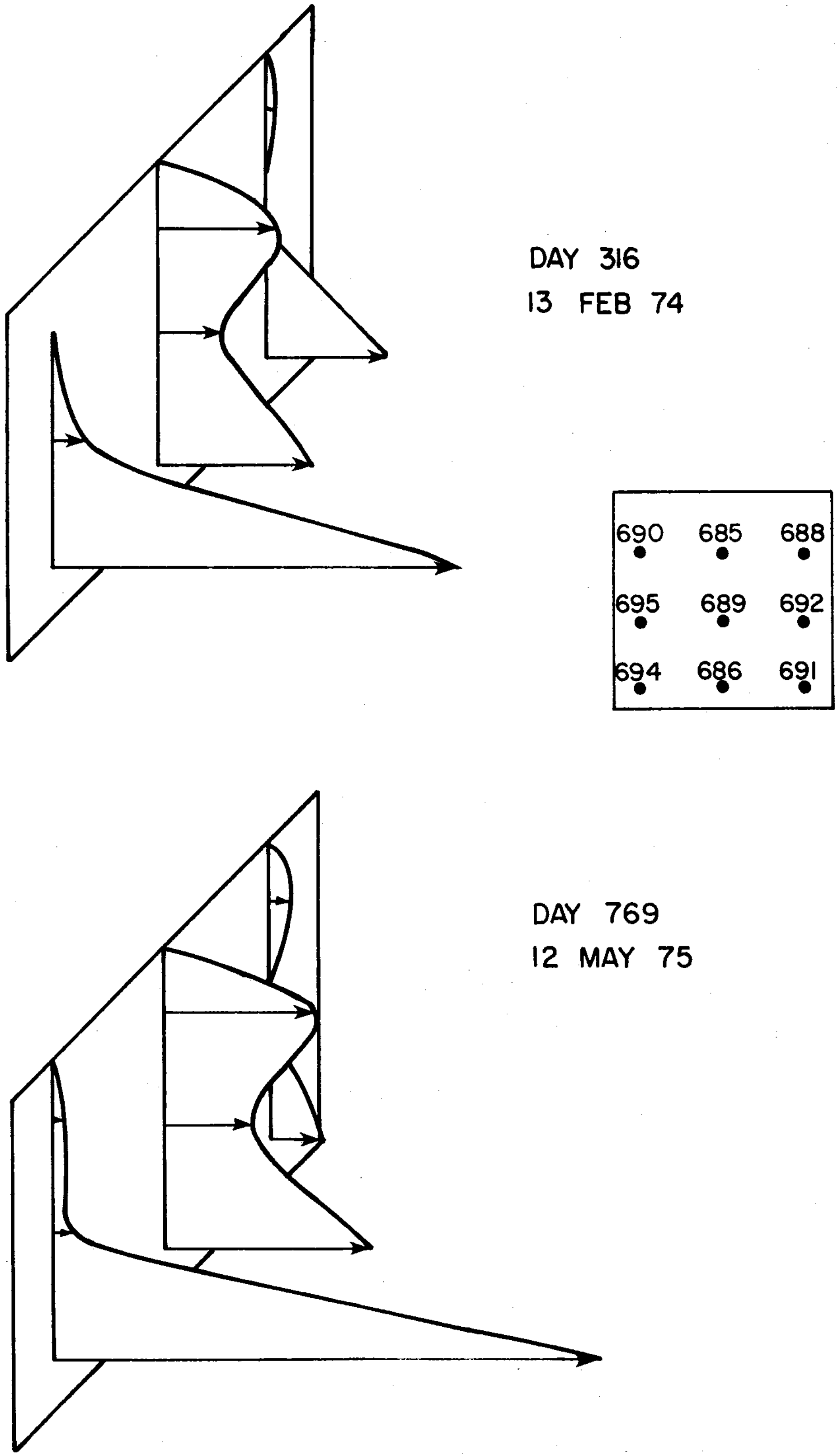


FIG. 18—PRESSURE DISTRIBUTIONS DAYS 316 & 769, PANEL WALL

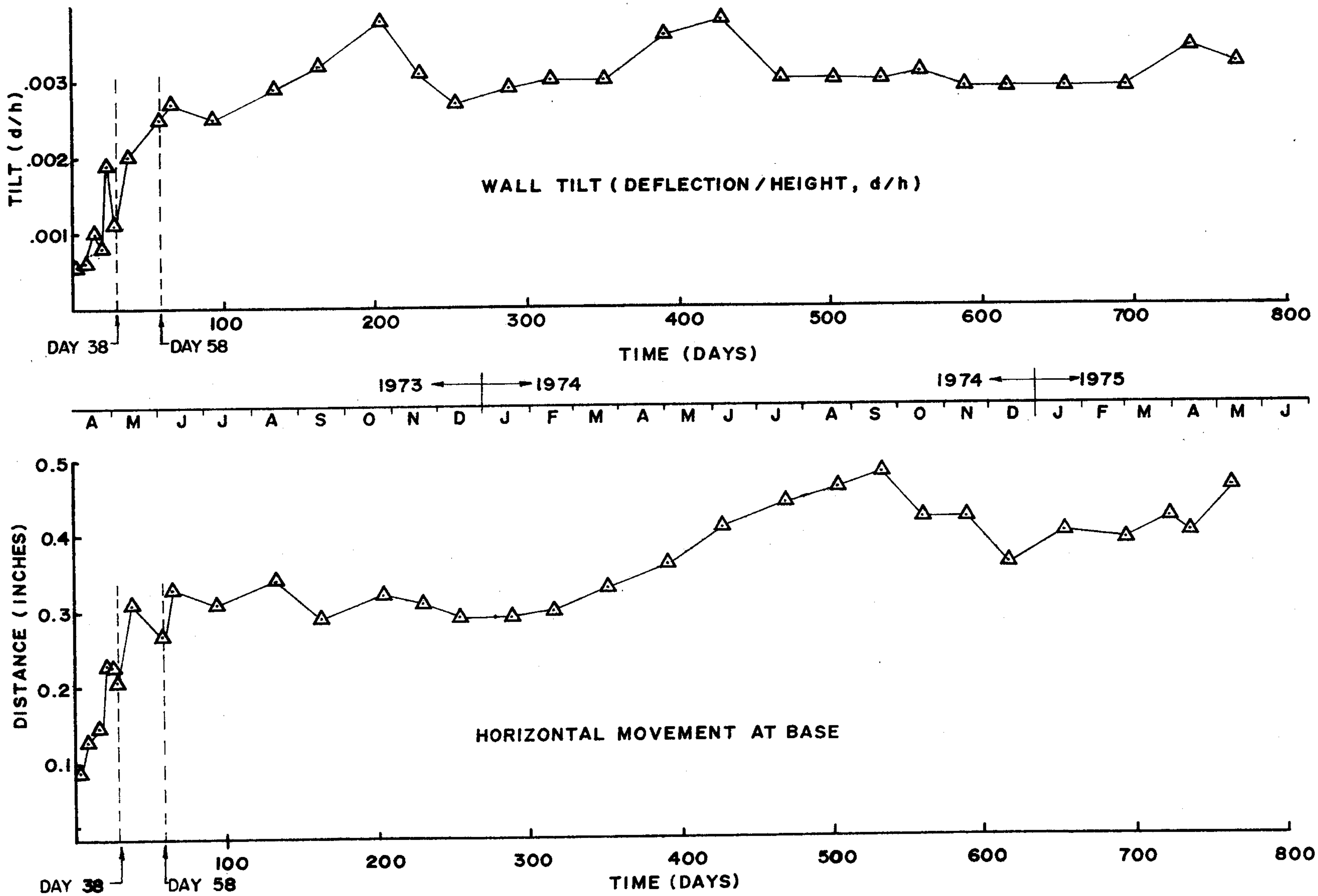


FIG. 19 - MOVEMENTS, PANEL WALL
(1 in = 25.4 mm)

Unlike the cantilever wall, the panel wall was relatively thick compared to its height. Very little curvature due to flexure was detected. The base of the wall was located three feet below ground level and was not accessible for measurement. However, horizontal movement at the base was estimated and the procedure used is shown in Fig. 20. The following is noted from presentation of the panel wall movement data in Fig. 19.

Wall Tilt - 1. Less than 20 percent of the tilt occurred during backfill.

2. Tilt increased rapidly after backfill reaching its average value, 0.003 $\frac{d}{h}$ at about day 150.

3. Tilt has not shown consistent increasing or decreasing trends.

4. Three intervals of periodic increase were measured. These are not seasonally related.

Horizontal Movement at Base

1. About 30 percent of the movement occurred during backfill.

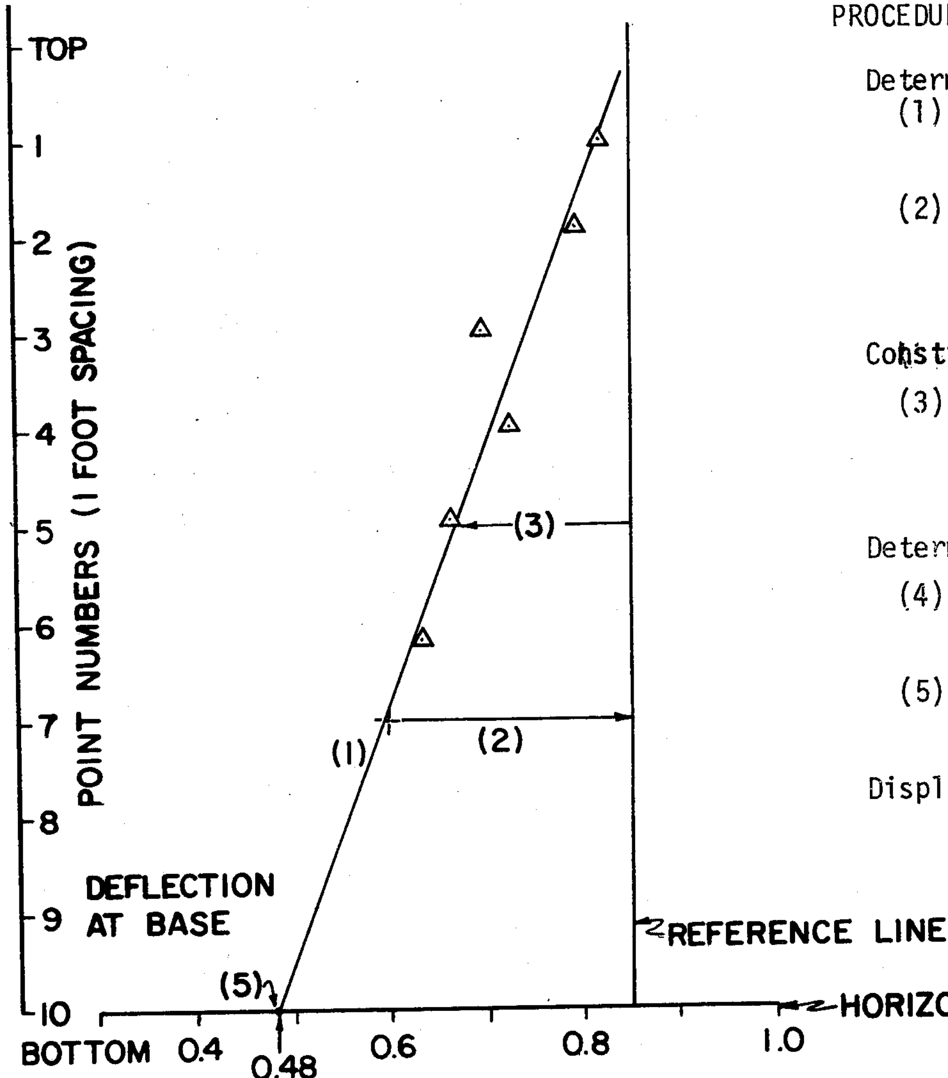
2. Two periods of increasing movement are shown. They were from backfill to day 100 and from day 300 to day 500.

Displacement plots for some of the data are shown in Fig. 21. The rotational and translational nature of early movements as well as the predominately lateral translation later in the program are evident.

Analysis of Results

Lateral Earth Pressures -- The increases in earth pressures after backfill are not in agreement with the earth pressure theories of Coulomb or Rankine. These theories indicate that lateral earth pressures should be highest at the completion of backfill if the wall moves outward from the backfill and external loads are not added to the backfill.

The study data indicate that a general trend of outward movement and increasing pressures took place between backfill and day 38. The greatest forces and overturning moments measured during the test occurred on day 38 as shown in Fig. 22. The clay surcharge was being placed on the backfill at this time. Although the constant activity



PROCEDURE

Determination of Reference Line Position

(1) Plot position of point 7 from fixed reference point.

(2) Lay off deflection distance for point 7 to right. This establishes the vertical reference line.

Construction of Wall Line

(3) Lay off deflection distance for remaining 6 points to left of reference line. This establishes wall line.

Determination of Deflection at Base

(4) Draw best fit straight line through wall points. Intersect the base line.

(5) Intersection of wall line and base line is the deflection at the base of the wall.

Displacement Base = 0.48 inches

FIG. 20 - DETERMINATION OF MOVEMENT AT BASE OF PANEL WALL
(1 ft = 0.305 m ; 1 in = 25.4 mm)

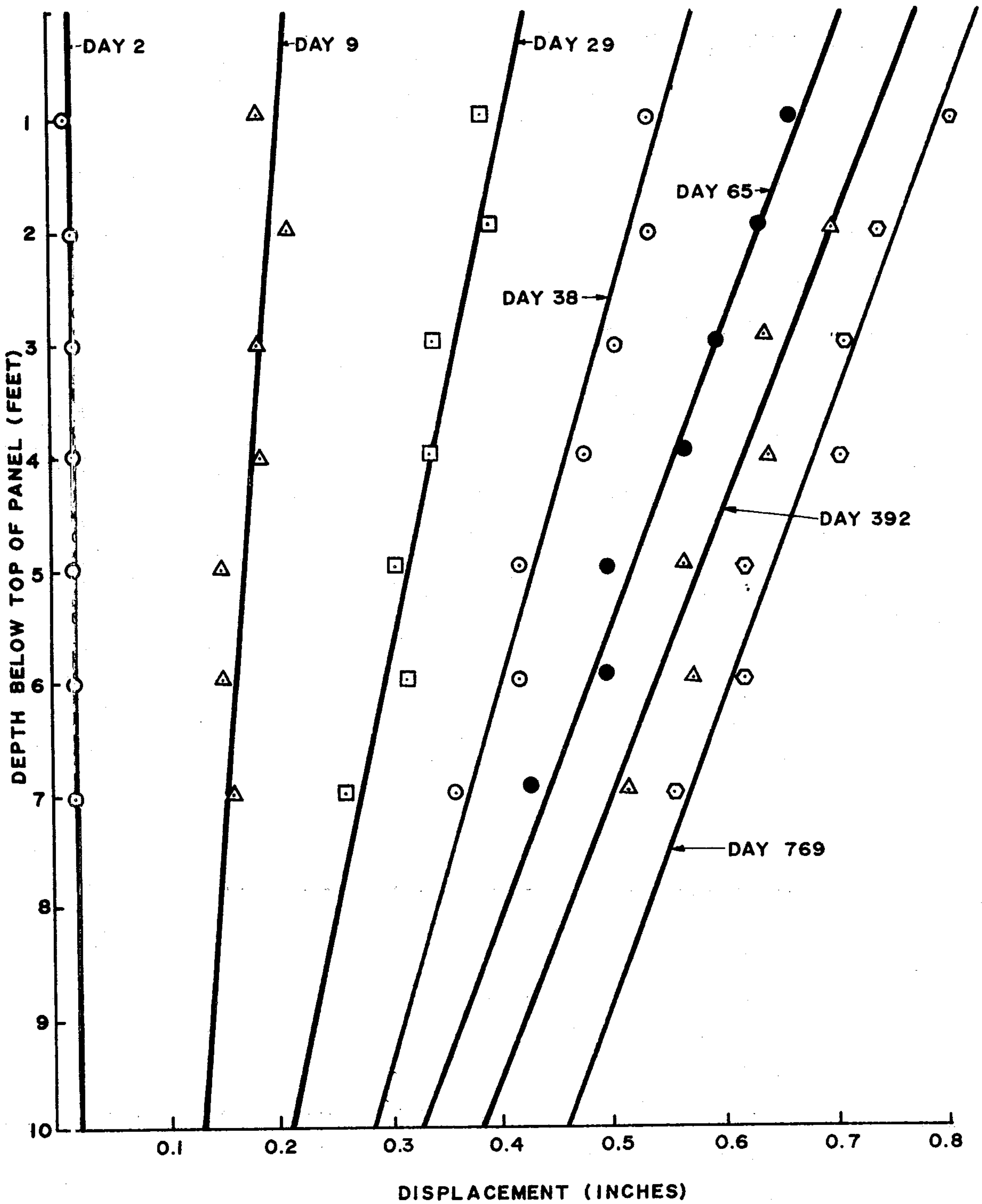


FIG. 21 - DISPLACEMENT OF PANEL WALL

(1 ft. = 0.305 m, 1 in. = 25.4 mm)

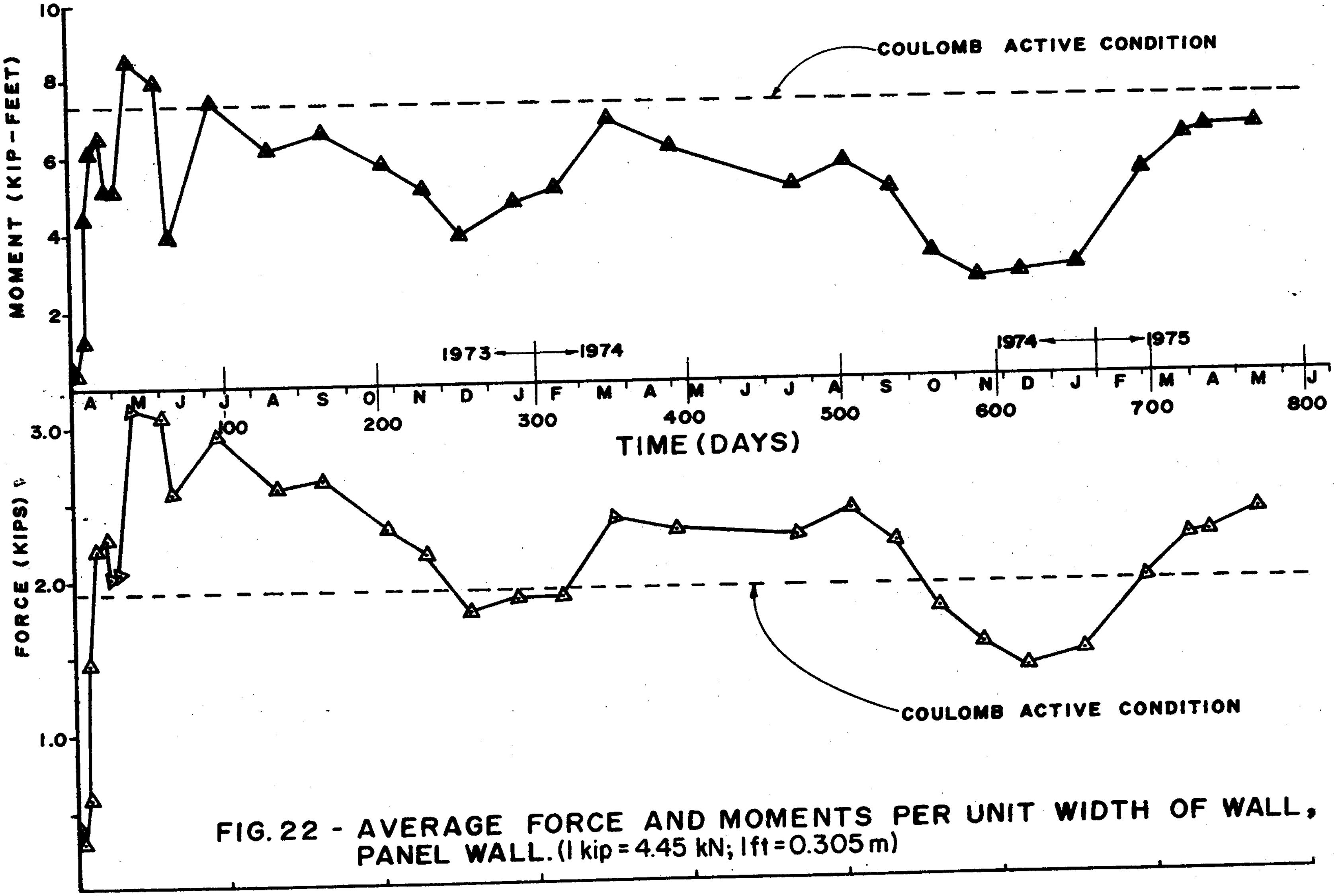


FIG. 22 - AVERAGE FORCE AND MOMENTS PER UNIT WIDTH OF WALL, PANEL WALL. (1 kip = 4.45 kN; 1 ft = 0.305 m)

may have accounted for part of the increase, it was not responsible for the early pressure increases. From completion of backfill to day 29 there was no construction activity on the backfill.

Subsequent to day 38 the changes in pressures are similar to those which occurred on the cantilever wall after backfill. Most cell pressures remained near their 38-day level. Some cell pressures decreased while others entered a seasonal cycle. In general, a steady state condition with no long term trends had been reached. The pressure distribution over the panel as a whole was complex. The following factors were considered to have possible effects on the distribution of pressures on the panel; movements, support conditions, temperature, arching, and apparent cohesion of the backfill.

<u>Wall Movements</u> -- For a typical dense sand Terzaghi (10) has given rough quantitative values of amounts of yield needed for the two types of active cases. These have been summarized by Taylor (8) as follows:

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

For this panel wall 0.59 inches (1.50 cm) of movement at the top would be required to attain a hydrostatic, totally active, pressure distribution. Only 0.029 inches (0.074 cm) of movement at the mid-height should be required to attain the arching active case. As pointed out by Taylor (8) essentially the same total thrust on the wall occurs for both active cases. The pressure distribution for the arching active case is not hydrostatic.

If the effective yield is considered to be the movements since the last backfill measurement, an estimated 0.55 inches (1.40 cm) of movement occurred at the top of the wall by day 150. This movement further increases to about 0.65 inches (1.65 cm) between days 325 and

425. The smaller yields required for the arching active case occurred within five days after backfill. These early movements were not accompanied by pressure reductions. Hydrostatic pressure distributions were not attained.

Lack of agreement with Terzaghi's estimates suggest that the state of stress in the backfill was affected by other factors as significant as movement. This was also indicated by the continuing increase in earth pressure after backfill. The average force on the wall reached a maximum on day 38. The wall yield prior to this date was ineffective in reducing the pressures. Coefficients of lateral earth pressure for day 10 and day 38 are shown in Table 10. The construction activity on day 38 probably caused stress changes. Pressure cell readings stabilized or began dropping at this time. The wall movements associated with the stabilized and dropping pressures were those recorded since day 38. Horizontal movement remained unchanged from day 38 until about day 325, but wall tilt increased from approximately .002 d/h to .003 d/h before stabilizing about .003 d/h. If the effective yield is taken as the movement since day 38, the movements are not sufficient to reduce the pressures to the hydrostatic distribution of the totally active case. The reductions in total force associated with the arching active case should occur. As shown in Fig. 22, force reductions to within 0.5 kip (2.33kN) occured by about day 200.

Panel Support Conditions -- The force transducer data shown in Fig. 23 indicate that the panel was probably not bearing evenly. Highest forces were measured by the transducers located diagonally on the lower left, No. 4, and upper right, No. 2, of the panel. Lowest forces were measured at the other diagonal corners. Highest forces were measured by transducer No. 4. Cell 694 was located 14 inches (35.6 cm) from transducer No. 4. Pressure changes of cell No. 694 closely correspond with force changes for transducer No. 4. This suggests that transducer No. 4 has been in good contact with the wall since backfill.

The measured forces on the upper right transducer, No. 2, were about two-thirds those measured across the diagonal at transducer No. 4.

TABLE 10 - CALCULATED COEFFICIENT OF LATERAL EARTH PRESSURE AFTER BACKFILL, PANEL WALL

	CELL	COEFFICIENT OF LATERAL EARTH PRESSURE, K 19 APR 73 Day 10 *	 11 MAY 73 Day 38**	ACTIVE EARTH PRESS. Coef. (Coulomb)
UPPER ROW				
DEPTH - 3'	690	0.160	0.274	0.290
(0.91m)	685	1.21	1.486	0.290
	688	0.091	0.320	0.290
MIDDLE ROW	695	0.046	0.126	0.290
DEPTH -6'	689	0.194	0.149	0.290
(1.83m)	692	0.057	0.130	0.290
LOWER ROW	694	0.815	1.410	0.290
DEPTH - 9'	686	0.274	0.396	0.290
(2.74 m)	691	0.937	1.143	0.290

*First measurements with completed backfill, 6 days after backfilling was completed

**Construction of clay fill in progress.

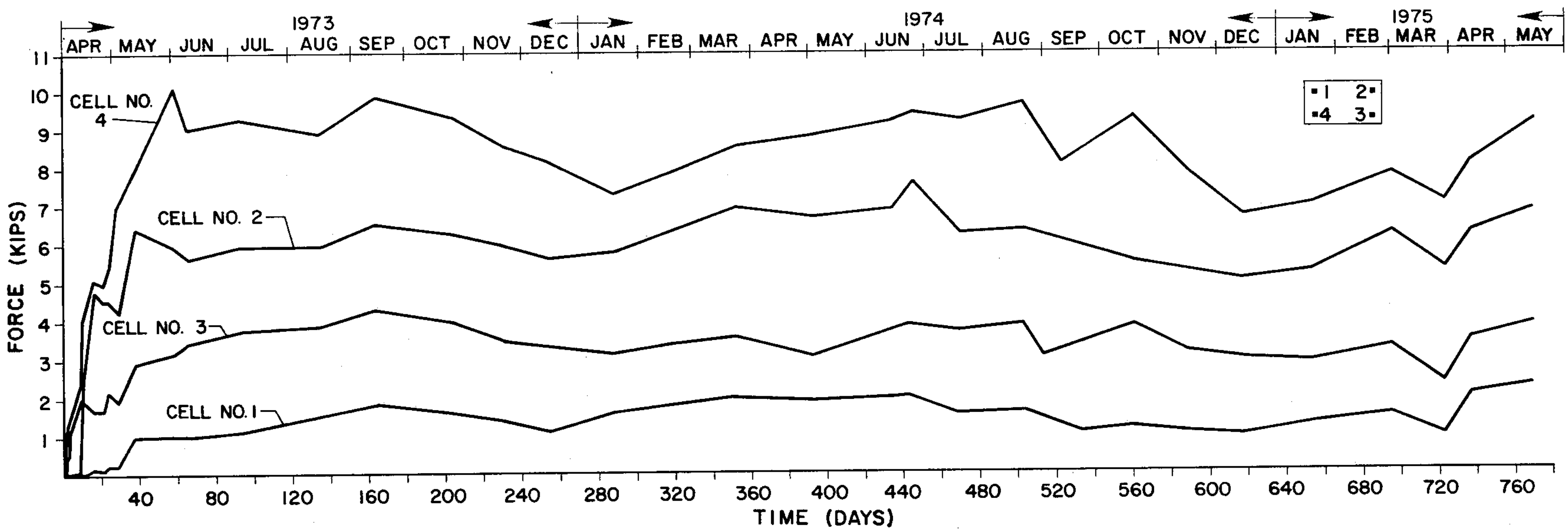


FIGURE 23 - FORCE CELL VARIATION WITH TIME PANEL WALL

NOTE: 1 KIP = 4.45 kN

The total forces for transducers No. 2 and No. 4 account for 70 to 75 per cent of total measured force. Although high forces were measured at transducer No. 2, small pressures, less than one psi, were measured at the closest pressure cell, No. 688. Forces could have been transferred to transducer No. 2 from areas of higher pressure probably near the center of the panel. Transducer No. 3 located at the lower right panel corner was close to pressure cell No. 691. Comparison between this force transducer and this pressure cell indicate that the large pressures measured during the first 29 days after backfill were not transferred to this force transducer. After day 38 a steady decrease in pressure was measured on cell No. 691. The force measurements from transducer No. 3 increased about 0.80 kips (3.56 kN) after day 38 and has remained fairly constant.

Unlike the other force transducers, the data from transducer No. 1 did not indicate a sharp rise associated with backfilling. This may be an indication that the panel was not bearing against the force transducer until after backfill. The forces measured from transducer No. 1 were about 10 percent of the total for the four cells.

In summary it was concluded that the panel was effectively bearing at three points. These were near the bottom at each end where the panel rested on the neoprene pads and against the force transducers and at force transducer No. 2 on the upper right side of the panel.

As noted previously movement measurements were made midway between the pilasters. The movements at the base of the wall near the pilasters where the neoprene support pads are located were not measured directly. Since shear forces that could be developed in the pads were not accounted for in the original force computations for the panel a test was conducted. This test was reported in detail in TTI Research Report Number 169-3 (7). A displacement of 0.1 inches (0.25 cm) produced a shear force of about 1.8 kips (8.1 kN). The movements at the force transducers were estimated to be less than 0.1 inches (0.25 cm). This estimate was based on consideration of the restraint conditions in this area of the panel. The pads were located 5 inches (12.7 cm) below the force transducers. Because these transducers were strain gage type they provided a rigid bracing. Since the transducers responded immediately to the placement of backfill it was assumed that no displacement of the wall was required to engage the transducer. Thus, based on the neoprene pad shear test and the estimated movements, the forces developed in these pads were probably less than 10 percent of the approximate 20 kip average force measured by the force cells.

Seasonal Temperature Variation -- The study data suggest that earth pressure changes seasonally. The changes in earth pressure cell readings correlate with the temperature changes measured adjacent to the cells as shown in Fig. 24. The force cell measurements follow a similar trend. It is significant to remember at this point that the results of calibration studies have shown that when temperature corrections are made, the pressure cell data are accurate to within plus or minus 0.5 psi.

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

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

Comparison of Pressure Cells and Force Transducer Data -- The pressure cells and the force transducers provided independent methods of obtaining the total earth pressure forces acting on the panel. These forces have been computed and are presented in Fig. 25. Total forces measured by the transducers were computed by adding the force

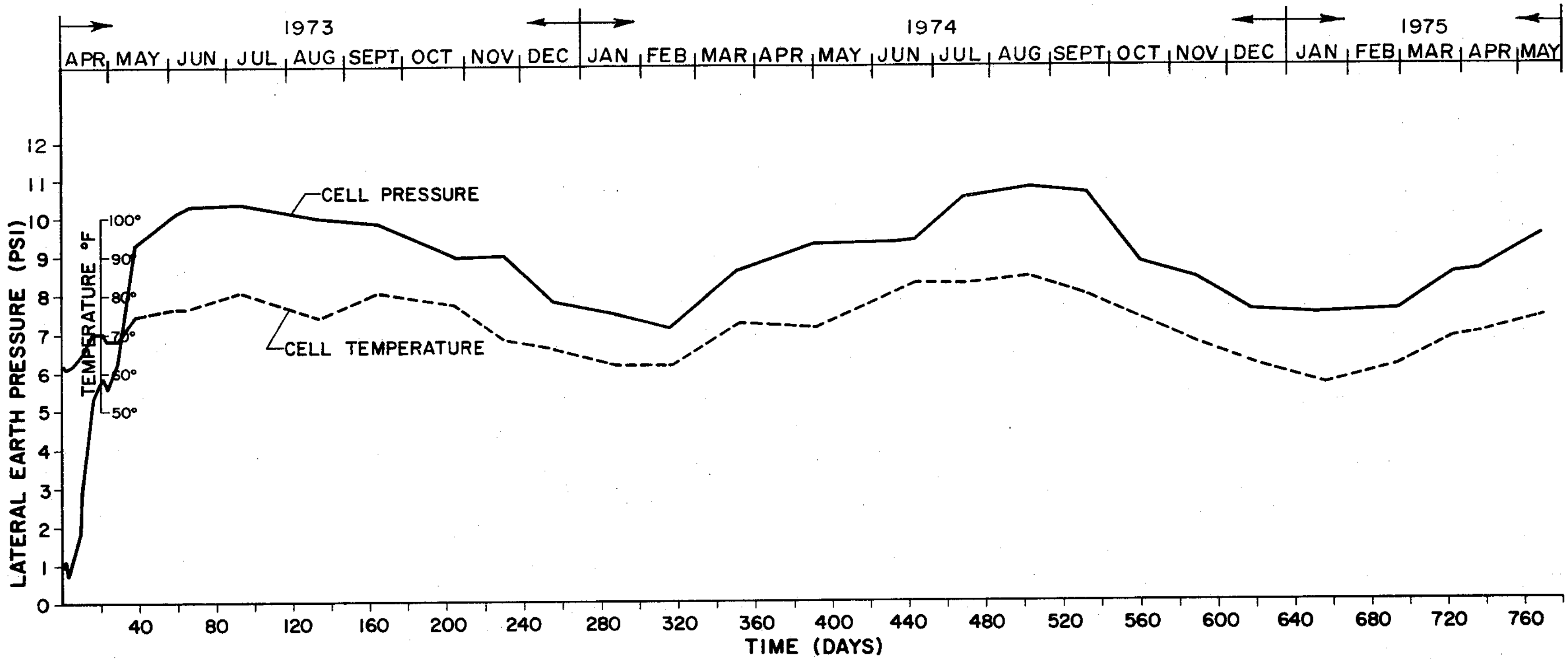


FIGURE 24 - TEMPERATURE AND PRESSURE RELATION, CELL 694 PANEL WALL

NOTE: 1 PSI = 6.9 kN/M^2

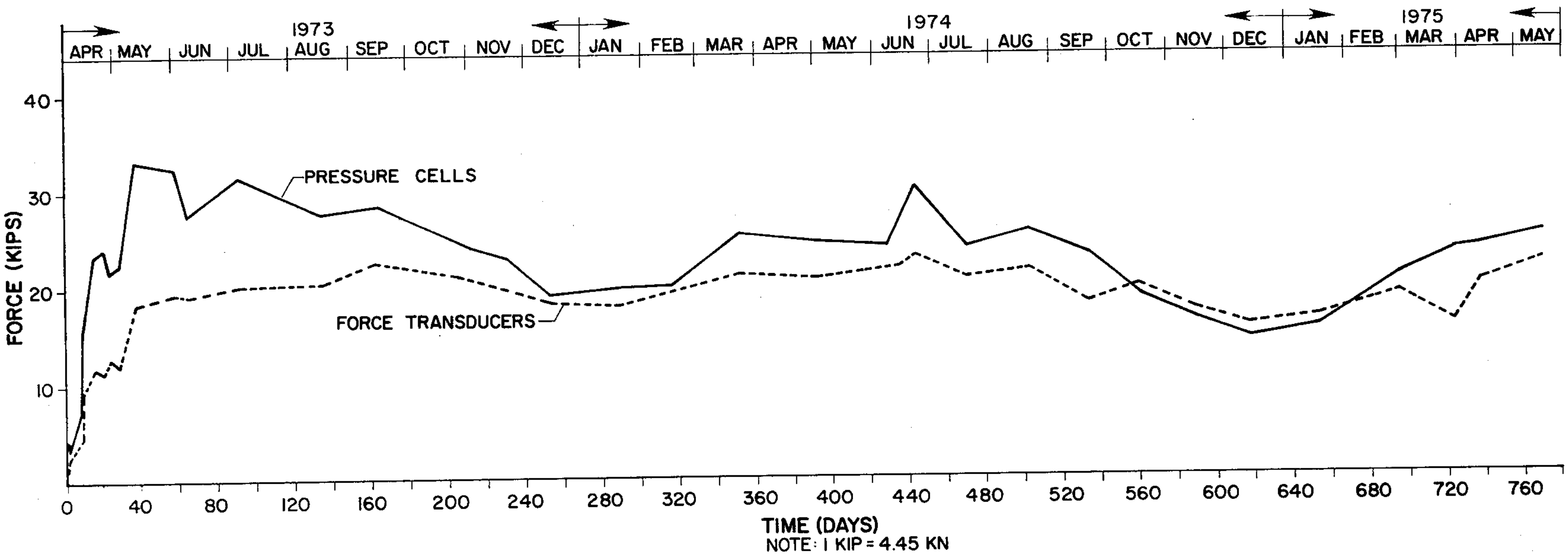


FIG. 25 — TOTAL FORCE ON PANEL WALL

transducer readings for each set of measurements. Computations of total force from the pressure cell data were more complex. Assumptions concerning the distribution of pressures between cells were required. The assumed distribution and a sample calculation are given in Appendix IV.

As shown in Fig. 25, there was good agreement between the cells and the transducers after about day 200. Differences were within the accuracy of the pressure cell readings and the pressure distribution assumptions. Between day 24 and day 200 the forces computed from the pressure cells were much greater than the forces computed from the force transducers. This resulted from the fact that cell No. 691 pressures were initially very high. These high pressures were not measured by the closest force transducer No. 3. The reasons for lack of agreement between cell No. 691 and transducer No. 3 have been discussed. The total force plot as shown in Fig. 25 suggests that cell No. 691 pressures were not transferred to other force cells. The reasons for these discrepancies are not known.

SUMMARY OF STUDY RESULTS

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

Pressure Increases after Backfill. -- Earth pressures continued to increase after backfill of the panel wall. In contrast, the pressures on the cantilever wall essentially leveled off at the end of backfill. The increases in pressure during a period of inactivity such as that immediately following backfill at the panel wall was not expected. Terzaghi in his paper, "Large Retaining-Wall Test" (11) noted that for both loose and dense backfills an intermission of several hours caused marked increases in the intensity of the earth pressure in spite of the fact that the wall did not move. Terzaghi explained that during the intermission the state of strain did not change and that pressure increases were the result of reductions in frictional stresses in the backfill and along the wall. He also explained that, "The stress required to produce a definite state of strain in the sand is invariably greater than required to maintain this state." The pressure increases associated with Terzaghi's explanation would be limited to pressures less than the at-rest values that existed before movement first occurred. Since the maximum lateral earth pressure coefficients measured for the panel wall were greater than one, the pressure increases after backfill cannot be completely accounted for by a reduction in frictional stresses.

The pressure increases after backfill may be related to the method of compaction of the fill. This is suggested by the difference in compaction procedures used at the two walls. The heavy compaction of the panel wall backfill material may have resulted in the development of residual shear stresses which continued to increase the pressures after backfill. Placement of the clay surcharge around day 38 could have resulted in a redistribution of stresses in the backfill and a corresponding change in pressure at that time. On the other hand the lighter compaction at high moisture content may not have caused residual stress to build up on the cantilever wall.

The argument that residual shear stresses can cause pressure changes of the type measured is subjective. Additional field data and/or laboratory tests are required.

Earth Pressure Distributions. -- Four vertical distributions of earth pressure have been measured; three on the panel wall, and one on the cantilever wall. After backfill, earth pressures near the base of the cantilever wall and on the panel wall at the bottom of the panel near each pilaster were approximately equal to the at-rest values reported by Terzaghi and Peck (12) for dense sands compacted by tamping in layers. The pressures near the top of the wall for these distributions were lower than the at-rest values. Two of these distributions changed only slightly throughout the test study, but the lower cell at the right side of the panel wall began to decrease after day 38. Although the movements of the panel wall near the pilasters were not measured, the restraint condition at these locations was similar to that of the cantilever wall. In contrast to the center of the panel, the ends were directly bearing on the pilasters which were formed on drilled shafts. This produced the same kind of restraint as the "H" piles of the cantilever wall. The principal difference was the fact that the massive pilasters provided higher resistance to tilting. The rigidity of the pilasters was probably not important because the measured earth pressures above the lower cells at both ends was well below even the Coulomb active value. The important point is that the rotational restraint provided by the foundation would require yielding of the wall stem to develop shear stress in the backfill. For walls founded on drilled shafts or piles the amount of yield required to effect a reduction in pressure can probably be attained only on the upper portions of the wall. This would depend on the stiffness or flexibility of the stem.

According to Kezdi (5) this type of pressure distribution may result from simple tilting about the top of the wall. Kezdi contends that the displacements required to produce frictional forces along a plane from the base of the wall to the backfill cannot be produced. Such a plane surface of sliding is assumed in the Coulomb and Rankine earth pressure theories. As an alternative, Kezdi suggests that based on the results of model tests, the surface of sliding originates some distance above the base. The result is that below the point of intersection of the plane of sliding and the wall the earth pressures will remain at rest as they have during this test study.

Effects of External Loads -- Construction loads during and after backfill did have an effect on the pressure cell readings. Vehicular traffic did not produce noticeable changes in earth pressures measured on the cantilever wall.

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

Two instances of pressure changes resulting from construction after the completion of backfilling have been observed. These were the revival of cell No. 570 on the cantilever wall and the high pressures occurring on the panel wall at day 38. Both of these events were associated with the movement of heavy construction equipment on the backfill near the wall.

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

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

DESIGN CONSIDERATIONS AND RECOMMENDATIONS

Design Considerations

General -- The recommendations which follow are applicable only to walls satisfying the following conditions:

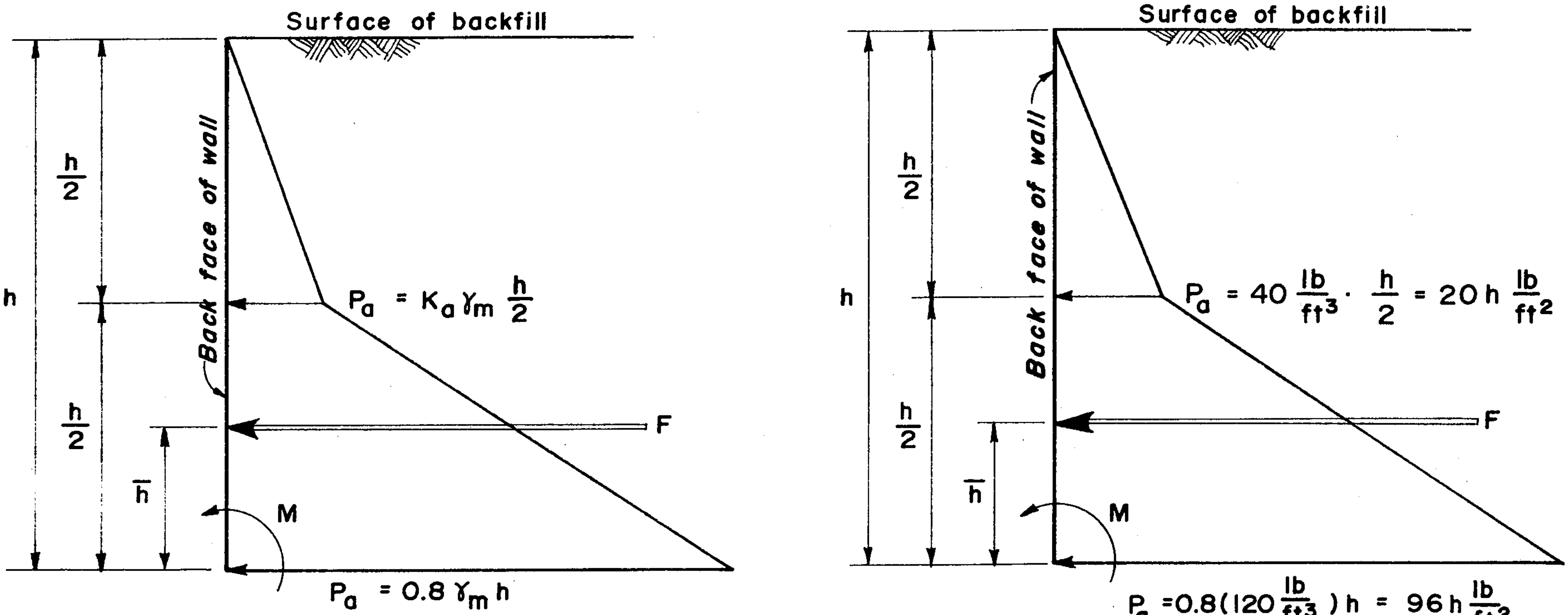
1) Cantilever and panel walls of the type tested and founded on piling or drilled shafts in a manner similar to the walls tested.
2) Walls backfilled with free draining cohesionless soil with less than twelve percent fines.
3) Walls in which an adequate drainage system is provided to prevent the build up of hydrostatic water pressures in the backfill.

Foundation Restraints -- A very important consideration in specifying the lateral earth pressure distributions to be used in design is the restraint provided. As Taylor points out "If a retaining wall ... is held rigidly in place ... it is likely that the wall cannot yield without breaking important members which restrain it. In such a case the wall must be designed to resist a thrust that is larger than the active value. And for the completely restrained case it should be designed to resist pressures at rest". On the other hand, Taylor indicates that "retaining walls that can yield a considerable amount without undesirable results, ..." can be designed on the basis of active earth pressures, and triangular distributions. Analysis of the test study results indicates that because the test walls were founded on drilled shafts and H-piles they can be considered to be held rigidly in place at the base. This consideration is based primarily on the long term measurement of at rest pressures on the lower portion of the walls. The rigid restraint condition appears to be limited to this area of the walls. Thus, on the whole, the restraint, of the walls appears to be such that a thrust larger than the active value but less than the at rest value, which corresponds to complete restraint should be used.

Structural Design -- For retaining walls which are founded on piles or drilled shafts it cannot be assumed that the foundation will tilt by an amount great enough to reduce earth pressures to the active values. The pressure reductions which do occur are to a great extent a result of structural deflections in the wall. Thus, for these retaining structures, there is an interaction between the resistance to bending and the resulting earth pressure. The greater the resistance to bending the less pressure reduction can be expected. On the other hand, if the wall is underdesigned, yield may be excessive and cracking could result. This is the basis for Taylor's previously quoted comments on yield and "undesirable results." The occurrence of cracking would not necessarily result in failure of the wall since some pressure reduction would result from the associated yield. Cracking of the upper part of the wall would result in pressure reductions in that area, and at rest pressures may remain acting near the base. If the wall should yield by cracking at the base of the stem, a more general reduction in pressure will occur all along the wall. Before the wall can collapse the lateral earth pressure will reduce to the theoretical active values. Thus, for walls designed for greater than active earth pressures where the pressure distribution is based on a consideration of the wall restraints, a factor of safety need not be applied. Based on these considerations the pressure distribution presented in the next section is recommended.

Recommended Design Criteria

The recommended design procedure for determining pressure distribution, forces, and moments is shown in Fig. 26. This distribution consists of two regions of linearly increasing pressure with depth. An active earth pressure distribution is assumed to act on the upper half of the wall. Below this point the pressure increases in a linear manner to an at rest value of 0.8 $\gamma_m h$ at the bottom of the wall. The overburden pressure at the base is $\gamma_m h$, where γ_m is the total unit weight of the backfill and h is the height of the wall. This distribution roughly corresponds to measured distributions of both test walls. For both the cantilever and the panel walls, the yield of the upper half of the wall should be sufficient to reduce the average pressures to the active value without causing cracking or other structural damage to the walls. For the lower half of the wall, measurements revealed that some yield will occur. The measurements did not indicate that this yield was sufficient to reduce the wall pressures significantly below the at rest pressures.



Resultant Force: $F = \frac{1}{4} \gamma_m h^2 (K_a + 0.8) \frac{lb}{ft}$

Overturning Moment: $M = \frac{1}{8} \gamma_m h^3 (K_a + 0.267)$ lb-ft

Point of Application: $\bar{h} = \frac{K_a + 0.267}{K_a + 0.8} \frac{h}{2}$ ft

(a) Recommended

$F = 34\,h^2 \frac{lb}{ft}$

$M = 9\,h^3$ kip-ft

$\bar{h} = 0.265\,h$

(b) Alternate

FIG. 26 - PRESSURE DISTRIBUTION AND DESIGN CRITERIA
(1 kip = 4.45 kN; 1 ft = 0.305 m; 1 pcf = 16.02 kg/m³)

Therefore active pressures should not be used for design in this area.

If the properties of the backfill soil are known, the resultant force, F; the overturning moment, M; and the point of application of the resultant force, $\overline{h}$, for a level backfill with no surcharge, can be computed by:

$$F = 1/4\ \gamma_m\ h^2\ (Ka + 0.8) \text{ lb per ft}; \tag{2}$$

$$M = 1/8\ \gamma_m\ h^3\ (Ka + 0.267) \text{ lb-ft}; \tag{3}$$

$$\overline{h} = h/2 \cdot \frac{Ka + 0.267}{Ka + 0.8} \text{ ft above base of stem.} \tag{4}$$

The equation for computation of K_a is given by Eq. (8) in Appendix III.

If the soil properties are not known, an "alternate" distribution for a level backfill with no surcharge is suggested. The alternate distribution is based upon an equivalent fluid pressure of 40 pcf (640 kg/m^3) from the surface to mid-depth. A soil unit weight of 120 pcf (1920 kg/m^3) and K_a = 0.8 is used in Eq. (1) to compute the pressure at the base of the wall. The pressure from mid-depth to the base is assumed to increase linearly from 20h lb per ft^2 at mid-depth to 96h lb per ft^2 at the base. The resultant force, overturning moment, and point of application are then given by:

$$F = 34\ h^2 \text{ lb per ft}; \tag{5}$$

$$M = 9\ h^3 \text{ lb-ft}; \tag{6}$$

$$\overline{h} = 0.265\ h \text{ ft above base of stem.} \tag{7}$$

Eqs. (2) through (7) are based upon a Rankine state in the backfill. If the Rankine state is not developed, the equations are approximate and will yield conservative results. The application of Eqs. (2) through (7) are illustrated by the following example problem:

Example:

For the cantilever wall, the wall geometry and engineering properties of the backfill are described by the following data:

$h = 16ft$ $\beta = 0^o$

$\gamma_t = 101$ pcf $\phi' = 32^o$

The computation of the Rankine earth pressure coefficient is given in Appendix III, the value being Ka = 0.307. The resultant force, overturning moment, and point of application obtained using Eqs. (2), (3), and (4) on the basis of the recommended pressure distribution are as follows:

$$F = 1/4\ \gamma_m h^2\ (Ka + 0.8)$$

$$= 1/4\ (101\ pcf)\ (16ft)^2\ (0.307 + 0.8)$$

$$F = 7160\ lb = 7.16\ kip$$

$$M = 1/8\ \gamma_m h^3\ (Ka + 0.267)$$

$$= 1/8\ (101\ pcf)\ (16\ ft)^3\ (0.307 + 0.267)$$

$$M = 29{,}700\ lb\text{-}ft = 29.7\ kip\text{-}ft$$

$$\bar{h} = h/2 \cdot \frac{Ka + 0.267}{Ka + 0.8}$$

$$\bar{h} = \frac{16\ ft}{2} \cdot \frac{0.307 + 0.267}{0.307 + 0.8}$$

$$\bar{h} = 4.15\ ft$$

If the alternate solution is used, the computed values are:

$$F = 34\ h^2 = 34\ (16\ ft)^2$$

$$F = 8700\ lb = 8.70\ kip$$

$$M = 9h^3 = 9(16\ ft)^3$$

$$M = 36{,}900\ lb\text{-}ft = 36.9\ kip\text{-}ft$$

$$\bar{h} = 0.265\ h = 0.265(16\ ft)$$

$$\bar{h} = 4.24\ ft$$

The values computed above are summarized in Table 11. Also shown in Table 11 are the values obtained by using Rankine's theory and the equivalent fluid pressure method. The data show that Rankine's theoretical solution yields forces and moments that are about 20% lower than those obtained by the equivalent fluid pressure method. The recommended and

TABLE 11. - COMPARISON OF FORCES AND MOMENTS FOR THEORETICAL ACTIVE AND RECOMMENDED EARTH PRESSURE DISTRIBUTIONS

Ka = 0.307 γ_m = 101 pcf	DESIGN METHOD			
	Rankine	Equivalent fluid pressure = 40 pcf	Recommended	Alternate
Total force on cantilever wall, kips	3.98	5.12	7.16	8.70
Overturning moment, kip - ft	21.2	27.3	29.7	36.9
Point of application, $\bar{h}$, in ft above base of stem	5.33	5.33	4.15	4.24

NOTE: 1 kip = 4.45 kN; 1 ft = 0.305m ; 1 pcf = 16.02 kg/m^3

alternate distributions yield approximately 40% to 70% larger forces and 10% to 35% larger moments than the equivalent fluid pressure method. It should be noted that the Rankine and the equivalent fluid pressure methods use a simple triangular pressure distribution, whereas, the recommended and the alternate methods use a compound triangular distribution with the linear increase of pressure per unit of depth being larger on the lower half of the wall. The near at-rest pressures at the base of the stem account for the larger forces and contribute to the increased moment when either the recommended or the alternate pressure distribution is used.

Recommended Construction Practices

Panel Walls -- Analysis of the individual earth pressure cell and force transducer data indicates that areas of locally high pressure were present on the panel. This may have resulted from the fact that the panel was effectively supported at only three points. Therefore, it is recommended that a hard grout be placed between the panel and the pilaster to insure a uniform bearing. This grouting was performed on all the other panels installed at the Dacoma Street test site and none have shown cracks. However, cracks have been observed on a similar panel wall installed under a railroad overpass at Lovelady, Texas. This wall was not grouted and most of the panels were not bearing uniformly. As a result, cracks were present around the points of bearing.

Compaction of Backfill -- Terzaghi (11), Casagrande (2), Terzaghi and Peck (12), and Lambe and Whitman (6) have pointed out that the earth pressure after backfill is dependent on the method of compaction. Casagrande (2) has warned that compaction can cause a permanent increase of earth pressure into the passive range. Lambe and Whitman conclude that intense compaction may cause large outward wall movement during construction. As observed in this study, for the panel wall which was heavily compacted, earth pressures continued to increase after backfill. According to Lambe and Whitman, moderate compaction will result in an increase in friction angle which will offset the disadvantage of an increase in unit weight (6). Thus, compacting should be limited to a few passes by a bulldozer in approximately eight-inch lifts. According to Casagrande, the bulldozer should compact no closer than five feet from the wall (2). Since heavy compaction should be avoided the moisture content need not be rigidly controlled. However, the backfill should not be compacted when saturated or very dry.

Recommendations For Future Research

General Comments -- As a result of the experience gained during this study the following recomendations are made to aid future studies:

1. Instrumentation and Measurements - For panel walls, the movements should be measured on the ends as well as the center. The movements of the pilasters should also be measured. The panel should be placed on rollers or Teflon blocks to provide a minimum of resistance to outward movement. Force transducers should be placed under the panel to measure the vertical load resulting from frictional stresses of the soil along the wall.
2. Measurement period - The time between measurements should be varied. Measurements should be taken frequently during backfill and at least on a daily basis thereafter until readings stabilize or establish a trend. Once trends are established readings should be spaced at regular intervals. Measurements should be taken at the same time of day, preferably in early morning. During periods of construction on the backfill the number of readings should be increased.
3. Properties of backfill material - In addition to the soil tests performed as part of this study, relative density tests are recommended. Moisture content and unit weights at several places in the backfill should be determined periodically so that density and moisture content changes can be determined.

Additional Retaining Wall Test -- Full scale field measurements of a cantilever wall not restrained at the base are required. These measurements could be used in conjunction with the results of this study to develop a general design procedure. This general procedure would be applicable to retaining walls of different types, restrained and unrestrained at their base.

Additional Earth Pressure Test -- The analysis of test results indicated two earth pressure phenomena which require additional study.

These are the increase in earth pressure following backfill of the panel wall and the seasonal pressure changes measured on both walls. A combination of field test and laboratory measurements would be desirable. Pressure cells and thermocouples installed in the soil during backfill would provide useful data. These measurements could be compared with the results of laboratory tests made under controlled conditions.

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APPENDIX II - NOTATION

h = depth, in feet (meters)

kip = one thousand pounds force

K_a = active earth pressure coefficient

K_o = at-rest earth pressure coefficient

K_p = passive earth pressure coefficient

No. = number

p = lateral earth pressure

pcf = pounds per cubic foot (kilograms per cubic meter)

psi = pounds per square inch (kilonewtons per square meter)

α = angle of back of retaining wall from horizontal

β = angle of backfill slope with horizontal

γ = unit weight of soil, in pcf (kg/m^3)

δ = angle of wall friction

ϕ = angle of internal friction of soil

APPENDIX III - THEORETICAL EARTH PRESSURE COMPUTATIONS

Theoretical Pressures According to Rankine

The equation for active pressure at a particular depth, based on the Rankine theory, is

$$p_a = \gamma' H K_a + u \tag{1}$$

where

$$K_a = \cos\beta \left(\frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi'}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi'}}\right) \tag{8}$$

and

K_a = active earth pressure coefficient,

H = vertical height of retaining wall

γ' = effective unit weight of the soil

ϕ' = angle of internal friction

β = angle of slope to horizontal

u = pore water pressure in the backfill

For dry backfill material $u = 0$ and when the ground surface is level ($\beta = 0$), the above equation simplifies to:

$$p_a = \gamma_t H K_a \tag{9}$$

also

$$K_a = \tan^2(45° - \phi'/2) \tag{10}$$

For the cantilever wall the following data applies:

γ_t = 101.3 pcf (1622.7 $^{kg}/m^3$)

ϕ' = 32°

β = 0

assume u= 0

H= 16 ft (4.88 m) at the bottom

Based on the above values, K_a = 0.307, and p_a = 3.46 psi (23.81 $kN/_{m^2}$) at the base of the wall.

The cantilever wall backfill was surcharged with 6 inches (15.24 cm) of base course weighing 118 pcf (1890 kg/m^3) and 8 inches (20.32 cm) of concrete weighing 150 pcf (2404.8 kg/m^3). The intensity of pressure at any depth H can be computed as follows (1):

$$p_a = (\gamma_t h + q) K_a - 2ck_a \qquad (11)$$

For a dry cohesionless sand c = 0. The equation reduces to:

$$p_a = \gamma_t H K_a + q K_a \qquad (12)$$

where q = surcharge computed for the cantilever wall as follows:

$$q = 8" \left(\frac{1 \text{ ft}}{12 \text{ ft}}\right) \left(150 \frac{\text{lb}}{\text{ft}^3}\right) + 6" \left(\frac{1 \text{ ft}}{12 \text{ in.}}\right) \left(118 \frac{\text{lb}}{\text{ft}^3}\right)$$

$$q = 159 \text{ psf } (7.62 \text{ kN/m}^2)$$

Thus: $q^{K}a = 150 \frac{\text{lb}}{\text{ft}} \cdot 0.307 \cdot \frac{1 \text{ ft}}{144 \text{ in.}} = 0.339 \text{ psi } (2.43 \text{ kN/M}^2)$

Using equation 12 the pressure at the base of the cantilever wall can be computed.

$$p_a = \gamma_t H K_a + q K_a$$
$$p_a = 3.46 + 0.339 = 3.79 \text{ psi } (26.15 \text{ kN/m}^2)$$

Theoretical Pressures According To Coulomb

The equation for active pressure at a particular depth, based on the Coulomb theory for a cohesionless soil, is

$$P_a = \gamma' H K_a + u \qquad (1)$$

where

$$K_a = \frac{\text{Sin}^2 (\alpha+\phi')}{\text{Sin}^2 \alpha \text{ Sin } (\alpha-\delta) \left[1 + \frac{\text{Sin } (\phi'+\delta) \text{ Sin } (\phi'-\beta)}{\text{Sin } (\alpha-\delta) \text{ Sin } (\alpha+\beta)}\right]^2} \qquad (13)$$

and δ = angle of wall friction. For a dry backfill u = 0 and when the ground surface is level at the top of the backfill, i.e. $\beta = 0^{\circ}$; the above equation simplifies to

$$P_a = \gamma_t H K_a \qquad (9)$$

where

$$K_a = \frac{\text{Sin}^2 (\alpha + \phi')}{\text{Sin}^2 \delta \text{ Sin } (\alpha-\delta) \left[1 + \frac{\text{Sin } (\phi' + \delta) \text{ Sin } (\phi')}{\text{Sin } (\alpha-\delta) \text{ Sin } (\alpha)}\right]^2} \qquad (14)$$

For the panel wall the following data applies:

γ_t =105 pcf (1682 kg/m^3)

$\phi' = 32^{\circ}$

$\beta = 0$

assume $u = 0$

$H = 10$ ft (3.05 m) at the bottom of the panel

$\delta = 2/3\ \phi = 21.3^{o}$ (1)

Based on the above values, $K_a = 0.290$, and $p_a = 2.11$ psi (14.59 kN/m²) at the base of the wall.

As shown in Fig. 11 the backfill was surcharged with a 3:1 clay slope. This sloping backfill may be handled as an equivalent uniform surcharge, q' (1). The magnitude of q' is computed as shown below:

$$q' = \left[6" + \frac{30" - 6"}{2}\right] \left(\frac{1\ \text{ft.}}{12\ \text{in.}}\right) \left(122\ \frac{\text{lb}}{\text{ft}^3}\right)$$

$$q' = 183\ {}^{\text{lb}}/\text{ft}^2\ (8.77\ \text{k}^{\text{N}}/\text{m}^2)'$$

where the unit weight of the surcharge is 122 $^{\text{lb}}/\text{ft}^3$ (1954 kg/m³). From equation 12, for a dry cohesionless backfill the pressure at the base can be computed as follows:

$$p_a = \gamma_t\ H\ K_a + q\ K_a \qquad (12)$$

where

H = height of the wall

$q = q'$

$P_a = 2.11$ psi + 0.369 psi

$p_a = 2.48$ psi (17.10 $\text{k}^{\text{N}}/\text{m}^2$) at the base of the wall

Special Note Regarding Surcharge

It should be noted that the AASHTO design surcharge of two feet of backfill results in a net increase of pressure equal to 0.431 psi for the cantilever wall, and 0.491 psi for the panel wall. These values are about 1/4 to 1/3 larger than the values computed by the Rankine and Coulomb theories, respectively. It was not possible to recognize any effect of the surcharge on the measured field data, or to attribute any pressure changes directly to the surcharge.

APPENDIX IV - PROCEDURE FOR COMPUTATION OF FORCES AND MOMENTS FROM MEASURED PRESSURES

Procedure

Forces -- The following method was used for calculating the total force exerted on the pre-cast panel by the backfill. The assumed pressure cell distribution is shown in Fig. 27. The calculations were based on the pressures measured by the earth pressure cells on the 10th day:

For a unit width (see Fig. 27)

$$P_4 = P_3 + \frac{P_3 - P_2}{h_3} h_4 \tag{15}$$

$$F = \frac{1}{2} P_1 h_1 + \frac{1}{2}(P_1 + P_2) h_2 + \frac{1}{2}(P_2 + P_3) h_3 + \frac{1}{2}\left[P_3 + \left(P_3 + \frac{P_3 - P_2}{h_3} h_4\right)\right] h_4 \tag{16}$$

substituting the values of h_1, h_2, h_3 and h_4, and reducing the force per unit width becomes:

$$F = 3P_1 + 2.884\ P_2 + 2.449\ P_3 \tag{17}$$

Fig. 28 shows the assumed panel width associated with each vertical row of pressure cells.

$$F_{left} = [3P_1 + 2.884P_2 + 2.449P_3][W] = [3\ ft\ (0.95\ psi) + 2.884\ ft\ (1.32\ psi) + 2.449\ ft\ (2.65\ psi)][3.33\ ft]\left[\frac{144\ in.^2}{ft^2}\right]\left[\frac{1}{1000\ lb/kip}\right] \tag{18}$$

$F_{left} = 6.30$ kips

$F_{mid} = [3(0.55) + 2.884(0.70) + 2.449(0.95)][4\ ft]$

$F_{mid} = 3.45$ kips

$F_{right} = [3(0.40) + 2.884(0.75) + 2.449(3.55)][3.33\ ft]$

$F_{right} = 5.78$ kips

$F_{total} = 6.30 + 3.45 + 5.78 = 15.53$

The average force per unit width of the wall was computed by dividing the total force by the length of the panel.

$$F_{avg} = F_{total} \div 10.66\ ft. \tag{19}$$

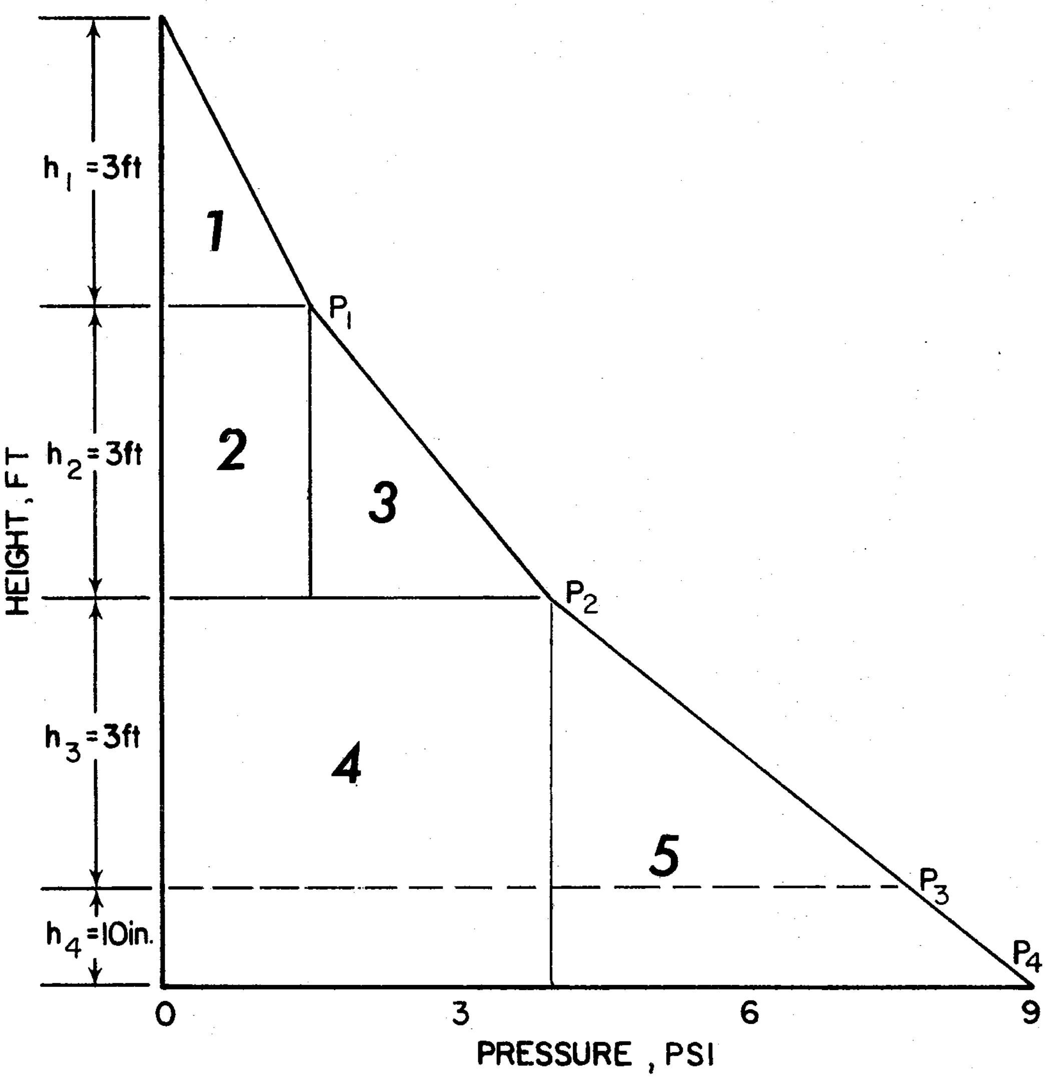

FIG.27 - HEIGHT VERSUS PRESSURE FOR A UNIT WIDTH

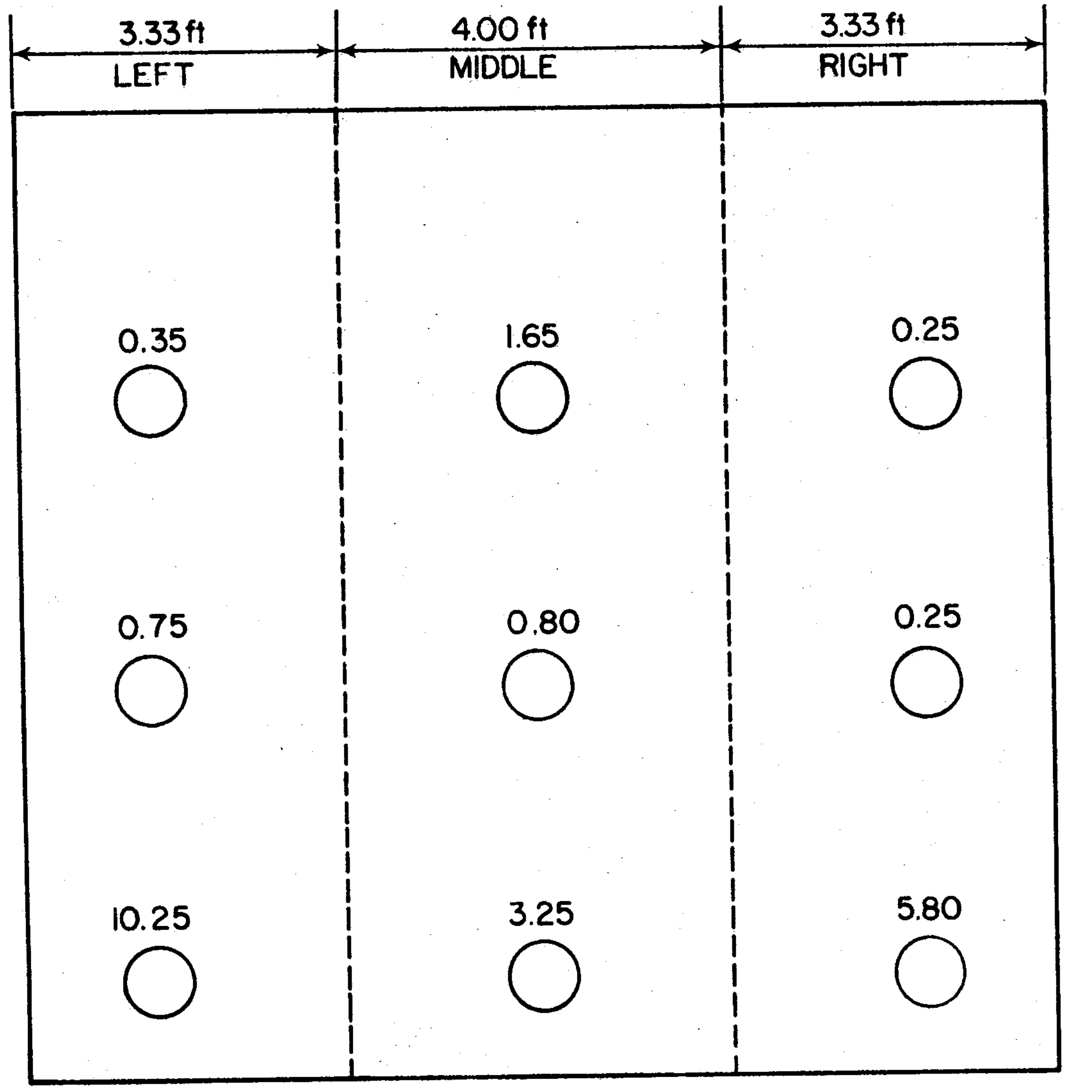

FIG. 28 – PRESSURE (PSI) AND WIDTHS USED FOR CALCULATING TOTAL FORCE ON PANEL

For day 10 $F_{avg} = \frac{15.53 \text{ kips}}{10.66 \text{ ft.}}$

$F_{avg} = 1.46$ kips/foot

For the cantilever wall a similar pressure distribution was assumed. Since only one row of cells was installed the computation does not involve averaging. The force per unit width was computed from the following:

$$F = (7/2P_1 + 3P_2 + 3/2P_3 + 6P_4) \cdot 0.144 \text{ (kips)} \tag{20}$$

Moments -- The overturning moments were computed for each area shown on Fig. 27. Moments were computed for an axis at the top of the wall. The resulting equation was:

$$\begin{aligned} M = {} & \frac{1}{2} P_1 h_1 (\frac{2}{3} h_1) + P_1 h_2 (\frac{1}{2} h_2 + h_1) + \frac{1}{2}(P_2 - P_1) h_2 (h_1 + \frac{2}{3} h_2) + \\ & P_2 (h_3 + h_4)[h_1 + h_2 + \frac{1}{2}(h_3 + h_4)] + \\ & [\frac{P_3 - P_2}{h_3} (h_3 + h_4)] \frac{1}{2}(h_3 + h_4)[h_1 + h_2 + \frac{2}{3}(h_3 + h_4)] \end{aligned} \tag{21}$$

Substituting the values of h_1, h_2, h_3 and h_4, and collecting terms the moment per unit width about the top of the wall becomes

$$M = 9P_1 + 16.89P_2 + 20.96P_3 \tag{22}$$

The panel width assumed to be associated with each vertical row was that shown in Fig. 28. The total moment is calculated for day 10 as follows:

$$\begin{aligned} M_{left} & = [9 \text{ ft}^2(0.95 \text{ psi}) + 16.89 \text{ ft}^2(1.30 \text{ psi}) + \\ & \quad 20.96 \text{ ft}^2(2.65 \text{ psi})] \; 3.33 \text{ ft} \; (\frac{144 \text{ in}^2}{\text{ft}^2})(\frac{1 \text{ kip}}{1000 \text{ lb}}) \\ & = 41.26 \text{ ft-kips} \end{aligned}$$

$$\begin{aligned} M_{mid} & = [9(0.55) + 16.89(0.70) + 20.96(0.95)] \; 4 \text{ ft} \; (0.144) \\ & = 21.13 \text{ ft-kips} \end{aligned}$$

$$\begin{aligned} M_{right} & = [9(0.40) + 16.89(.75) + 20.96(3.55)] \; 3.33 \text{ ft} \; (0.144) \\ & = 43.48 \text{ ft-kips} \end{aligned}$$

$$M_{total} = 41.26 + 21.13 + 43.48 = 105.87 \text{ ft-kips}$$

The location of the center of pressure was then computed by dividing the total moment by the total force.

$$\text{Center of Pressure} = \frac{43.48 \text{ ft-kips}}{15.53 \text{ ft}}$$

$$= 6.82 \text{ ft (Below the top of the wall)}$$

$$\text{or } 6.82 - 9.83 = 3.01 \text{ ft (Above the base of the wall)}$$

The average overturning moment per unit width of wall was computed by multiplying the distance to the center of pressure by the average force per unit width.

$$\text{Overturning Moment} = (3.01 \text{ ft})(1.46 \text{ kips})$$

$$= 4.40 \text{ ft-kips}$$

For the cantilever wall a similar pressure distribution was assumed. Again averaging was not required. The moment per unit width was computed from the following equation:

$$M = 42.167 \text{ ft}^2 P_1 + 27 \text{ ft}^2 P_2 + 16.5 \text{ ft}^2 P_3 + 12 \text{ ft}^2 P_4 \qquad (23)$$

APPENDIX V - INSTRUMENT CALIBRATION STUDIES

General -- The seasonal variations in earth pressure cell and force transducer data were initially believed to have occurred because of the soil-cell loading characteristic. Laboratory tests were performed to evaluate this loading characteristic. As more data were obtained it was observed that these seasonal variations correlated closely with annual temperature variations. The variation in pressure cell and force transducer readings with temperature was examined in a second series of tests.

Test Set-up -- A cross section of the laboratory test chamber is shown in Fig. 29. A Terra Tec pressure cell was potted into a platform and placed in the bottom of a steel tank. The platform was supported by three legs which were instrumented with electrical resistance type strain gages to constitute a force transducer system. The force transducers installed on the precast panel wall were also instrumented with electrical resistance strain gages. The laboratory measurement system was constructed to resemble the configuration of the field measurement system in an attempt to simulate the conditions, soil-structure interaction, and measurement system response of the field installation as closely as possible.

Loading Characteristics of Pressure Cells and Force Transducers -- To test the loading and unloading characteristics of the measuring system the bag pressure was increased to 10 psi (69 kN/m^2) then decreased to zero psi (0 kN/m^2) in increments of 1 psi (6.9 kN/m^2). The pressure cell and force transducer readings were taken at each increment of bag pressure and are shown in Fig. 30. The bag pressure regulator had a lower range limit of 2 psi (14 kN/m^2); thus, measurements could not be obtained below this limit. As shown in Fig. 29 sand could be placed between the bag and the pressure cell. For the loading test the sand thickness was varied in two inch increments from no sand to 6 inches of sand. With no sand the response of the pressure cell and force transducers versus applied pressure (Bag Pressure) was linearly related and nearly equal for both the loading and unloading portions of the test. This test indicated satisfactory performance of the test apparatus. The loading cycle is shown in Fig. 30.

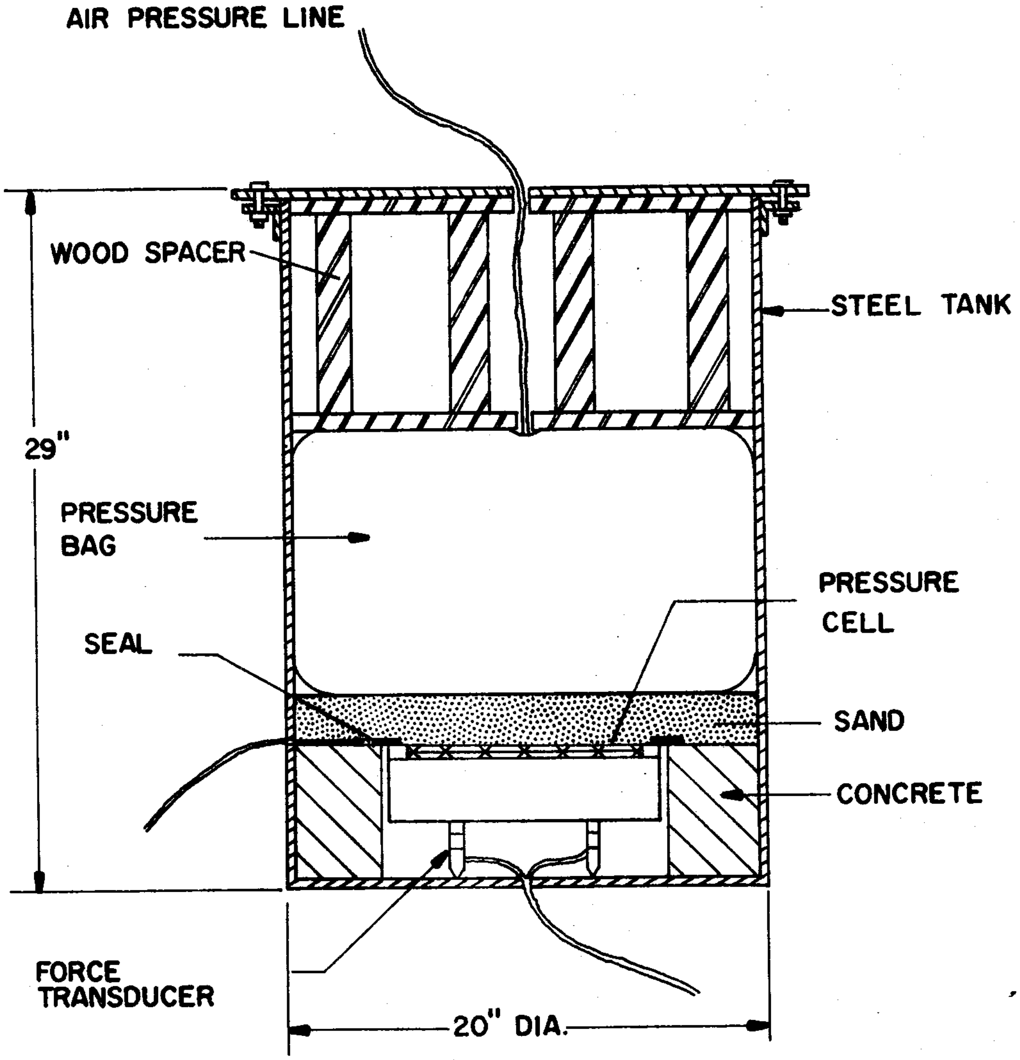

FIG. 29 CROSS SECTION OF LABORATORY TEST CHAMBER

(1 in. = 25.4 mm)

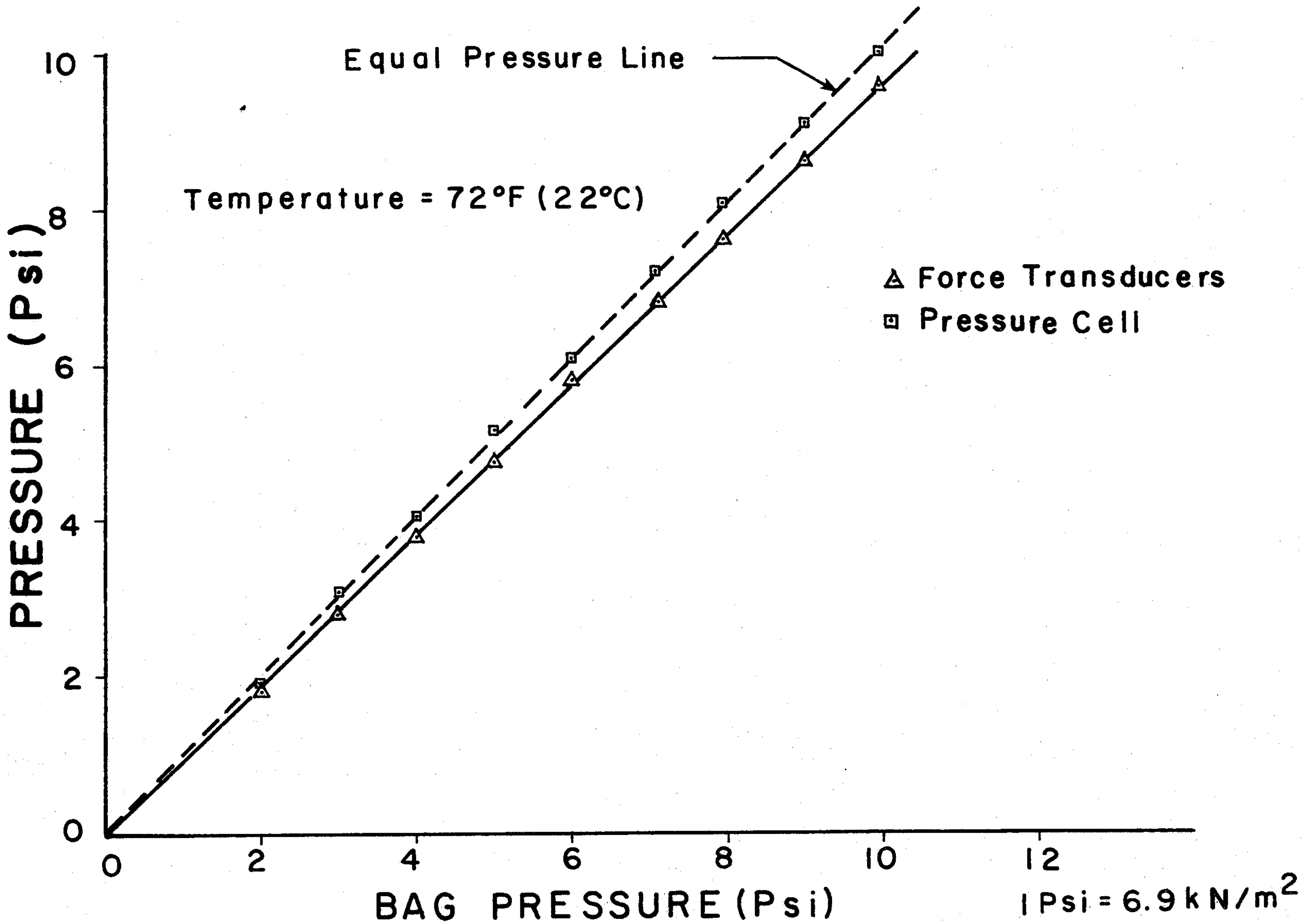

Fig. 30–TEST CHAMBER CALIBRATION WITH NO SAND

The loading test with two inches of sand in the chamber is shown in Fig. 31. Again, the Terra Tec cell and the bag pressure readings are nearly equal for both the loading and unloading cycles. As shown in Fig. 31 the force transducer measurements do not increase linearly with increases in bag pressure but instead show a slight curvature. The unloading cycle becomes linear and nearly equal to the bag pressure after the bag pressure is reduced below 7 psi. For greater thicknesses of sand the force transducer readings were even more nonlinear and for sand thicknesses greater than 4 inches the bag pressure and the pressure cells did not agree. It was concluded that for sand thicknesses greater than two inches the loading and unloading linearity was influenced by wall friction in the tank. However, for sand layers of two inches or less the response of the cell and transcuders can be considered linear. Thus, the soil-cell loading characteristics simulated in the laboratory at a single temperature do not appear to cause large errors in indicated pressures that could account for the seasonal variations noted in the field data.

<u>Variations in Pressure Cell and Force Transducer Measurements with Temperature</u> -- In order to examine the effects of temperature, the change of the zero stress reading or the zero offset was observed for temperatures of 100F (38°C) and 15°F (-9.4°C). During the zero offset test no pressure was applied to the rubber bag. The chamber was placed in the 100°F (38°C) temperature room and the variations of the pressure cell and force transducer readings were recorded with time. After the readings had stabilized, the test chamber was allowed to cool back to 72°F (22°C). The chamber was then placed in the 15°F (-9.4°C) temperature room and the pressure variations were again recorded. Additional tests were conducted, identical to the first set of tests, with the exception that a regulated pressure of 10 psi (69 kN/m^2) was applied to the rubber bag. Again, the pressure cell and force transducer measurements were recorded until indicated pressures stabilized. These readings were then corrected by subtracting the zero offsets for the corresponding test temperatures. The stabilized pressures are presented in Table 12. Note that tests were conducted with and without sand and that both loose and dense sand was used.

As shown in Table 12 the force transducer pressures are within 0.5 psi of the Terra Tec pressures for all test conditions. Thus, for

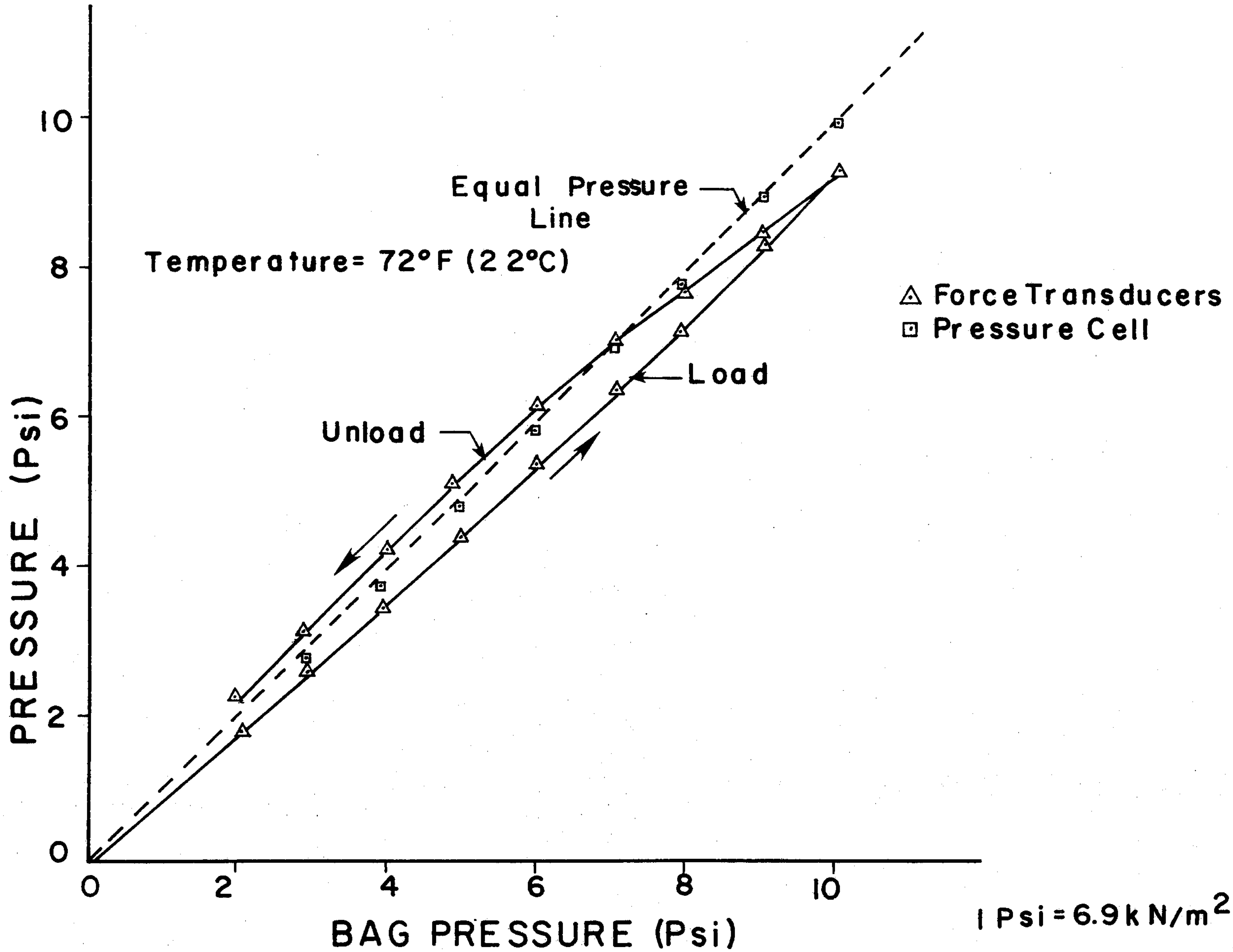

Fig. 31-TEST CHAMBER CALIBRATION WITH 2 IN. OF SAND

TABLE 12

VARIATIONS IN PRESSURE CELL AND FORCE TRANSDUCERS
WITH TEMPERATURE

Sand Condition (10 psi bag pressure)	PRESSURES (PSI) 15°F (-9.4°C)		100°F (38°C)	
	Pressure Cell	Force Transducers	Pressure Cell	Force Transducers
No Sand	10.05	9.58	10.30	10.12
2 in Loose Sand	9.29	9.49	10.00	10.19
2 in Dense Sand	9.55	9.68	10.15	9.71
ZERO OFFSET (0 psi bag pressure)	4.22	0.60	5.42	0.18

1 psi = 6.9 kN/m^2

the temperature extremes of the test conditions, 15°F (-9.4°C) to 100°F (38°C), there was good agreement between the pressure cell and the force transducers. Based on these test results it is concluded that the seasonal pressure variations noted in the field data are not solely the result of temperature related instrument error.

APPENDIX VI - MEASUREMENT OF PASSIVE PRESSURE ON A DRILLED SHAFT

INTRODUCTION -- During the fifth year of the study the feasibility of using earth pressure cells to measure the lateral earth pressure acting on a drilled shaft was investigated although this task was beyond the scope of the original study.

INSTRUMENTATION -- Instrumentation consisted of three Terra Tec pressure cells installed in a drilled shaft supporting a precast panel type retaining wall. The test site, shown in Fig. 32, is located at State Highway 19 and the Missouri-Pacific railroad overpass south of Lovelady, Texas. The retaining wall was constructed as shown in Fig. 32 to correct an earth slide which has occurred at the south header bank of the structure. The 30-in. (0.76m) diameter drilled shafts were placed at 12 ft (3.7 m) centers and pilasters were cast on top of the shafts. The precast concrete panels were placed between the pilasters to form a wall approximately nine feet (2.7 m) high. The shafts extended 16 ft (4.9 m) below natural ground, and the pressure cells were located at depths of three, six and nine feet (0.9 m, 1.8 m, and 2.7 m).

The method of installation of the cells is shown in Fig. 33. The cells were embedded in the soil prior to placing the concrete. A cavity was cut in the side of the hole facing the railroad tracks and the cell was placed against the soil. Dowel pins cut from steel reinforcement bars were used to hold the cell in place. Grout was packed around the periphery of the cell to prevent intrusion of concrete at the interface of the soil and the back surface of the cell. A thermocouple was placed near each cell.

SOIL PROPERTIES -- Properties of the soils at the test site are shown in Table 13. In general, the soil around the shaft was a highly plastic gray clay. Hand samples were obtained from the area of the original slide as well as driven tube samples from directly in front of the instrumented shaft. As shown in Table 13 the unit weight of this material was 122.5 pcf (1962 kg/m^3)with a moisture content of 24.3 percent. Although the wall was partially backfilled in December 1974, spreading and compaction of the fill material was not completed during the measurement period. For this reason the unit weight of the backfill was not

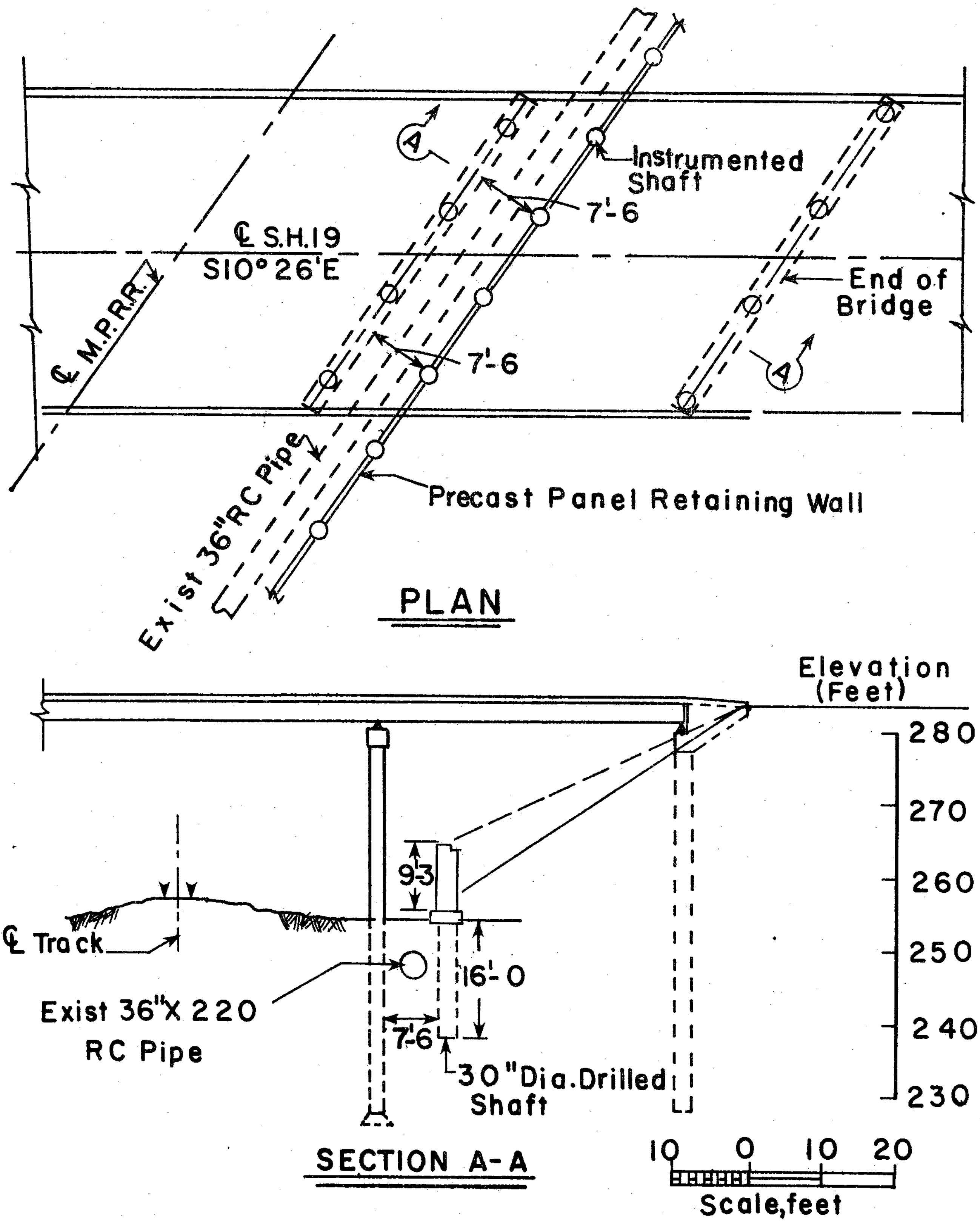

Fig. 32- LOVELADY, TEXAS, TEST SITE

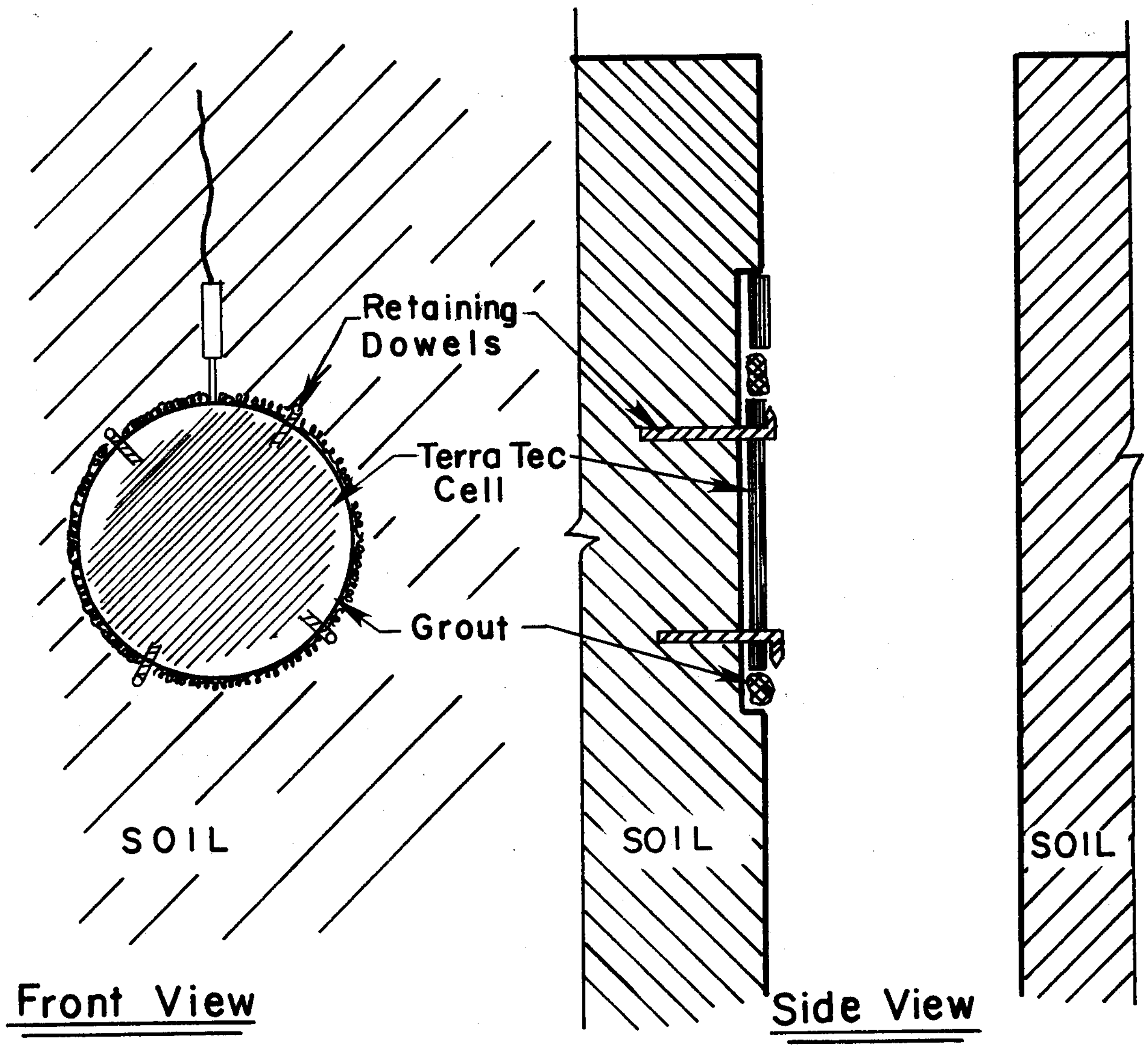

Fig. 33 - INSTALLATION METHOD FOR EARTH PRESSURE CELLS

TABLE 13 - SOIL PROPERTIES, LOVELADY TEST SITE

PROPERTIES	SAMPLE LOCATION		
	NEAR DRILLED SHAFT	FROM ORIGINAL SLIDE PLANE	BACKFILL MATERIAL
Unit Weight	122.5 pcf	-	-
Moisture Content	24.3 %	-	-
Liquid Limit	51	103	27
Plastic Limit	27	44	21
Plasticity Index	25	59	6
% Passing No. 200 Sieve	100	100	6.22
Classification (based on Unified Soil Classification System)	CH	CH	SP-SC
SAMPLING METHOD	DRIVEN SAMPLE TUBE	BAG SAMPLE	BAG SAMPLE

NOTE: 1 pcf ≑ 16.02 kg/m^3

determined. However, a laboratory soil classification test revealed the fill soil to be a sand with about six percent fines. Laboratory test results for the backfill are also shown in Table 13.

EARTH PRESSURE MEASUREMENTS -- Lateral earth pressures were measured over a period of 244 days. These measurements are plotted in Fig. 34 and tabulated in Table 14. A zero offset versus temperature calibration was not made. However, an initial zero offset was determined for each cell at the test site prior to placing of the concrete and this offset was subtracted from the subsequent field readings.

Analysis of the pressure changes as shown in Fig. 34 reveal the following:

1) The initial pressures were measured prior to set of the concrete. Pressures decreased as the concrete began to set and gain strength.
2) Pressures remained low until backfilling began in November. The slight pressure increase occurring in November resulted from partial backfilling of several panels not directly bearing on the instrumented drilled shaft. Backfilling was completed prior to the December readings. The large pressure increase which occurred during this period, as shown in Fig. 34, resulted from backfilling.
3) Cell pressures began to decrease after December, dropping about 3 psi (21 kN/m^2) by April. A slight increase occurred between April and May.
4) The lower two cells have measured nearly equal pressures since December. The upper cell readings have been about 2 psi (14 kN/m^2) below those of the lower cells.

COMPARISON WITH THEORETICAL PASSIVE EARTH PRESSURES -- The passive earth pressure for saturated clays in undrained loading is computed as follows (12):

$$P_p = \gamma Z + 2C \tag{24}$$

where: P_p = Passive earth pressure

Z = Depth (below ground level)

C = Soil cohesion (from unconsolidated undrained shear strength test)

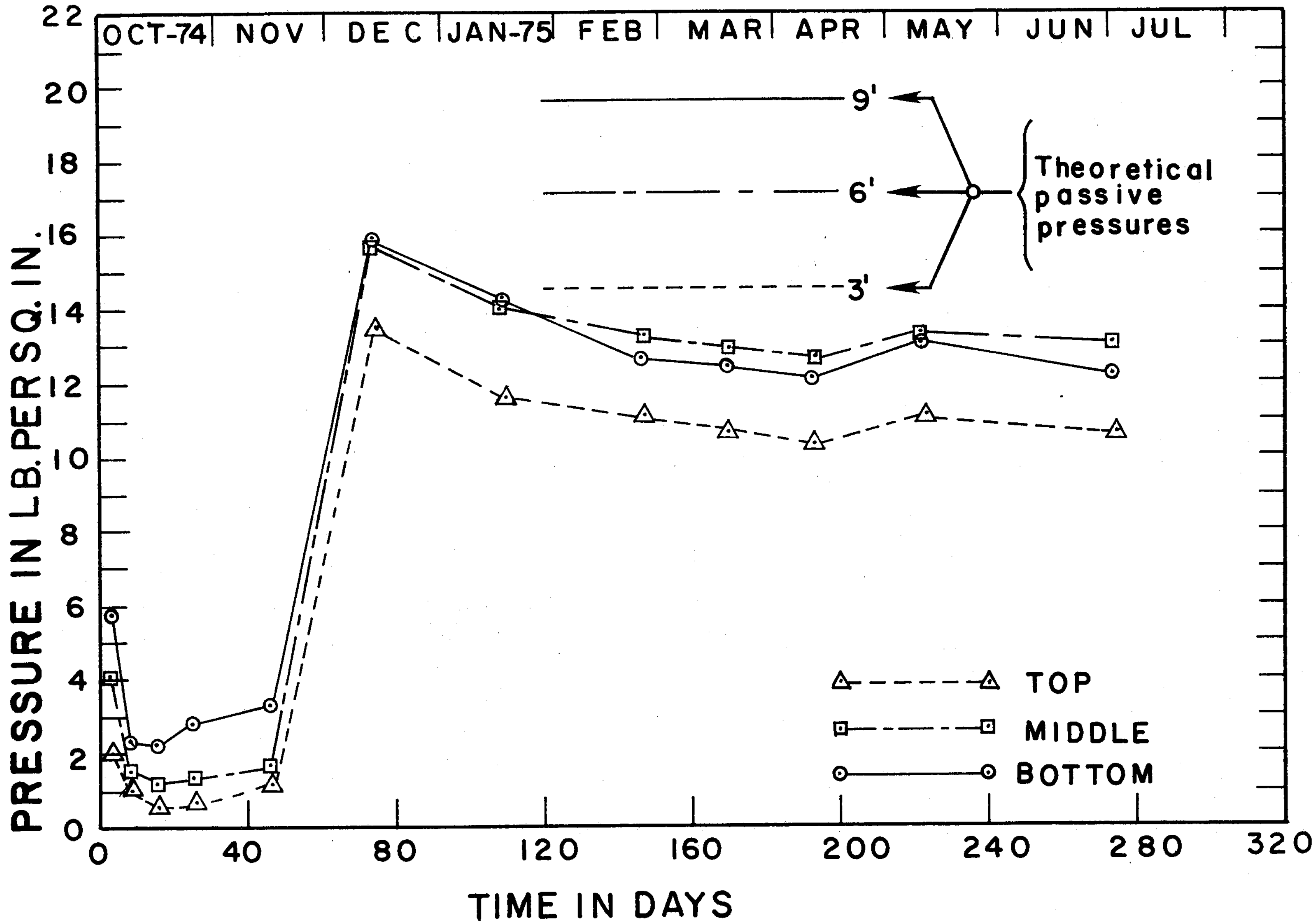

Fig 34- PRESSURE VS. TIME FOR LOVELADY DRILLED SHAFT

TABLE 14 - MEASURED LATERAL EARTH PRESSURES, LOVELADY TEST SITE

DATE	TOP CELL No. 735		MIDDLE CELL No. 736		BOTTOM CELL No. 737	
	Temp °F	Earth Pressure, psi	Temp, °F	Earth Pressure, psi	Temp, °F	Earth Pressure, psi
3 Oct. 74	--	2.0	--	4.1	--	5.8
8 Oct. 74	82	0.95	81	1.5	78	2.30
15 Oct. 74	74	0.65	74	1.25	70	2.15
25 Oct. 74	69	0.65	70	1.3	70	2.75
15 Nov. 74	63	1.2	65	1.65	65	3.3
13 Dec. 74	55	13.45	58	15.7	60	15.85
17 Jan. 75	51	11.65	56	14.1	59	14.25
24 Feb. 75	62	10.95	68	13.2	70	12.65
19 Mar. 75	56	10.65	55	12.9	56	12.4
11 Apr. 75	56	10.35	57	12.6	57	12.05
13 May 75	64	10.95	61	13.3	64	12.55
1 July 75	62	10.55	61	13.0	60	12.25

NOTE: 1 psi = 6.9 kN/m^2

For this case the following values were used:

γ = 123 pcf (1970 kg/m^3)

Z = 3 ft, 6 ft and 9 ft (o.9 m, 1.8 m, and 2.7 m)

C = 860 psf (41.2 kN/m^3)

The values of P_p are given in Table 15 below.

TABLE 15 - THEORETICAL PASSIVE EARTH PRESSURES, LOVELADY TEST

Depth	γZ (psi)	P_p (psi)
3'	2.56	14.51
6'	5.13	17.07
9'	7.69	19.63

NOTE: 1 psi = 6.9 kN/m^2

These pressures are shown for comparison purposes on Fig. 34. It can be seen in Fig. 34 that the measured pressures are lower than the theoretical passive values.

CONCLUSIONS -- The Terra Tec cells in conjunction with the installation procedures used in this test have been shown to provide a reasonable method for determination of passive earth pressures acting on a drilled shaft.

As in the case of active pressures, the magnitude of passive pressures depends on the amount of movement between the cell and the soil. An accurate comparison of theoretical and measured pressures requires a precise knowedge of the relative movements involved. Thus, it is recommended that movement measurements be taken if these procedures are used in future programs.

NOTES