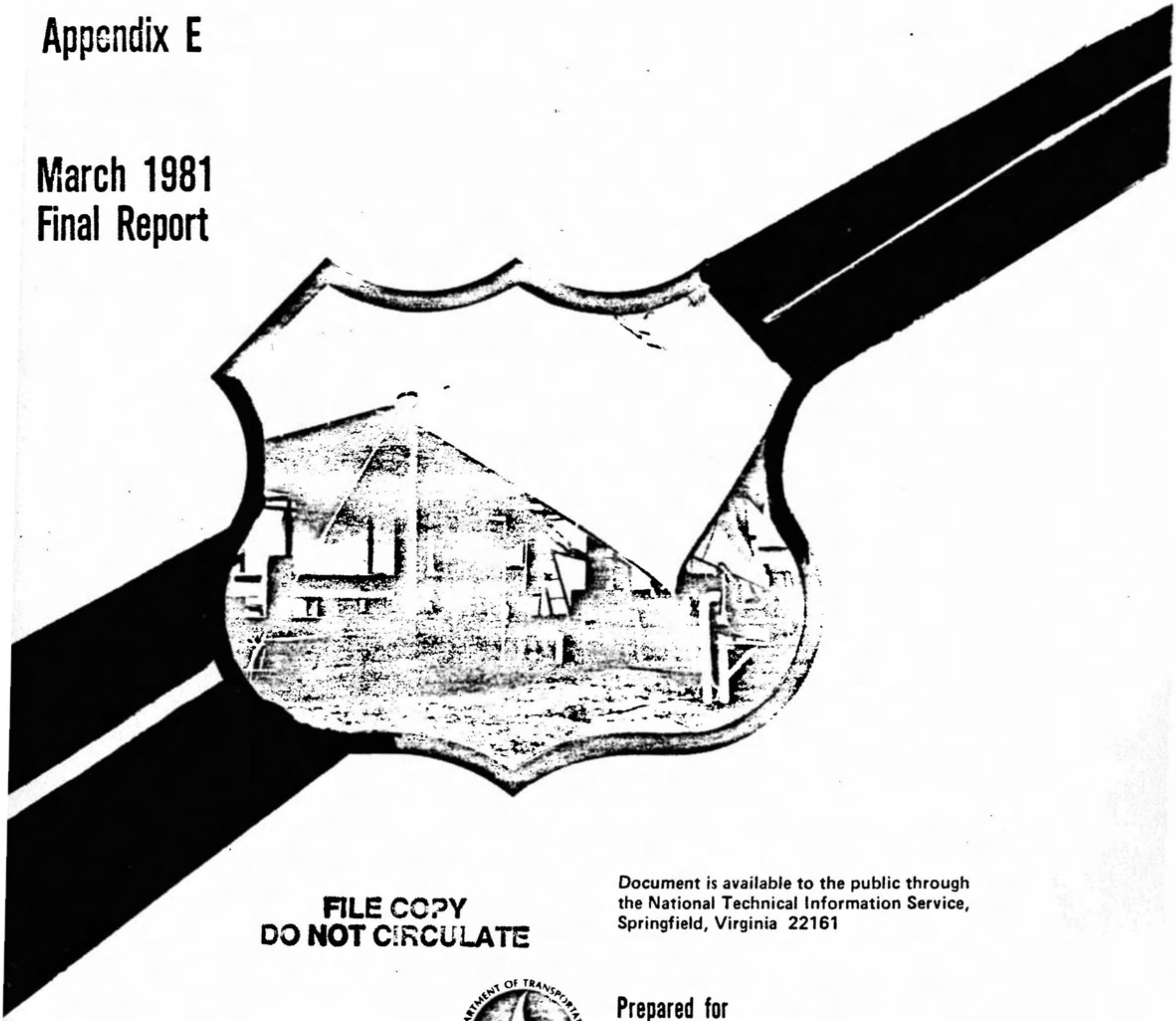
HWA/RD-81/007

UDY OF PILE GROUP ACTION

Appendix E

March 1981
Final Report



Document is available to the public through
the National Technical Information Service,
Springfield, Virginia 22161

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Materials Division
Washington, D.C. 20590

Technical Report Documentation Page

1. Report No.
FHWA/RD-81/007

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

FIELD STUDY OF PILE GROUP ACTION
Appendix E: Evaluation of Instrumentation.

5. Report Date
October 1980

6. Performing Organization Code

7. Author(s) A. H. White, N. C. Peterson, J. R. Skytta, and M. W. O'Neill

8. Performing Organization Report No.

9. Performing Organization Name and Address
RAYMOND INTERNATIONAL BUILDERS, INC.
2801 SOUTH POST OAK RD
HOUSTON, TEXAS 77027

10. Work Unit No. (TRAIS)
FCP 34H2-032

11. Contract or Grant No.
DOT-FH-11-9526

12. Sponsoring Agency Name and Address
OFFICES OF RESEARCH AND DEVELOPMENT
FEDERAL HIGHWAY ADMINISTRATION
U.S. DEPARTMENT OF TRANSPORTATION
WASHINGTON, D.C. 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
M/0687

15. Supplementary Notes

FHWA Contract Manager: Mr. Carl Ealy (HRS-21)

16. Abstract

This report is Appendix E; Evaluation of Instrumentation, of the final report for a study involving the static vertical load testing of a full scale, instrumented pile group. The test group consisted of nine pipe piles instrumented for settlement, load transfer, pore pressures, total pressures and inclination. Appendix E describes in detail problems encountered with the various pile and soil instrumentation systems, documents transducer performance, describes pile calibration and describes the procedure used for fitting strain gage data. Sources and evaluation of errors in deformation measurements are also considered.

The results of this study are available in the following FHWA publications.

FHWA/RD-	Field Study of Pile Group Action-
81/001	Interim Report Describes several mathematical models for pile groups
81/002	Final Report Summarizes the prominent results of the field experiment
81/003	Appendix A: User's guide for Program PILGP1
81/004	Appendix B: Documentation for Program PILGP1
81/005	Appendix C: Geotechnical Investigation
81/006	Appendix D: Detailed Graphical Presentation of Reduced Data
81/008	Appendix F: Supplementary Information
81/009	Dynamic Pile Driving Measurements for University of Houston Pile Group Study

17. Key Words

Piles, Clay soils, Pile groups, computer model, pile driving

18. Distribution Statement

No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	55	

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

Preface

This is the second and final report for a project entitled "Field Study of Pile Group Action." The Interim Report, dated March, 1979, precedes this report. The Interim Report describes several mathematical models for pile groups, presents an analysis of a proposed field experiment using one of the models, and describes details of instrumentation and procedures for that experiment. This report describes the results of the field experiment, which involved the load testing to failure of an instrumented, full-scale 9-pile group and two control (reference) piles at several times after installation. Two tests were also performed on subgroups of piles within the main 9-pile group, and uplift tests of several individual piles were also conducted.

This report is divided into a main text and six appendices, labeled A-F. The main text summarizes the prominent results of the study. Appendix A is a user's guide for Program PILGP1, a mathematical pile group model; Appendix B contains documentation for PILGP1; Appendix C contains detailed geotechnical data for the test site; Appendix D contains selected load-settlement, load distribution and load transfer plots; Appendix E is an evaluation of instrument performance; and Appendix F contains graphs and tables that support the main text that were not considered essential to the intergrity of the main text. Appendices A-F are bound separately from the main body of the text and from each other.

The project was sponsered by the Offices of Research and Development, Federal Highway Administration, U.S. Department of Transportation. Raymond International Builders, Inc., was the prime research contractor. The University of Houston Central Campus (UHCC) was a subcontractor responsible for mathematical modeling, pile instrumentation, electronic data acquisition, analysis of results, and report preparation. Fugro Gulf, Inc., was a subcontractor responsible for the geotechnical study and for the ground instrumentation systems.

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
Angstroms	0.0000001 (10^{-7})	millimetres
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square inches	0.00064516	square metres
square feet	0.09290304	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
grams	0.001	kilograms
pounds (mass)	0.4535924	kilograms
tons (2000 pounds)	907.1847	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.59327631	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (force) per square foot	4.882428	kilograms per square metre
miles per hour	1.609344	kilometres per hour
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

---

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

APPENDIX E

TABLE OF CONTENTS

APPENDIX E

Evaluation of Instrument Performance

GENERAL

The purpose of this appendix is to evaluate performance of the principal instrumentation systems used in the Federal Highway Administration's pile group research project conducted on the Central Campus of the University of Houston.

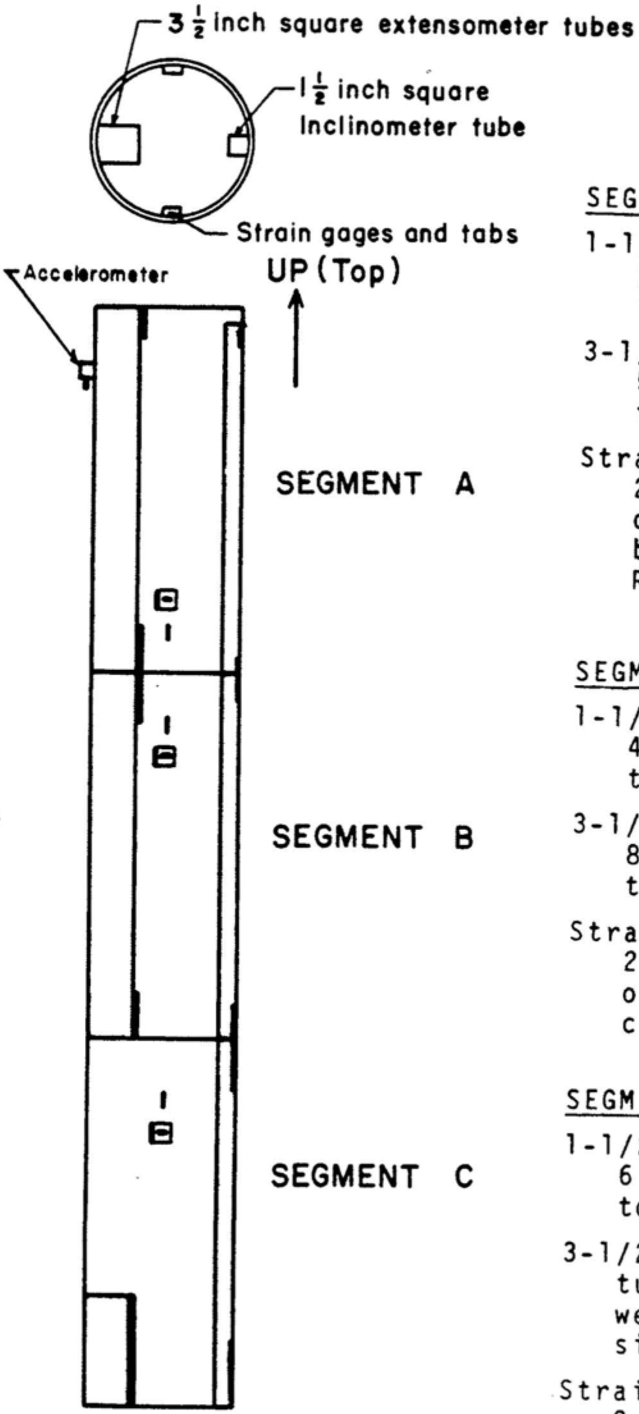
The principal instrumentation systems considered include the strain gage system, the mechanical extensometer system, the lateral pressure cell system, the inclinometers, and the data acquisition system. In addition, consideration is given to measurement of pile deflections, ground pore water pressures, and ground movement. The reader is referred to Chapter 5 of the Interim Report for details of these systems.

It was desired to use simple, proven systems, as far as possible, as opposed to systems that would require development as a part of the project, and to provide redundancy where feasible. Experiences with the various systems will be summarized to include documentation of successful systems and problems encountered in installation and operation of the systems.

INSTALLATION OF INSTRUMENTATION

Test Segments

Prior to the instrumentation of the FHWA load test prototype piles, a short test pile was constructed to evaluate the materials, assembly procedures, welding techniques, various adhesives, and instrumentation that were thought to be sensitive to driving. The test pile consisted of three segments of pipe identical to the prototype, each 5 feet (1.5 m) long, welded end-to-end, for a total length of 15 feet (4.5 m). Each section contained a full-bridge strain gage circuit, a 3-1/2-inch (89 mm) square extensometer tube, and a 1-1/2-inch (38 mm) square inclinometer tube. Weld lengths were varied from segment to segment to assess the optimum welding pattern for the prototypes. In addition, 34-conductor, 28-gage ribbon cable lead wire was included. This wire was to be used in the prototypes to keep order in wiring and for ease of installation. The wire was attached to the inner walls of the pile sections using a hot melt bonding compound supporting 90% of its length, with free zones at the segment joints. A schematic of the test pile with section variations is shown in Fig. E1. Also included in the test pile was some lateral pressure cell pneumatic tubing. The tubing was seated in "U"-shaped steel brackets and potted with either "Bondo" (an automobile body repair compound) or silicon rubber. All welding was of the short arc M.I.G. type, which was used on the prototypes (except where later noted) to minimize heat.



SEGMENT A

1-1/2 inch square tube;
2 inch weld, both sides, top and bottom.

3-1/2 inch square tube;
5 inch weld, both sides, top and bottom.

Strain Gage Tabs
2 inch weld, one side only, 11 inches from bottom, covered with Bean RTC epoxy.

SEGMENT B

1-1/2 inch square tube;
4 inch weld, both sides, top and bottom.

3-1/2 inch square tube;
8 inch weld, both sides, top and bottom.

Strain Gage Tabs
2 inch weld, one side only, 13 inches from top coated with Bondo.

SEGMENT C

1-1/2 inch square tube;
6 inch weld, both sides, top and bottom.

3-1/2 inch square tube;
tube was 18 inches long, welded full length, both sides, located at bottom.

Strain Gage Tabs
2 inch weld, one side only, 15 inches from top, coated with Hysol 3X epoxy.

Note: 1 in.=2.54 cm.

FIGURE E1. TEST PILE FOR ASSESSMENT OF DRIVING RESISTANCE OF VARIOUS ATTACHMENTS (SCHEMATIC)

Because the characteristics of the pile test and driving system differed from actual prototype driving, an accelerometer was mounted on the side of the pile to measure test accelerations. The pile was driven dead-headed by about 2000 blows from a Raymond Type 1-S hammer at the Raymond Shell Plant in Baltimore Maryland, on May 24, 1979. Acceleration amplitudes were measured to be 700 g's (single amplitude), which was more than twice the peak acceleration ultimately observed in the prototype piles during actual driving. Furthermore, during the test, the test pile was driven approximately 2000 blows, while the prototype piles were actually struck with a total of only about 250 blows each. Thus, the test represented much more severe conditions than were later encountered with the prototypes.

Upon completion of this test, the pile was flame-cut longitudinally and laid open. It was noted during inspection that:

1) A 2-inch (50 mm) fillet weld on the inclinometer tubing had been broken at the top of the pile (Segment A), probably due to radial spreading of the pile head.
2) The welds on two strain gage tabs on Segments B and C had failed and the tabs had fallen off the pile.
3) Ribbons remained well-bonded using the hot melt procedure.
4) Lateral pressure cell tubing remained well-bonded with both adhesives.

There was also considerable zero shift in the middle (Segment B) and bottom (Segment C) strain gage bridges after 500 blows. Analyses of the data revealed that the probable cause of the zero shift in the strain gages was relative movement of the steel tabs and pile wall (at the weld) during driving which stretched the wire connecting the dummy strain gage and the solder tab. To insure against this happening in the prototypes, these wires in the prototypes were potted in a soft epoxy channel, which allowed some relative movement between the tab and pile wall without stretching the wire. Furthermore, the welding process used in attaching the tab to the pile wall was improved by beveling the tab to a 45° angle prior to attachment, thus allowing more penetration of the weld, and the cleaning of all mill scale from the tab and pile wall (not done on test section).

When the test segments were welded together, temperature measurements were taken one foot (0.3 m) from the weld, which was the approximate distance of the strain gages from each main weld. Since damage may be done to strain gages when the temperature reaches 150°C, it was necessary to know the distance from the weld at which the strain gages could safely be laid. It was determined that the five foot (1.5 m) pile segments could be welded together safely with an M.I.G. welder using Linde 8G-.035 inch (1.1 mm) wire by making three consecutive circumferential passes in a period of about one hour. The temperature in the pile remained under 100°C at one foot (0.3 m) from the weld using this process.

Preparation of Piles for Instrumentation

Prior to the placement of instrumentation on the prototype piles, a systematic process was developed to prepare the piles for instrumentation.

The piles arrived at the shop in thirteen 48-foot (14.6 m) lengths. Of the thirteen lengths, the eleven that were in the best condition were chosen as the primary lengths for the piling. The technique followed in preparing the piles is described below:

1) The first length was placed on jackstands at approximately a 4-foot (1.2 m) height off the floor to provide a comfortable working height.
2) The entire length of the pile was rough-marked with chalk at the proper segment lengths, and each segment was marked T-A-11 (top of Segment A, Pile Number 11) through Section T-J-11 with chalk.
3) The pile was then chalk-lined from end-to-end for alignment, and punch marks were stamped 3 inches (80 mm) above and 3 inches (80 mm) below the pile segment rough cut mark. In this way the piles could be reassembled in exactly the same configuration as existed in manufacture to aid in assuring proper alignment.
4) The length of the pile was then color-coded with one line of spray paint to prevent any mix-up of pile segments upon reassembly. The mill lacquer which existed on the piles on their arrival was not removed.
5) The pile was marked with the desired segment lengths (allowing 1/8 inch (3 mm) for a 45° flame cut) beginning at the bottom end of the pile. The bottom segment (J) was then cut out and the cut beveled with a torch. The top of this section was then stamped with punches T-J-11 (Top, Segment J, Pile 11). This process was continued to the top section (T-A-11). Odd lengths, approximately 3-1/2 feet (3 m) long, were cut from the remaining two lengths to complete the extension segments on the group piles.
6) This procedure was followed for all eleven piles. After each pile was cut, the sections were placed together according to pile number on the floor of the work area.

During the process of the pile cutting, other production tasks took place concurrently. All the tubes for the inclinometers and the extensometers were cut to the proper length. The tabs for the temperature-compensating dummy strain gages were also cut, cleaned and gaged. The tab preparation proceeded as follows:

1) The tabs were cut from extra lengths of the pipe to a dimension of 2 in. x 2 in. x 3/8 in. (50 mm x 50 mm x 10 mm).
2) One edge of the tab was ground to a 45° angle to allow for good penetration of the weld when installing the tab in the pile segment.

3) The surface of the tab was then sanded to a smooth finish, removing all mill-scale and pits.
4) The tab was then strain gaged. (This procedure will be discussed later.)

After one pile had been segmented work was begun on the individual segments to prepare them for the instrumentation. Individual segments were placed one at a time on a work table, and the following preparations were performed:

1) The segment was placed on variable-speed driven rollers that rotated the section at approximately ten revolutions per minute. While the section was rotating, the inside was sanded with a rotary sander and the ends were beveled with a 1/8 inch (3 mm) flat area on each end. The squareness of the ends was checked, and the ends were reground if there were any high spots. The precise length of each segment was then noted so that overlength or underlength segments could be compensated for on succeeding segments on a given pile.
2) The instrument locations and the tube positions were marked in the segment with chalk using a template that fit over the end of the segment and indicated positions for the instruments.
3) The extensometer tubes and tabs were then clamped down in their position in the section and were welded. Each tab was welded 1 inch (25 mm), allowed to cool, and then the other 1 inch (2.5 cm) was welded.

Some of these steps may be seen in Fig. E2.

Once these tasks were performed, the segments were then moved into an environmentally controlled work room where the strain gages were installed.

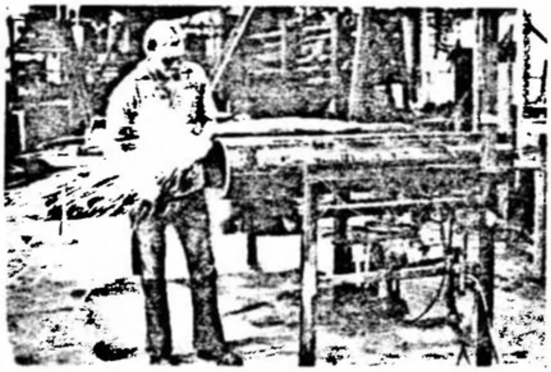
The instrumentation and subsequent reassembly process began with Pile 11 and proceeded to Pile 1. The entire instrumentation and calibration process required about five months to complete.

Strain Gages

The strain gages for measurement of static force were installed in the interiors of the eleven test piles as shown in Fig. E3. The placement of the gages in the interior of the piles permitted flushing of the ambient air with dry nitrogen, thus minimizing the build-up of moisture on the gage elements and thereby enhancing long-term stability.

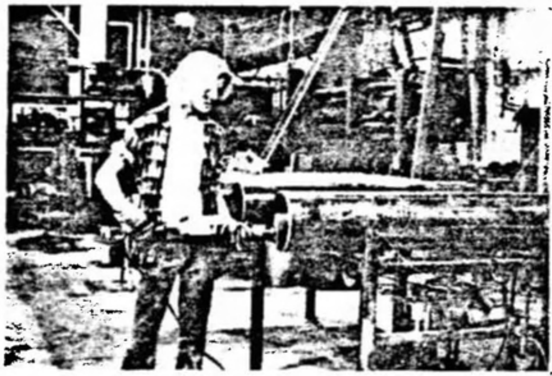
Tab and Pile Wall Preparation

The steel tabs used for the temperature-compensating strain gages and the pile wall area where the active gages were laid were prepared in the same manner. The preparation and gage installation procedures were as follows:

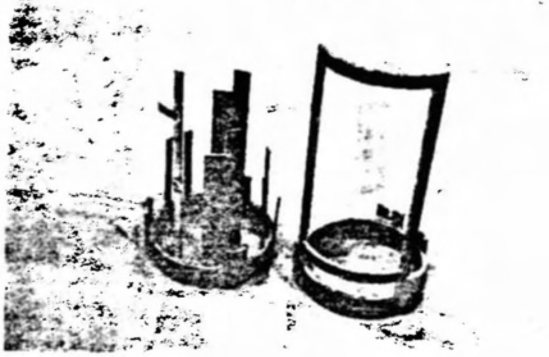


a. Facing segment end

b. Marking instrument locations



c. Cleaning interior of segment



d. Instrumentation templates

FIGURE E2. PREPARATION OF PILE SEGMENTS

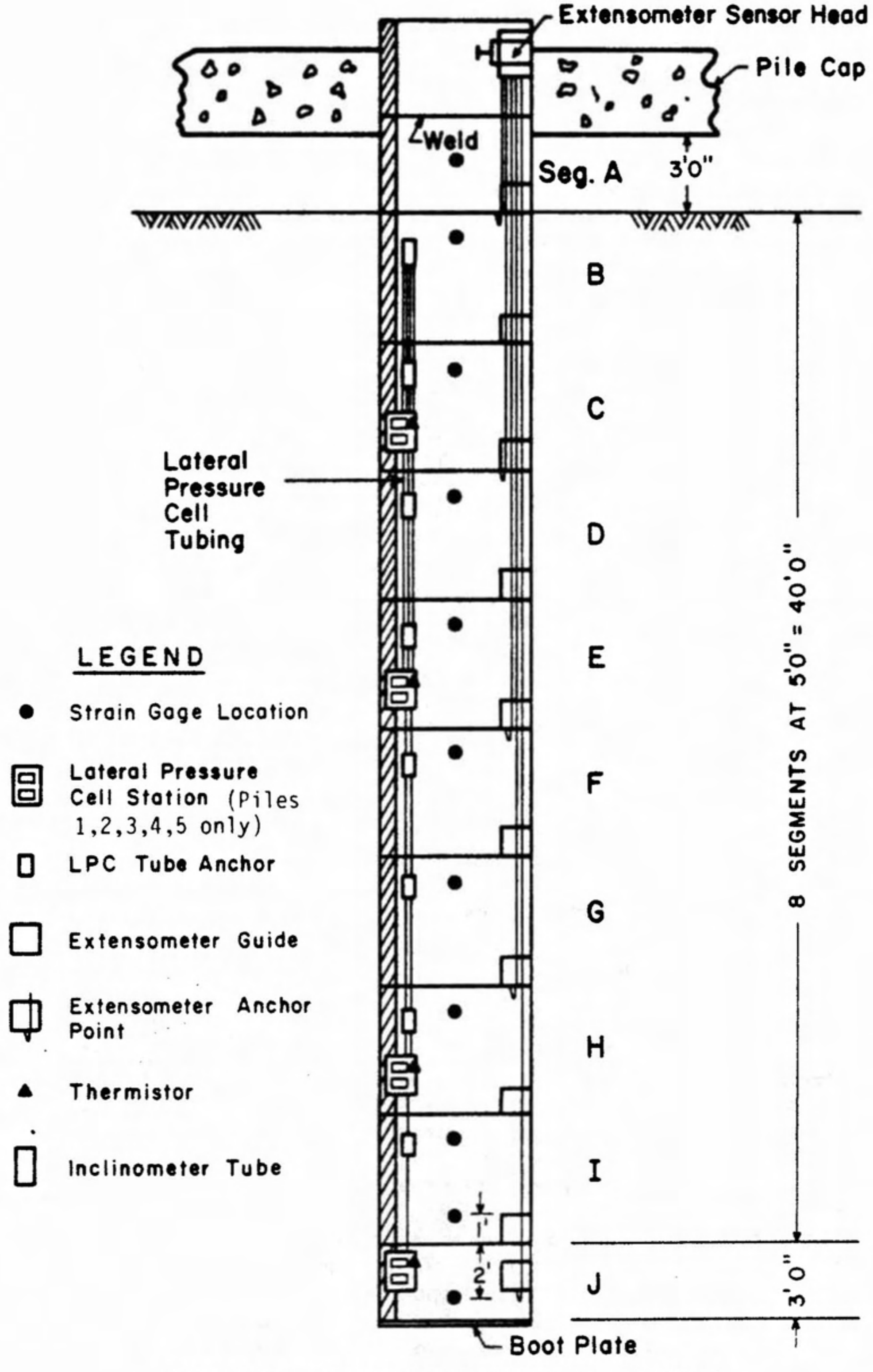


FIGURE E3. INSTRUMENTATION SCHEME FOR PILES
(1 ft = 0.305 m; 1 in = 25.4 mm)

1) The steel (tab or pile wall) was sanded to a smooth finish using a high-speed rotary sanding disk.
2) The steel was then sanded with 320 grit silicon carbide strips saturated with Bean Metal Conditioner.
3) The area was then wiped with dry tissue.
4) The tabs and pile wall were then wiped with tissue saturated with Bean Neutralizer Solution.
5) The tabs and pile wall were wiped dry again.
6) The gages were then placed face down on 1/2-inch (13 mm) mylar tape, and the backs of the gages were swabbed with neutralizer.
7) The gages were then placed in their respective positions on the tabs and pile wall and bonded with Bean RTC epoxy.
8) The gages on the tabs were then cured in an oven for approximately 24 hours at a temperature of 80°C, after which the tabs were welded into the appropriate pile segments, as described previously. The active gages, which were not placed until the dummy gages and tabs had been welded, were cured using heater bands around the pile segment for approximately four hours at 95°C with a 10 psi (69 kN/m^2) pressure applied to the tops of the gages using spring-loaded rods and soft rubber squares to protect the gages.
9) The active and dummy gages were then wired to a CEG 75C barrier tab.
10) The gage resistance (350 ohms) and the resistance to ground (100 megohms minimum) were then measured to insure that the gages had been successfully bonded.
11) The wires from the gages were then "painted" into place using a silicon rubber cement, the whole assembly was waterproofed with Epoxy Patch, and the resistance was once again checked when the epoxy cured.

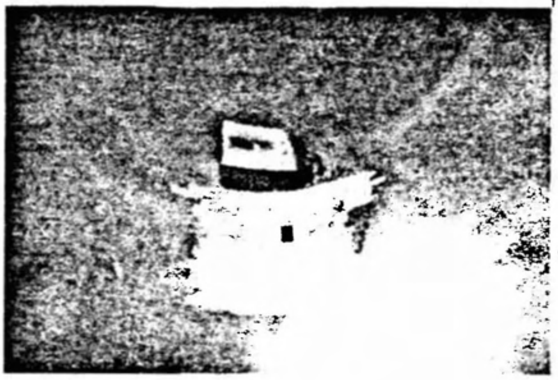
Some of these steps are illustrated in Fig. E4.

Lateral Pressure Cell Installation

The manufacturer of the total pressure cells had indicated that buckling of the flat pressure cell sensor plate was possible if the temperature of the cell rose above 40°C, due to expansion of fluid behind the sensor plate. Therefore, in order to assess the effects of welding of the cell into the wall of the pile, heat tests were first conducted, as described here. Prior to installation of the pressure cells, a coupon the size of the pressure cell backing plate was cut out of a short section of leftover pipe used for the piles and welded back into the pipe to determine the temperatures that may be expected during installation. (The lateral pressure cells were not tested on the short test pile described previously because prototype cell models were not available at the time.) The temperature of the coupon rose to greater than 95°C as the coupon was welded back into the pile section. Attempts to cool the coupon with a carbon dioxide fire extinguisher were not successful. Large amounts of the CO_2 were shot directly on

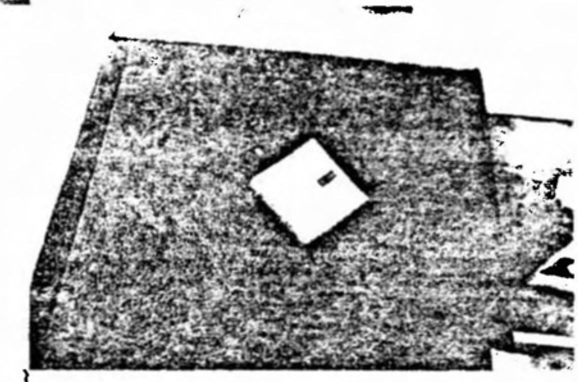
a. Dummy tab in place; active gage location marked

b. Active gage epoxied into place



c. Active and dummy gages wired to barrier

d. Dummy gage on tab



e. Heat curing of gages with band heater

FIGURE E4. VARIOUS STEPS IN PLACING STRAIN GAGES the coupon, but the CO_2 evaporated too quickly to cool the coupon effectively.

A steel box (Fig. E5) was then fitted above the coupon, and ice water was circulated through the box over the coupon as it was welded in. Temperature measurements were taken on the bottom of the coupon inside the pile approximately where the total pressure cell would be located. The temperature was kept at less than 38°C by this method where the pressure cell would be located. It was decided to use this method to cool the prototype cells during placement into the prototype piles.

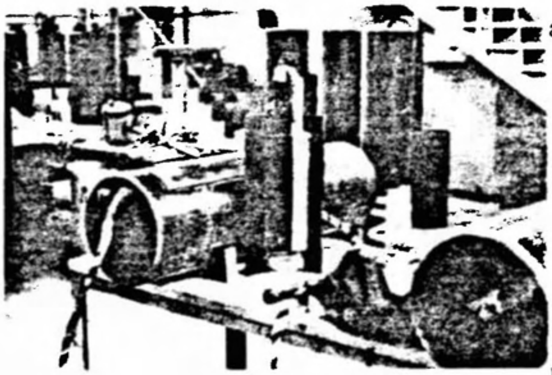
The lateral pressure cells, each consisting of one total pressure cell and one piezometer, were prefabricated by a geotechnical instrumentation specialist subcontractor. The cells are shown pictorially in Fig. E6. They arrived mounted in a curved plate of the same steel used in the piles. The plate had the same thickness and approximately the same curvature as the pile walls. The cell design is described in more detail in the Interim Report. The preparation of the pressure cells before installation on the pile segments consisted of placement of a thermistor (0.005°C-sensitive, compatible with Budd P-350 readout device) and the securing of the pneumatic tubing (cut to predetermined lengths) to the cells.

The total pressure cell zero readings were found to be very sensitive to cell temperature. The total pressure cells were thus calibrated for apparent pressure versus indicated temperature and indicated temperature versus actual temperature under no load conditions. This calibration procedure is described later.

Once the cells were calibrated they were installed in the appropriate pile segments on Piles 1 through 5. The lateral pressure cell numbering scheme is shown in Fig. E7. The numbers shown there are the manufacturer's cell numbers.

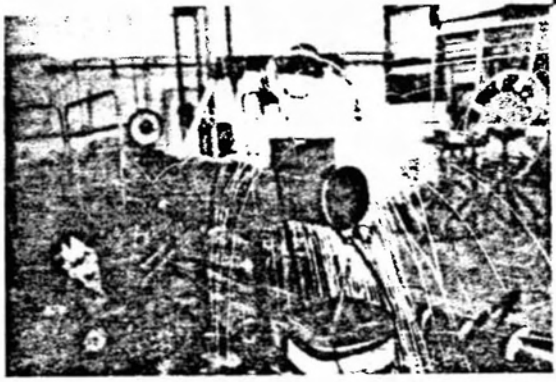
The method of installation was as follows:

1) A coupon was cut out of the appropriate position (previously marked with a template) from a pile segment.
2) The cell was placed into the cut-out and was tack-welded in according to best fit. The supplier had welded stiffeners to strengthen the cells behind the backing plates in such a way that the plates were slightly warped in a concave fashion. To insure that the piezometer and total pressure cell faces would be flush against the soil after installation, it was decided to rotate the top edge of the plate outward about 0.2 inches (5 mm) to fit the cells so that the total pressure cell plate would be flush with, or would protrude slightly from, the general pile surface. Pressure cells 5, 14, and 20, on Piles 4 and 5, were installed in this manner, but this method proved to be unsatisfactory in general because the cell dimensions varied enough that a structurally sufficient weld could not be laid on the top edge of all the cells. It was decided, therefore, to use a standard fit for the remainder of the cells as follows: the top of the cell projected outside the pile by 1/8 inch (3 mm) and the bottom of the cell was flush with the outside of the pile.



a. Pressure cell prior to attachment and tack welded into pile segment

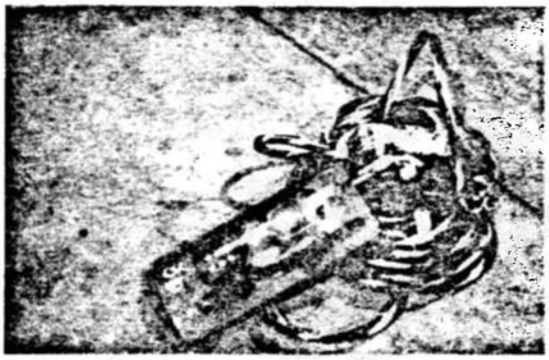
b. Top view of cell fitted into pile segment



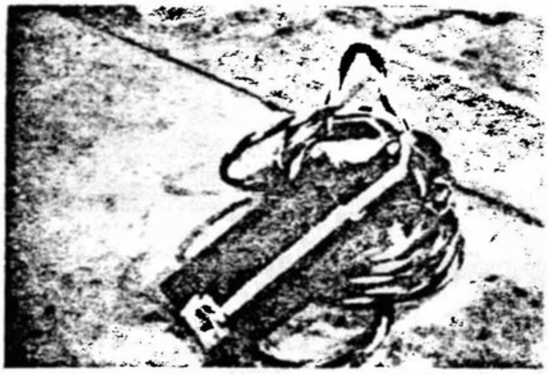
c. Welding of cell into segment

d. Water bath used to cool cell during welding

FIGURE E5. LATERAL PRESSURE CELL INSTALLATION



a. Top view of cell and tubing



b. Bottom view of cell, showing thermal sensor

c. Cutout for cell on pile segment

FIGURE E6. VIEWS OF LATERAL PRESSURE CELLS

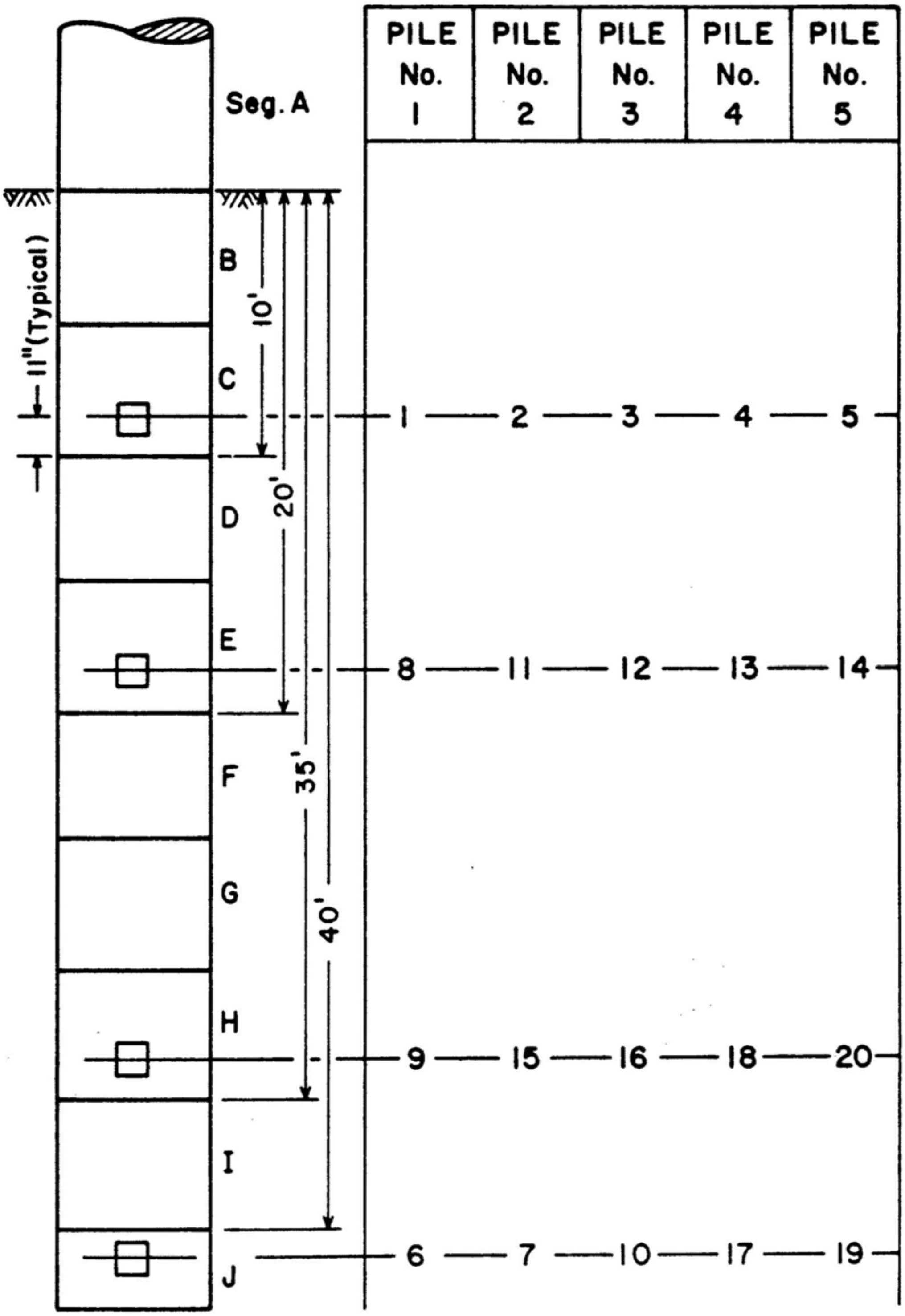


FIGURE E7. LATERAL PRESSURE CELL NUMBERING SCHEME
(1 ft = 0.305; 1 in = 25.4 mm)

3) Each cell was then welded into place all around its perimeter in two or three passes with an M.I.G. welder. (It was kept cooled by the chilled water vessel mentioned earlier.)
4) The weld was then ground flush with the outside of the pile wall, and all protruding steel on the cell face was ground away by hand. This process left some small irregularities in the pile surface along the line of pressure cells. Such irregularities had an average double amplitude of about 3 mm with respect to the cylindrical face of the pile. A catalog of cell irregularities, is given in Fig. E8 and in Table E1. The small "knob" just above the top edge of the total pressure plate could not be removed because heat generated by grinding in close proximity to the cell face could have caused permanent damage.
5) Once the cell was welded into the segment, the segment was placed in a temperature-controlled environment, and the pressure-temperature calibration was again checked. On three cells a zero shift was discovered, requiring the resetting of the total pressure zeros. This was accomplished by repeated, cushioned hammer blows to the sensor face.

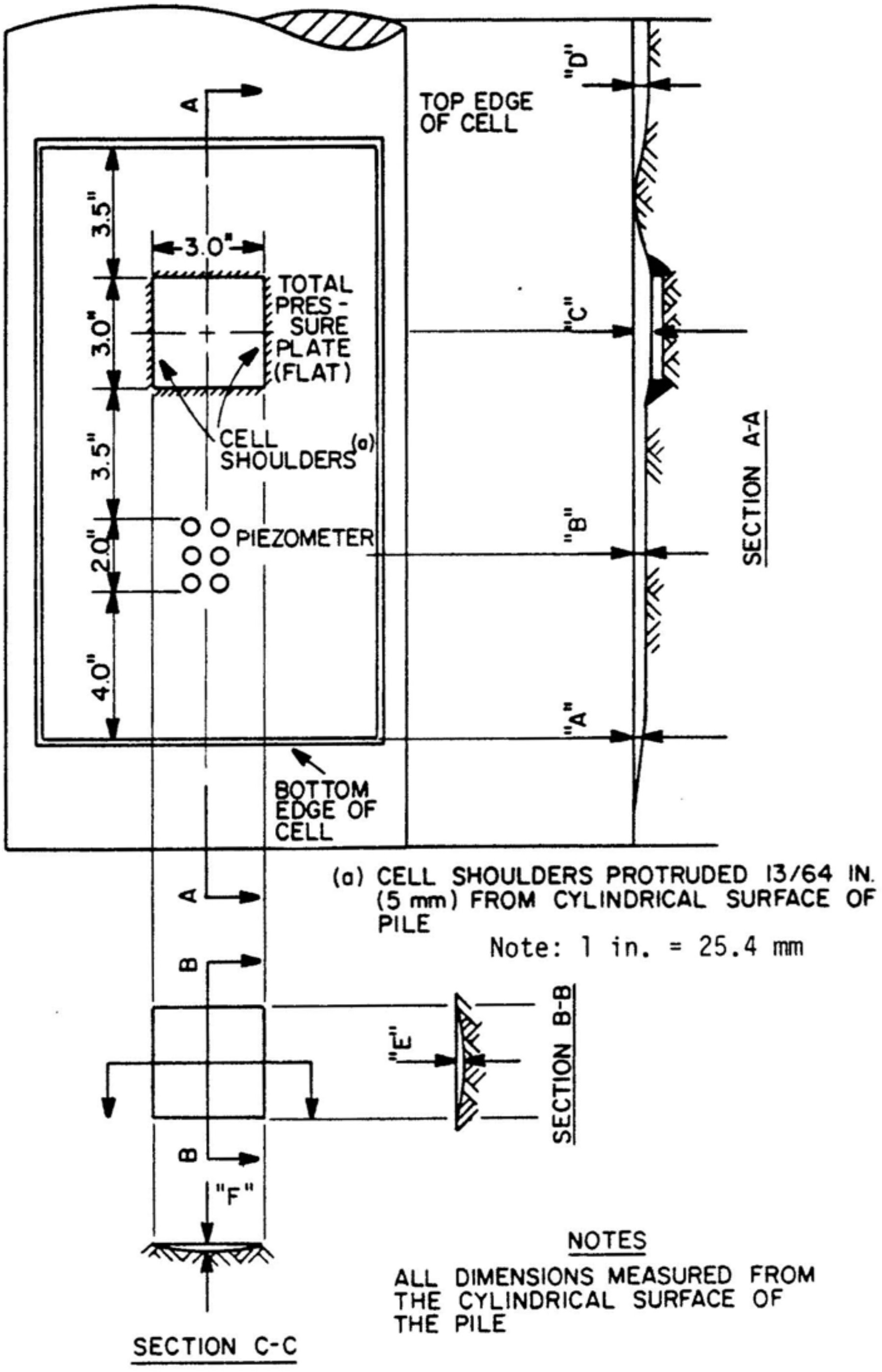
Pile Assembly

Prior to the pile reassembly, several steps were taken to insure ease of production and to eliminate blunders. These were:

1) The ribbon cables for all eleven piles were pre-cut to the proper lengths, and the back of each was deposited with hot melt wax.
2) The tubes for the inclinometers were cut to two 24-foot (7.3 m) lengths, rather than the 5-foot (1.5 m) lengths used in the test pile, to reduce the number of joints to be aligned to one per pile.

The pile reassembly process consisted of:

1) The area [a 3-inch (76 mm) wide strip] where the ribbon cable would be laid was cleaned by hand sanding and then wiped clean with acetone and tissue.
2) Two sections (beginning at the bottom, Segments I and J) were aligned on a heavy H-beam using the punch marks previously placed upon disassembly, and were then welded together.
3) The ribbon cable was pulled through toward the top of the pile, the strain gages wired, and the wiring then waterproofed with Epoxy Patch. Individual strain gages for dynamic response were then placed at appropriate levels, and their leads were brought up in a bundle with the pressure cell tubing.
4) Heater bands were placed on the two sections and heated to approximately 75°C to melt the hot melt compound, and the ribbon cable was then secured to the pile using a roller. (The wire was not fastened for 6 inches (150 mm) on either



(a) CELL SHOULDERS PROTRUDED 13/64 IN. (5 mm) FROM CYLINDRICAL SURFACE OF PILE

Note: 1 in. = 25.4 mm

NOTES

ALL DIMENSIONS MEASURED FROM THE CYLINDRICAL SURFACE OF THE PILE

FIGURE E8. SECTIONS OF AS-BUILT LATERAL PRESSURE CELLS, SHOWING IRREGULARITIES (SCALE EXAGGERATED)

TABLE E1. PILE PRESSURE CELL IRREGULARITIES, AS-BUILT (1 in. = 25.4 mm)

PRESSURE CELL NUMBER	SECTIONAL DIMENSIONS (in.) (Refer to Fig. E8)					
	"A"	"B"	"C"	"D"	"E"	"F"
1	4/64	9/64	10/64	2/64	4/64	1/64
2	4/64	6/64	5/64	6/64	5/64	2/64
3	2/64	6/64	9/64	10/64	4/64	1/64
4	4/64	6/64	9/64	7/64	4/64	<1/64
5	4/64	2/64	6/64	4/64	2/64	<1/64
6	1/64	6/64	8/64	4/64	4/64	1/64
7	11/64	8/64	7/64	5/64	3/64	1/64
8	6/64	2/64	8/64	1/64	5/64	1/64
9	6/64	2/64	6/64	4/64	4/64	1/64
10	9/64	3/64	8/64	3/64	2/64	1/64
11	8/64	4/64	5/64	5/64	1/64	<1/64
12	3/64	2/64	6/64	6/64	3/64	1/64
13	3/64	5/64	10/64	7/64	5/64	1/64
14	5/64	1/64	10/64	5/64	4/64	<1/64
15	8/64	4/64	6/64	5/64	2/64	1/64
16	2/64	4/64	8/64	9/64	4/64	1/64
17	3/64	7/64	8/64	4/64	5/64	2/64
18	1/64	5/64	7/64	3/64	5/64	1/64
19	2/64	4/64	7/64	3/64	4/64	1/64
20	3/64	3/64	7/64	12/64	3/64	1/64

side of the joint. Room was left to protect the instrumentation and wiring at the joint with asbestos cloth.)

5) Succeeding segments were aligned and welded, and gages were completed in a like manner.
6) The inclinometer tubing was welded into each section using a 6-inch (150 mm) weld on each side every 5 feet (1.5 m) (top end of each segment) rather than the 4-inch (10 cm) weld that failed on the short test pile.
7) The output of every strain gage bridge was checked with a strain indicator after each new segment was welded into place.

An overall picture of the pile assembly area is shown in Fig. E9. Note that two parallel lines were used to speed the reassembly process.

The procedure just described was followed for all eleven piles with the exception that the lateral pressure cell tubing was potted in with "Bondo" (an automobile body patching compound) on the last five piles (Piles 1-5) reassembled. Salient aspects of the procedure are shown in Fig. E10.

Extensometer System Installation

The mechanical extensometers were installed after the piles had been driven. They were installed in all eleven piles at depths of 0, 10, 20, 30, and 42 feet (1, 3, 6, 9, and 13 m) from ground level. (It was originally intended to install one more extensometer at 35 ft (10.6 m) below the ground surface, but it was not possible to do so without tangling the aluminum rod for this level with the rod for the level below.) The installation procedure followed was:

1) Specially designed spearhead anchors (see Interim Report) were connected to 3/16-inch (5 mm) diameter high strength aluminum rods using ferrule-type tubing connectors. The rod was shipped to the site in pre-cut and pre-straightened individual lengths.
2) The anchors were pushed down the pile through the guide tubes with a rigid setting tool and were engaged to a specific square tube that had been prewelded during pile assembly.
3) Once the anchor had been engaged, the setting tool was extracted, and the free end of the rod was held at the pile top and notched with a file for identification.
4) The anchors were installed from the bottom upwards to the top.
5) Once the top anchor was in place, the extensometer head was slipped over all five wires and into a 3-1/2-inch (89 mm) diameter pipe section which had been affixed to the inside of the pile just below its upper end. This pipe section, described in the Interim Report, served as a stay and a reaction for the head.
6) Once the head was in place, the aluminum rods were tensioned by hand and fastened permanently against the compression assembly of the head.

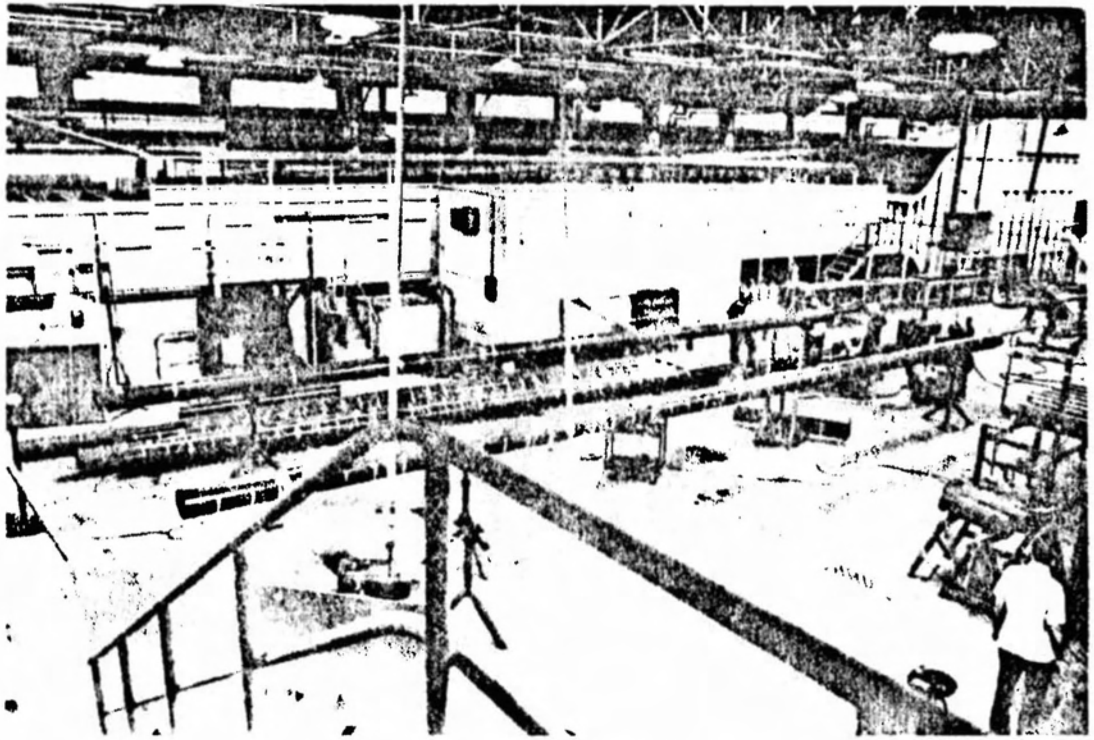
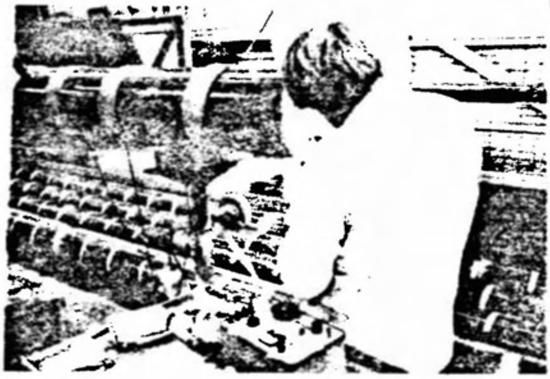


FIGURE E9. PILE ASSEMBLY AREA

a. Ribbon cable wires ready for attachment to barrier terminal. LPC tubing and extensometer tube also visible

b. Ribbon cable wires attached to barrier terminal before final waterproofing



c. Hot-melt bonding of lead wire to pile wall and checking bridge continuity

d. Welding pile segments together

FIGURE E10. PILE ASSEMBLY

7) The compression assembly was then released and all wires were pulled to a tension of about 100 pounds (0.45 kN).
8) The dial gage mount frame was then attached over the rod heads.

The readout device was a 4-inch (102 mm) travel dial indicator which was inserted into the proper hole in the dial gage mount frame (reference surface) and read manually.

Problems Encountered in Pile Assembly

During the process of reassembly, all of the welds joining the pile segments were visually inspected. It was found that 22 of the welds had some form of surface cracking, all on Pile Nos. 2 and 3. These welds were magnafluxed, whereupon many of the cracks were found to be continuous. The suspect welds were X-rayed, whereupon metallurgical analysis revealed the cause of these cracks as possible lack of fusion caused by improper operation of the low heat M.I.G. welder by the welder operator reassembling these two piles. Fourteen of the welds were judged to be defective to the extent that they may not have withstood driving. All 14 were on two piles (nos. 2 and 3) and were all made by one welder. The remaining welds had all been made by another welder. Six welds made by that welder were radiographed at random and found to be acceptable. The 14 potentially bad welds made by the first welder were then carefully replaced by a process which involved cutting windows in the pile at each joint to gain access to cables and tubing in order to protect them from the heat of rewelding, grinding out the defective welds, and rewelding the joints (and windows) using a stick-type welder in three passes. This process is believed to have had some effect on long-term strain gage stability as discussed later.

Also, during the process of rewelding, it is believed that spatter from the welding may have made some of the full-bridge strain gage circuits inoperative and thus leaving only 1/4 bridge resolution. These levels are documented later.

Installation of Ground Instruments

The ground instruments were installed as described in Chapter 5 of the Interim Report with no significant difficulty. Care was taken to saturate the ground piezometers before they were pushed into final position.

The most significant drawback to the method of installation was that it was not possible to verify the plumbness of the access holes, although care was taken to level the reaction truck and to plumb the rod at the surface. No anomalous events occured during punching of the access holes for either the piezometers or the vertical movement points, suggesting that the access holes were essentially plumb.

CALIBRATION OF PILE INSTRUMENTS

General

There are several factors which require that the instrumented piles be calibrated in order to obtain accurate values of axial load from strain gage readings. Included in these factors are the variation from the nominal cross-section and the nominal modulus of elasticity of the pile, errors in gage orientation, and variations in the quoted gage factors. If accurate values of all the parameters were known, then accurate values of axial load could be obtained by analytical techniques alone. Consequently, the accuracy of the measured strain would depend only on the accuracy with which the electrical signals from the strain gages were known. Unfortunately, the properties of the piles and gages were not known precisely, and the influence of the various factors could only be determined by calibrating the piles by applying known axial loads.

The calibration of the piles, while eliminating the unknowns mentioned in the previous paragraph, introduced an additional approximation that must be considered. This factor was the accuracy with which the applied loads could be measured during calibration.

The procedures followed for the axial calibration are covered in the following section.

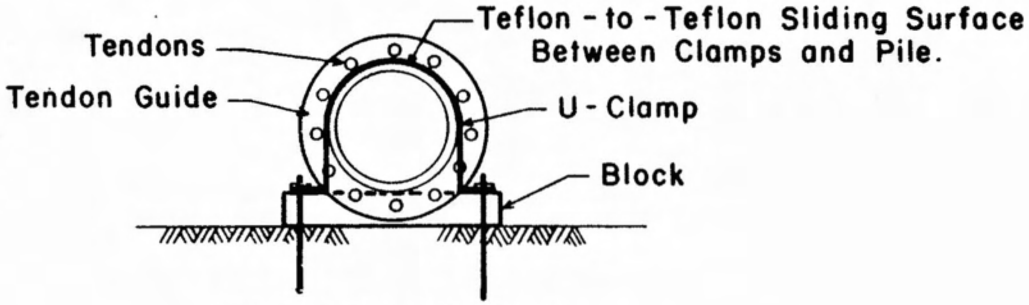
Each pile was calibrated separately. For the group piles, this was done before the last extension segment was welded to the top of the pile. For the reference piles, calibration was done after complete assembly. The device used for axial calibration is shown in Figs. E11 and E12. This device consisted of a loading jack, heavy steel loading heads on each end of the pile, a load cell (NBS calibrated), an end reaction plate for the load cell, an end reaction plate for the jack, wood blocks and pile clamps (to align the piles), prestressing tendons to apply the load, and tendon guides. The tendon guides were carefully designed to minimize eccentricity of loading and thus to prevent buckling of the piles during calibration. Use of this simple device permitted compressive loads of 300,000 lb (1330 kN) to be applied to each pile.

Axial Calibration

An NBS calibrated load cell was used to measure the load on each pile. An excitation voltage of 10.00 volts was used to power the bridges, and the output from each bridge was measured with the same data acquisition system to be used throughout the testing program.

Before a pile was calibrated, it was exercised three times to 300,000 lb (1330 kN). Wave equation analyses, as well as static analysis, indicated that the piles could possibly be loaded to that level during both driving and testing; hence, that preload value was selected.

After the pile was exercised, each strain gage circuit level was read with no load, and the output of each circuit was recorded. The leads (ribbon wire) from the gage circuits were plugged into the patch



TYPICAL SECTION

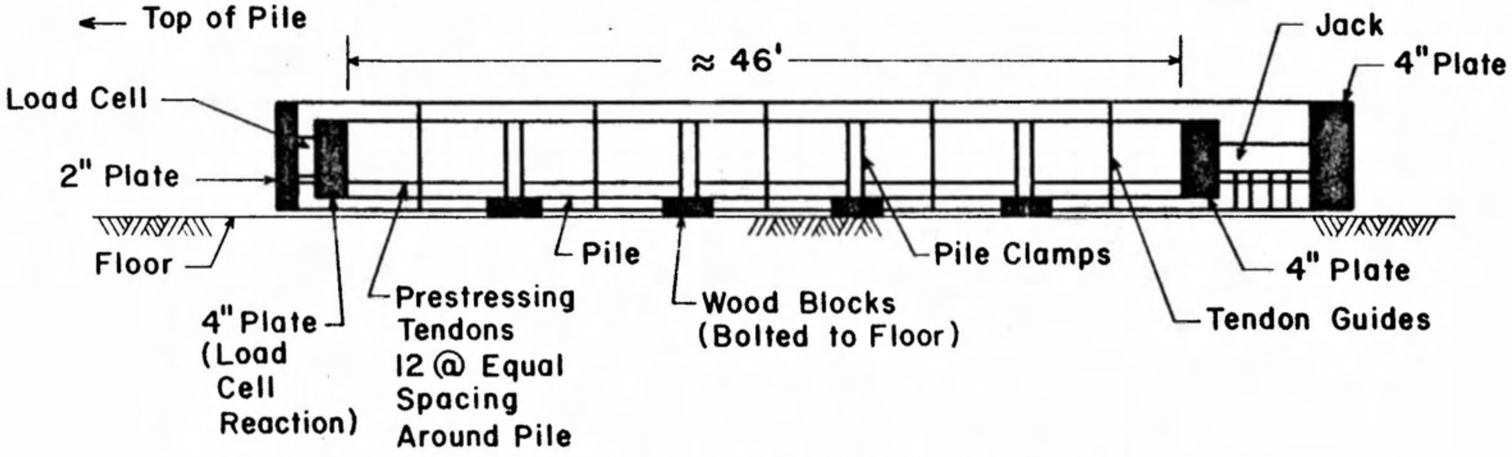
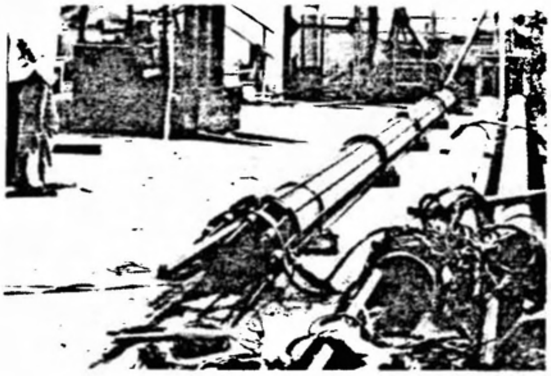
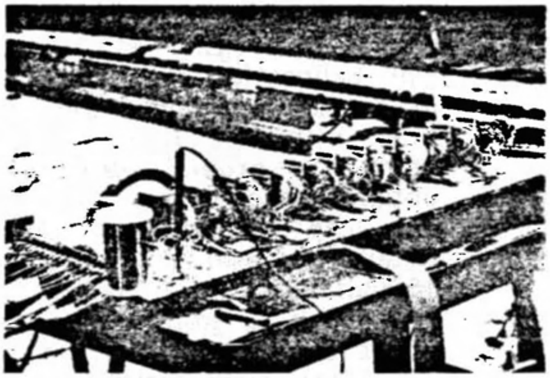


FIGURE E11. AXIAL CALIBRATION DEVICE (SCHEMATIC)
(1 ft = 0.305 m; 1 in = 25.4 mm)



a. View of calibration device

b. Patchboard



c. Gold contact electrical switches

FIGURE E12. PHOTOGRAPHIC VIEWS OF CALIBRATION DEVICE AND PATCHBOARD

board. A picture of the patch board is shown in Fig. E12. The lengths of the connecting wires in the patch board assembly were varied as required to bring the no-load count level to approximately zero (±200 A-to-D counts). One count corresponded to approximately 200 pounds (0.9 kN) of applied load or 8.06 micro-strain with a gage factor of 2.00.

(The presence of the variable wire lengths created problems during driving and testing, because small temperature changes in the patch board produced indicated zero drift. Consequently, it was necessary to house this assembly on the test site in a box which had a thermostatically controlled heater placed within it so as to keep the temperature of the board essentially constant.)

The piles were then calibrated for axial compression. The procedure followed involved applying a known load and measuring the output from each strain gage circuit in the pile. The piles were loaded in increments of 25 tons (220 kN) to a final calibration load of 150 tons (1330 kN). At each load increment, readings were taken on the outputs of the strain gages. The resulting points were quite linear and the data for each strain gage bridge were fitted with a linear curve. The calibration constant was taken as the slope of that curve. The calibration constants thus obtained are shown in Table E2 for all eleven piles. In this table the designation "C" indicates a level of gages above the ground surface which could be used as a backup level to obtain load on a pile head if Level 1 malfunctioned.

The constants in Table E2 were then used during the tests to obtain the load at a particular level by multiplying bridge output (for 10 volt excitation) in A-to-D counts by the appropriate constant. In a few cases a small offset to the calibration curve existed which was added to (or subtracted from) the above product.

Note that several of the constants were in the order of 0.4. These represent the levels at which 1/4 bridges existed.

Lateral Pressure Cells

Initial Pressure Cell Calibration. This operation was required in order to calibrate the indicated pressure readings from the total pressure cells under no load with the cell temperature.

The temperature problem described previously for the total pressure cells was not expected during design. In order to circumvent the problem, a thermistor was placed on each dual lateral pressure cell in the pile assembly shop so that temperature readings could be taken each time the total pressures were read during the pile load tests. The thermistors used were Micro-Measurements Type TG bondable resistance-thermometer gages (ETG-50D). They were epoxied onto the inside of the backing plate just below the pore pressure cell location. The thermistor lead wires were bundled with the lateral pressure cell tubing and then run out of the pile to a switchbox and from there to a network that:

1) attenuated the resistance change slope to the equivalent of 100 microstrain per degree Fahrenheit; and

TABLE E2. PILE AXIAL CALIBRATION CONSTANTS (kips/A-D counts)

DEPTH (ft.)	PILE NUMBER					
	1	2	3	4	5	6
-1(C)	.195841	.190912	.409350	.190309	.183619	.191690
1(1)	.195841	.199759	.200706	.192747	.185803	.197080
6(2)	.196001	.197941	.200639	.194391	.185804	.198728
11(3)	.195310	.200962	.396754	.192660	.187687	.206952
16(4)	.366996	.412523	.200801	.192886	.368452	.200555
21(5)	.195615	.198486	.202262	.191192	.187899	.198490
26(6)	.196905	.203417	.199281	.194012	.186985	.195083
31(7)	.392600	.199521	.202509	.195138	.186288	.199359
36(8)	.196537	.196848	.203169	.191412	.186845	.201607
39(9)	.196223	.198412	.196075	.191558	.186845	.198491
42(10)	.196378	.198229	.201344	.199433	.177859	.200045

DEPTH (ft.)	PILE NUMBER				
	7	8	9	10	11
-1(C)	.201628	.195115	.190546	.191763	.353169
1(1)	.192381	.205628	.197160	.194397	.353169
6(2)	.203581	.200507	.193873	.193648	.189250
11(3)	.196462	.211880	.192900	.194929	.188250
16(4)	.196928	.186192	.189104	.195158	.190476
21(5)	.189825	.193823	.194250	.194024	.381242
26(6)	.192530	.196490	.193873	.194627	.190186
31(7)	.190605	.189639	.191865	.193723	.191058
36(8)	.192604	.193905	.192158	.192528	.191058
39(9)	.382408	.195611	.190766	.190113	.192450
42(10)	.382408	.190961	.190766	.190113	.384900

Notes: Characters in ( ) denote level designation
1 kip = 4.450 kN.; 1 ft.= 0.305 m.

2) linearized the gage-resistance-versus-temperature characteristic from approximately -200°C to +300°C.

From the network, a Budd P-350 strain indicator was connected to the leads, which enabled a direct readout of temperature. A sketch of the circuit is shown in Fig. E13. It was therefore theoretically possible to relate the total pressure "zero" to the cell temperature as read on the strain indicator. The true total pressure would then be the difference between the actual reading and the temperature related zero.

During temperature calibration, the actual temperatures were read by a separate carefully calibrated thermal pickup along with the apparent temperatures (temperatures read with strain indicator) in order to relate indicated temperature to actual temperature. The actual temperatures were read both on the pressure cell sensor plate and on the backing plate next to the temperature sensors with a temperature probe accurate to 0.001°C. There was only a small difference between the readings taken on the total cell plate and the readings taken next to the temperature sensor when the cells had been in a temperature stable environment for some time. The readings taken on the plate were used to relate actual to indicated temperatures.

In order to accomplish the calibration, the pressure cells were placed in an unloaded condition in an isolated, temperature-controlled room, and the temperatures were varied slowly. Many of the total pressure cells appeared to be insensitive to temperature changes at low temperatures (below 16°C). The relationships of indicated pressure to temperature were not linear as the temperature was allowed to increase and the cells became sensitive to temperature change. In addition to this, some of the cells appeared to be insensitive to pressure applied to the total pressure plate with the palms of the hand when the temperature was below about 16°C. Following the advice of the manufacturer, a 1/2-inch (13 mm) thick aluminum block was placed over the cell plate and was tapped on lightly with a small hammer. This procedure sensitized the total pressure cells, possibly by removing minute bows in the total pressure plates. Once the cell temperatures reached about 16°C, the indicated no-load pressure became a linear function of temperature.

A linear regression method was used to fit the pressure versus temperature relationships in the temperature range above 17°C, which was the lowest temperature expected to exist in the ground at the test site. This is shown in Figs. E14 and E15 for typical cells. The effect of sensitizing (tapping) the cells was to cause an upward offset in the pressure-temperature lines. The slopes of the lines from before and after sensitizing the cells were nearly equal. From this behavior it was concluded that the cells could be sensitized to read in the temperature ranges that were anticipated. Consequently, all the cells were sensitized so that they read at least 10 psi (69 kN/m^2) at about 18°C.

Three pressure cells were placed in the direct July sunlight to determine what effects heating the cells would have on the calibration. The cell temperature rose to approximately 60°C. Pressure readings were taken after the cells cooled, and it was determined that there had been some permanent set in the pressure plates, such that the indicated

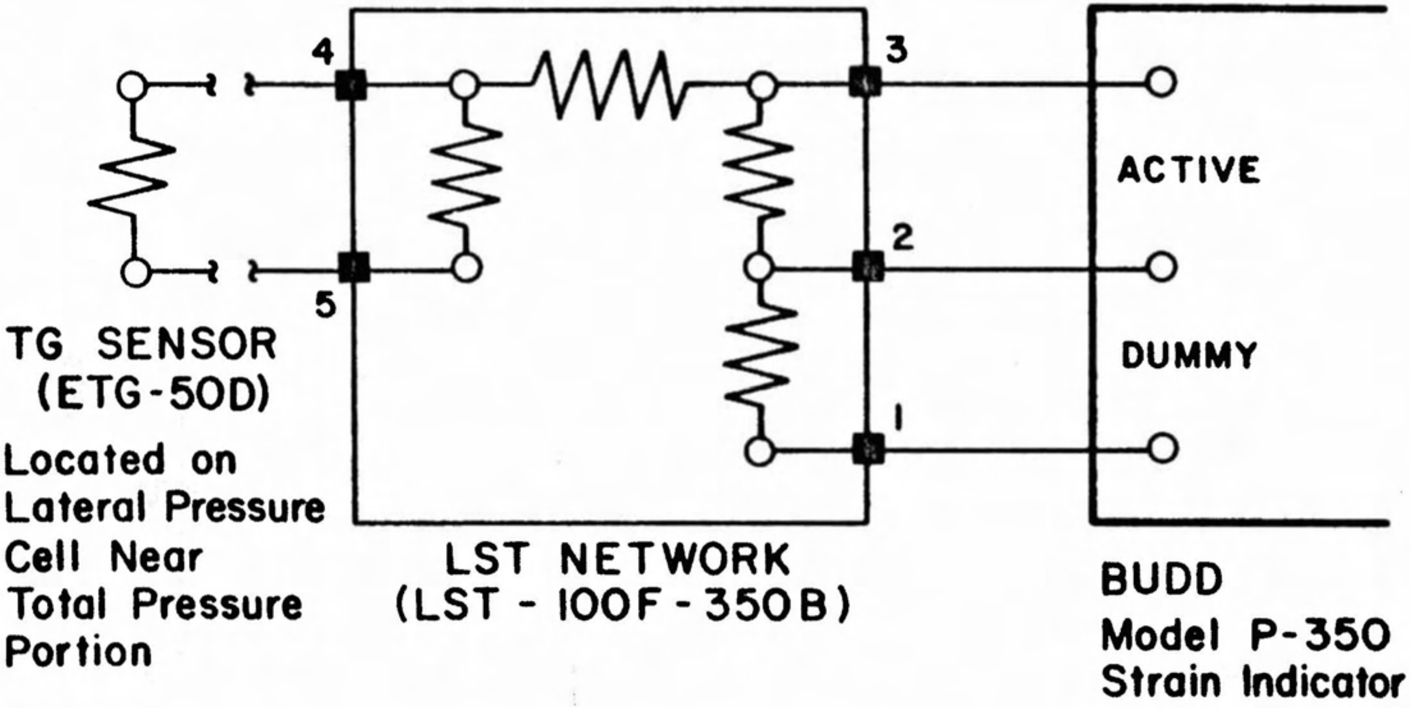


FIGURE E13. THERMAL SENSOR CIRCUIT (SCHEMATIC)

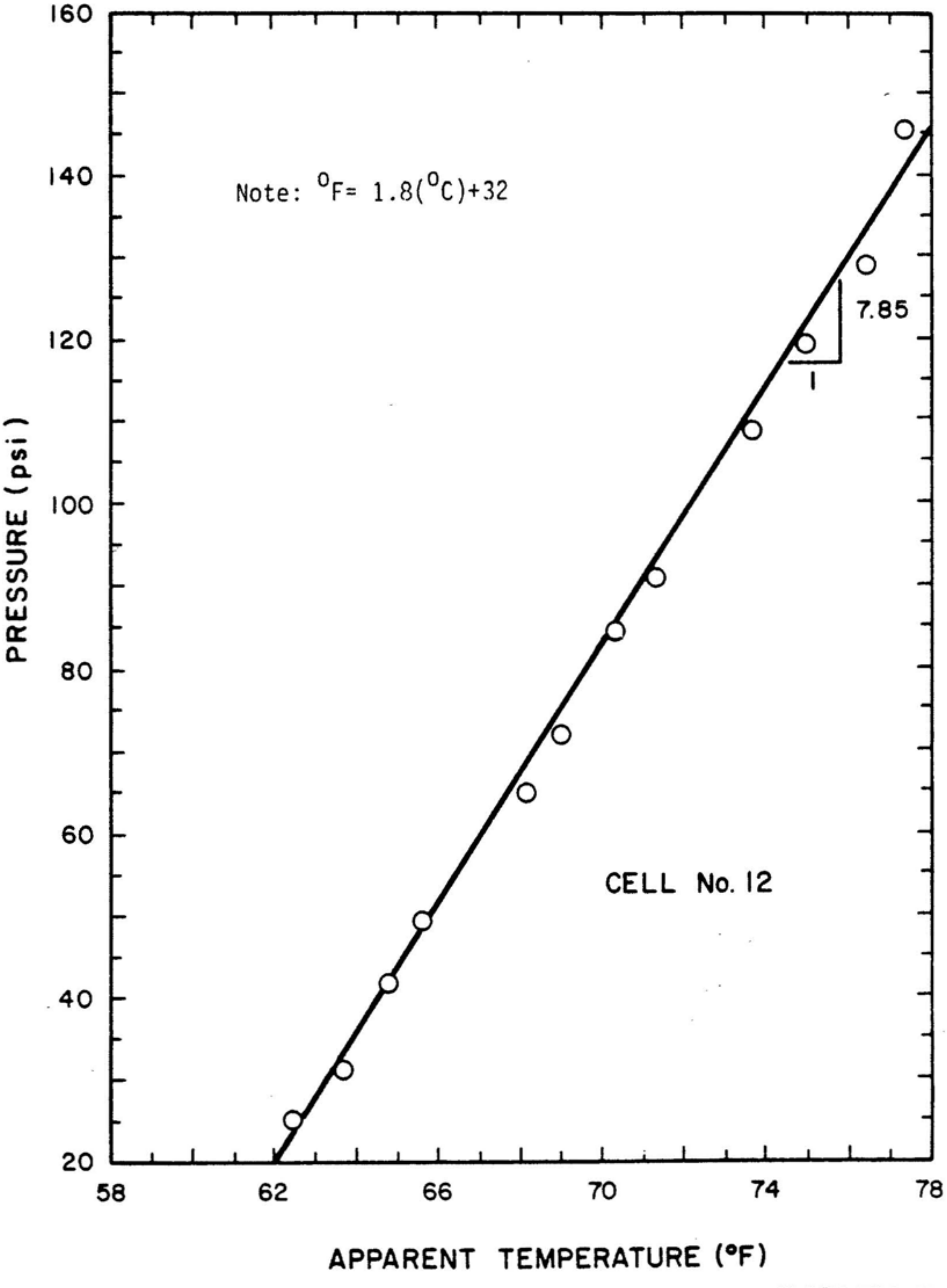


FIGURE E14. INDICATED TOTAL PRESSURE VS. TEMPERATURE INDICATED BY THERMAL SENSOR - CELL NO. 12 (NO LOAD CONDITION)
(1 psi = 6.89 kN/m^2)

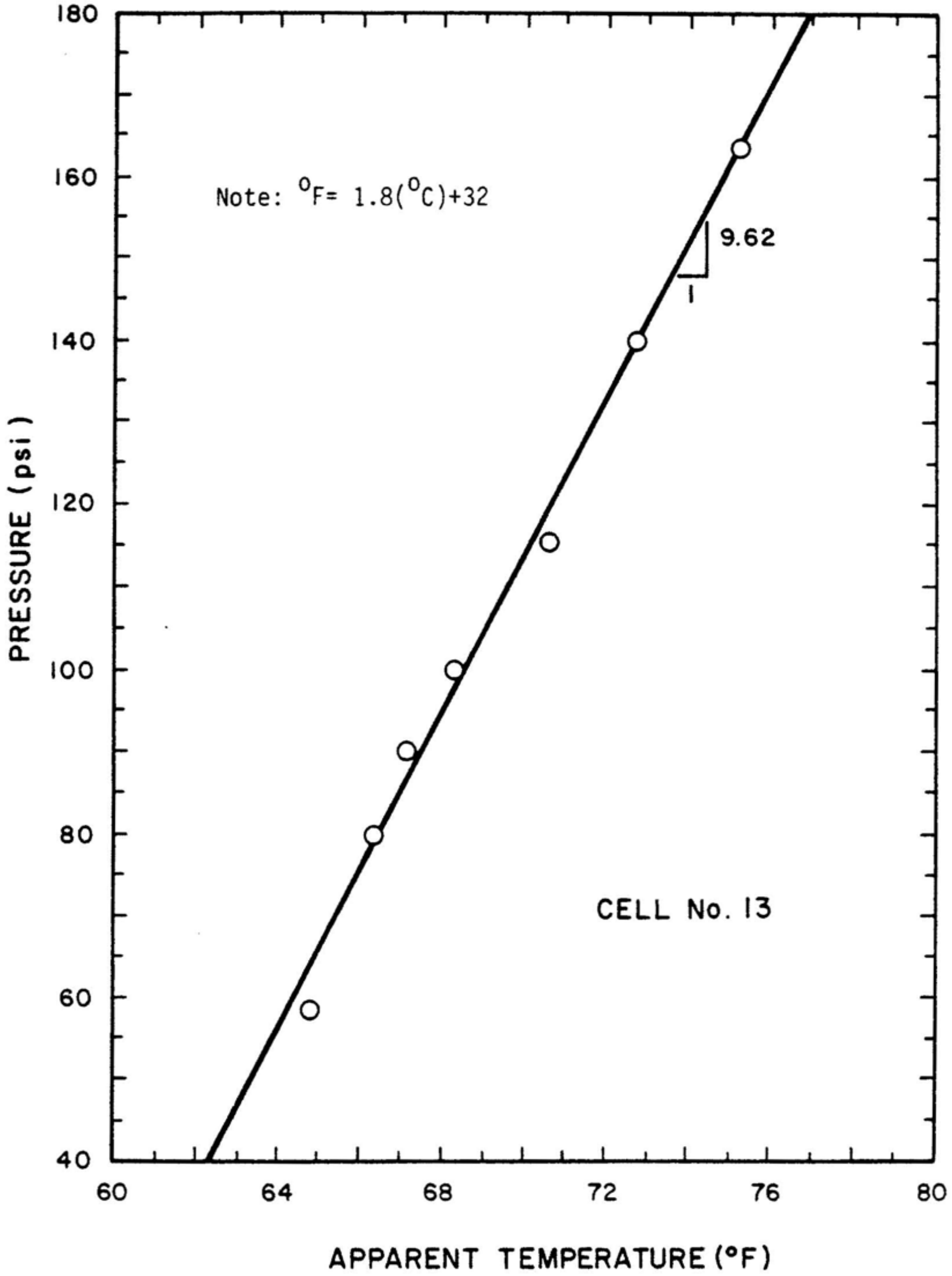


FIGURE E15. INDICATED TOTAL PRESSURE VS. TEMPERATURE INDICATED BY THERMAL SENSOR - CELL NO. 13 (NO LOAD CONDITION) (1 psi = 6.89 kN/m^2)

no-load pressure decreased for the same temperatures at which pressures had been read previously. From this it was concluded that the pressure cells, after being placed on the piles, could not be exposed to direct sunlight.

Two of the pressure cells placed in the sunlight were able to be sensitized back to the desired zero readings. The other cell, Cell Number 1, had pressure readings that remained too high and very erratic after sensitizing. This cell was then heated to 75°C in an oven. This produced the opposite effect of sensitizing the cell such that the pressures were now lower than they were previously. An attempt was made to sensitize the cell by tapping again, but the pressures then read too high. However, the pressure-temperature relationship was linear, so the cell was re-calibrated as it was. This cell was fairly insensitive to temperature with the pressure change only being about 1 psi (6.9 kN/m^2) per degree Fahrenheit (per 0.55°C).

Based upon this study, it was concluded that the cells could be calibrated for temperature effects as long as thermal gradients did not exist between the thermal sensor and the total pressure cell and as long as thermal sensor lead wires and the readout device were at about the same temperature as the cell. These conditions were not entirely duplicated in the field. The pressure cells could be sensitized by tapping on the aluminum block in order to obtain the desired no-load zeros. The tapping shifted the pressure-temperature line upward. The cells could also be heated in order to shift the pressure-temperature line downward. Additionally, calibrations of apparent temperature versus actual temperature were obtained. The latter calibration would later be necessary in order to estimate the apparent temperature on cells where the temperature sensors were inoperative.

It was concluded, partly through communication with and assistance of the manufacturer, that the principal reason for the temperature sensitivity of these cells was the fact that the design was a miniaturization of a larger, proven pressure cell which did not have sufficient internal compliance to permit internal fluid expansion or contraction without registering readable pressure changes on the readout device.

Load Test on Cell. Prior to placement in the piles, two pressure cells were placed in a loading frame, and the top of the backing plate was loaded parallel to the axis of the cell to a stress of 1000 psi (6900 kN/m^2) to check cross sensitivity of the total pressure plate. This was done to see if the total pressure plate was sensitive to axial stress in the backing plate (or pile). The applied stress was considerably less than would occur in the prototypes. However, there was no edge restraint in the cell assembly so the strains in the pressure plate may have been greater than if the coupon were in the pile and loaded to higher stresses. Pressure Cells Number 2 and 11 were tested. Each cell was loaded three times and each time temperature and pressure readings were taken. These readings are shown in Table E3. This study provided some evidence that there would be no significant zero shifting or false readings of pressure when the piles were loaded axially. However, based upon these observations, it was concluded that it was impossible, based on this type of load testing, to know with

TABLE E3. LOW-LOAD CROSS-SENSITIVITY TESTS

PRESSURE CELL NO. 11

APPARENT TEMP(°F)	PRESSURE (psi)	LOAD (lb)	APPARENT TEMP(°F)	PRESSURE (psi)	LOAD (lb)
69.31	109	-0-	72.21	145	2000
69.54	111	-0-	72.21	146	3500
72.21	145	-0-	72.19	145	-0-
72.21	145	1500	72.19	145	1000
72.21	145	2500	72.22	146	2000
72.21	145	3500	72.22	146	3000
72.19	145	-0-	72.22	146	3500
72.21	145	1000	72.22	146	-0-
			72.20	146	-0-

PRESSURE CELL NO. 2

APPARENT TEMP(°F)	PRESSURE (psi)	LOAD (lb)	APPARENT TEMP(°F)	PRESSURE (psi)	LOAD (lb)
71.33	88	-0-	71.27	88	-0-
71.30	87	1000		88	1000
71.28	87	3000	71.26	87.5	1500
71.31	87	3500	71.25	87.5	2500
71.30	88	-0-	71.25	87	3500
71.28	88	1000	71.29	88	-0-
71.27	87	2000			
71.28	87	3500			
71.28	88	-0-			

Note: 1 psi= 6.89 kN/m^2
1 lb= 4.45 N
°F= 1.8(°C)+32

assurance whether a problem would exist when the cells were welded into the piles and the piles were loaded. It was decided to proceed to place the cells in the piles and test them again for cross sensitivty during pile calibration.

Pore Pressure and Total Pressure Cell Sensitivity Test

Cells Number 8 and 13 were immersed in an underwater acoustics tank in order to measure the effects of hydrostatic pressure on the cells. Pore pressures and total pressures were read with the cells at depths of 1, 10, and 18.1 feet (0.3, 3, and 5.5 m), both during lowering and raising the cells in the water. The readings indicated some change in pore pressure and total pressure. The pressure change was nearly the same for pore pressures and total pressures, but there was some difference between the theoretical and measured pressure changes. The differences were thought to be associated with the inaccuracies in the readout device at the very low pressures encountered. These sensitivity test results are shown in Table E4.

Lateral Pressure Cell Cross Sensitivity Check in Assembled Piles

Cross-sensitivity checking of the total pressure cells in the assembled piles was done in the calibration device during axial calibration of the strain gage circuits. The procedure was to take temperature and pressure readings before applying any load to the pile. The piles were then exercised by applying a load of 300,000 lb (1330 kN) three times. Another set of readings was taken and then the pile was loaded to 200,000 lb (890 kN) in four steps and total pressure readings were taken at each load. Final readings were taken at no load. The results are shown in Table E5. The mean indicated change in pressure at 150,000 lb (670 kN) was -1.5 psi (-10.3 kN/m^2), while the mean offset upon unloading was +0.9 psi (+6.2 kN/m^2). These errors were considered acceptable; however, it was not possible to ascertain whether the dynamic action of repeated hammer blows would have the same effect. Experiences with other larger cells of similar design indicate that little further offset effect would be experienced during driving.

Other Instruments

Manufacturers' calibrations were used for the inclinometer, ground piezometers (which were direct reading devices in which no calibration was actually required), and the dial gages used to measure translational movement during the load tests. No straightforward means was found to calibrate either the ground movement points or the pile extensometers; therefore, direct readings made on these instruments were assumed to be correct, with due consideration for temperature effects (in the ground movement system only) described in Appendix D.

TABLE E4. HYDROSTATIC PRESSURE TEST RESULTS

PRESSURE CELL NO. 8

DEPTH OF WATER (ft)	WATER PRESSURE (psi)	APPARENT WATER TEMP. (^{o}F)	PORE PRESSURE READING (psi)	TOTAL PRESSURE READING (psi)	PORE PRESSURE CHANGE (psi)	TOTAL PRESSURE CHANGE (psi)
1	0.43	76.82	6	165	0	-
10	4.32	76.90	9	169	+3	+4
18.1	7.82	76.90	12	172	+3	+3
10	4.32	76.92	9	169	-3	-3
1	0.43	76.97	6	166	-3	-3

PRESSURE CELL NO.13

1	0.43	77.83	6	183	-	-
10	4.32	77.63	9	188	+3	+5
18.1	7.82	77.52	12	191	+3	+3
10	4.32	77.57	9	188	-3	-3
1	0.43	77.66	6	185	-3	-3

Initial water temperature was not
used for "zero" for test.

Note: 1 ft.= 0.305 m.
1 psi= 6.89 kN/m^2
^{o}F= 1.8(^{o}C)+32

TABLE E5. IN-PILE CROSS SENSITIVITY CHECKS. VALUES SHOWN IN PSI FOR LOAD IN TONS (1 psi=6.89 kN/m^2; 1 ton=8.9 kN)

CELL NO.	PILE SEGMENT	BEFORE EXERCISED	AFTER EXERCISED	50	100	150	200	0
1	C-1	-2	0	-1	-1	-1	-1	+1
8	E-1	+4	0	-5	-7	-10	-13	+2
9	H-1	-4	0	-2	-4	-5	-6	+1
6	J-1	-9	0	+1	+1	+3	+2	+3
2	C-2	0	0	-1	-3	-4	-5	0
11	E-2	0	0	+3	+5	+10	+14	+4
15	H-2	-	0	+4	+6	+5	+7	+6
7	J-2	-	0	0	-2	-3	-3	-1
3	C-3	-	0	+2	+5	+6	+9	0
12	E-3	-	0	-2	-3	-4	-7	+1
16	H-3	PRESSURE CELL INOPERATIVE						
10	J-3	PRESSURE CELL INOPERATIVE						
4	C-4	-2	0	+3	-2	0	-2	+4
13	E-4	NO TEMPERATURE READINGS						
18	H-4	PRESSURE CELL INOPERATIVE						
17	J-4	PRESSURE CELL INOPERATIVE						
5	C-5	NO TEMPERATURE READINGS						
14	E-5	-	0	+1	-1	-1	-1	-4
20	H-5	-	0	-4	-7	-11	-14	-2
19	J-5	-	0	-3	-4	-6	-6	-2

PERFORMANCE OF INSTRUMENTATION
AND SOURCES OF ERROR

Strain Gages

Prior to driving the piles, twelve of the 119 strain gage levels in the piles had to be set on 1/4 bridge configuration, rather than full bridge, due to damage to the wiring during the pile reassembly process or transportation to the test site. These levels are indicated by calibration constants in the order of 0.4 in Table E2. Several levels malfunctioned during the course of the test program, as cataloged in Table E6.

Observations Relative to Strain Gage Attrition

1) Gage attrition was accompanied by lowered resistance to ground, indicating that the bad circuits slowly became partially shorted to the piles, probably due to moisture intrusion.
2) Almost all of the levels of lost gages were in Piles 1-4 (14 of the 18 that were lost by the end of the testing program). These piles, which also contained about half of the 1/4 bridge circuits, were subjected to more severe mechanical handling during assembly than the remaining piles, as follows:
   a. Pile 4: A window was cut in the pile near Level 4 after all instruments were installed to repair a pneumatic tube. The window was rewelded, during which protection of strain gage lead wire, which was already bonded to the interior of the pile, was not possible to control completely. Some small spot-burns may have occurred in the wire at this time through which moisture later entered.
   b. Piles 2 and 3: Defective M.I.G. welds were found in these piles after assembly was completed and all instruments had been placed. Repair of the welds necessitated the cutting of small windows adjacent to each main weld to insert asbestos cloth to protect the instrumentation leads while the main M.I.G. welds were ground out and replaced with rod welds. Some weld spatter may have occurred during this operation and during subsequent rewelding of the windows (also done with welding rod) which was done with "blind" protection of the lead wire. The small burns which may have resulted may have affected long-term gage stability as described for Pile 4.
   c. Pile 1: The piles were assembled in reverse order to their numbering. Thus, Pile 1 was not assembled until after the defective M.I.G. welds in Piles 2 and 3 had been discovered. In order to avoid the defective weld problem in Pile 1, this pile was welded completely with 6060 rod, which produced more heat and weld spatter than the M.I.G. welder, possibly again spot-burning

TABLE E 6. LEVEL NUMBERS OF INOPERABLE STRAIN GAGE LEVELS BY EVENT

EVENT (DATE) / PILE NO.	INSTALLATION (29 Oct. 79- 2 Nov. 79)	9-PILE TEST 1 (16 and 21 Nov.79)	9-PILE TEST 2 (18 and 22 Jan.80)	9-PILE TEST 3 (14 and 19 Feb.80)	5-PILE SUBGROUP TEST (26 Feb.80)	4-PILE SUBGROUP TEST (29 Feb.80)	UPLIFT TESTS (19 Mar.80- 3 Apr.80)
1	7	7	7	3,5,7	3,5,7	3,5,7	3,5,7
2	-	-	1,4,5,7	1,3,5,7	1,3,5,7,10	1,3,7	1,3,5,7,9
3	-	3,8	3,8	3,8	3,7,8	3,7,8	3,7,8
4	-	-	-	-	4	4	2,4,9
5	-	-	4	4	4	4	4
6	-	-	-	-	-	-	-
7	-	4,8	4,8	4,8	4,8	4,8	4,8
8	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-
11	-	1	1	1	1	1	1
TOTAL NO. OF INOPERABLE GAGE LEVELS (% OF TOTAL)	1 (1%)	5 (5%)	11 (10%)	13 (12%)	16 (15%)	14 (13%)	18 (16%)

NOTE: A level was declared inoperable if it was used in quarter-bridge and yielded results incompatible with other piles or other levels on the same pile or if excessive no-load drift occurred. Began with 110 levels (calibration levels excluded from this table). (Level 1 was at top of Segment B. Level 10 was at bottom of Segment J.)

NOTE: When Level 1 was inoperative, Level 2 or calibration level readings were substituted.

some of the lead wire and producing the gage stability problem described previously.

3) Most testing occurred on rainy and humid days, during which time the piles were not in a sealed dry nitrogen environment. Thus, small amounts of moisture could have entered the piles on test days and later migrated into the lead wires through pin-hole sized spot-burns, causing partial shorts to ground.
4) Level 1 on Pile 11 was struck by a tool dropped into the pile during attachment of the extensometers, after the pile was driven.
5) The loss of Gage Levels 4 on Pile 5 and 4 and 8 on Pile 7 are unexplained.

Strain Gage Data Fitting

In order to account for the generally random errors introduced by the existence of 1/4 bridges due to local bending and other related effects, it was decided to fit the raw load values, which were obtained by multiplying the raw A-to-D counts from the piles by the appropriate calibration constants from Table E2, with segments of a second order least-squares polynomial through each successive sequence of four gaging points. Unit side resistance (f) was then obtained at each mid-depth between the central two gaging points by taking the derivative of the polynomial at that depth and dividing by the circumference of the pile, except between Levels 1 and 2 and between Levels 9 and 10, where the derivative was taken between the highest and next highest or lowest and next lowest levels, respectively.

Figure E16 compares the results of side resistance obtained from the fitted curves (denoted FF' in the data) with the raw side resistance obtained from simple differences in indicated load between two successive levels divided by the peripheral area of the pile between those levels (denoted FF in the data). This figure was developed for the average of the edge piles in the second nine-pile group test for two different levels of load. Note that the fitted unit side resistance tends to be somewhat lower than the raw resistance near the 20-foot (6 m) level and somewhat higher than the raw resistance near the 28-foot (9 m) level.

Fitted unit side resistance values were used in the interpretation of test results. Uncorrected end bearing values were utilized throughout, however.

Problems Encountered In Strain Gages After Driving

Immediately after the driving of the piles, considerable scatter occurred in the strain gage readings, making it difficult to assess exact patterns of residual stresses. It is believed that this scatter was due to the lack of opportunity to stabilize temperatures in the electrical patch board described earlier (which also contained balancing wire whose resistance was sensitive to temperature). The patchboard, through which the readout system was attached to the strain gages,

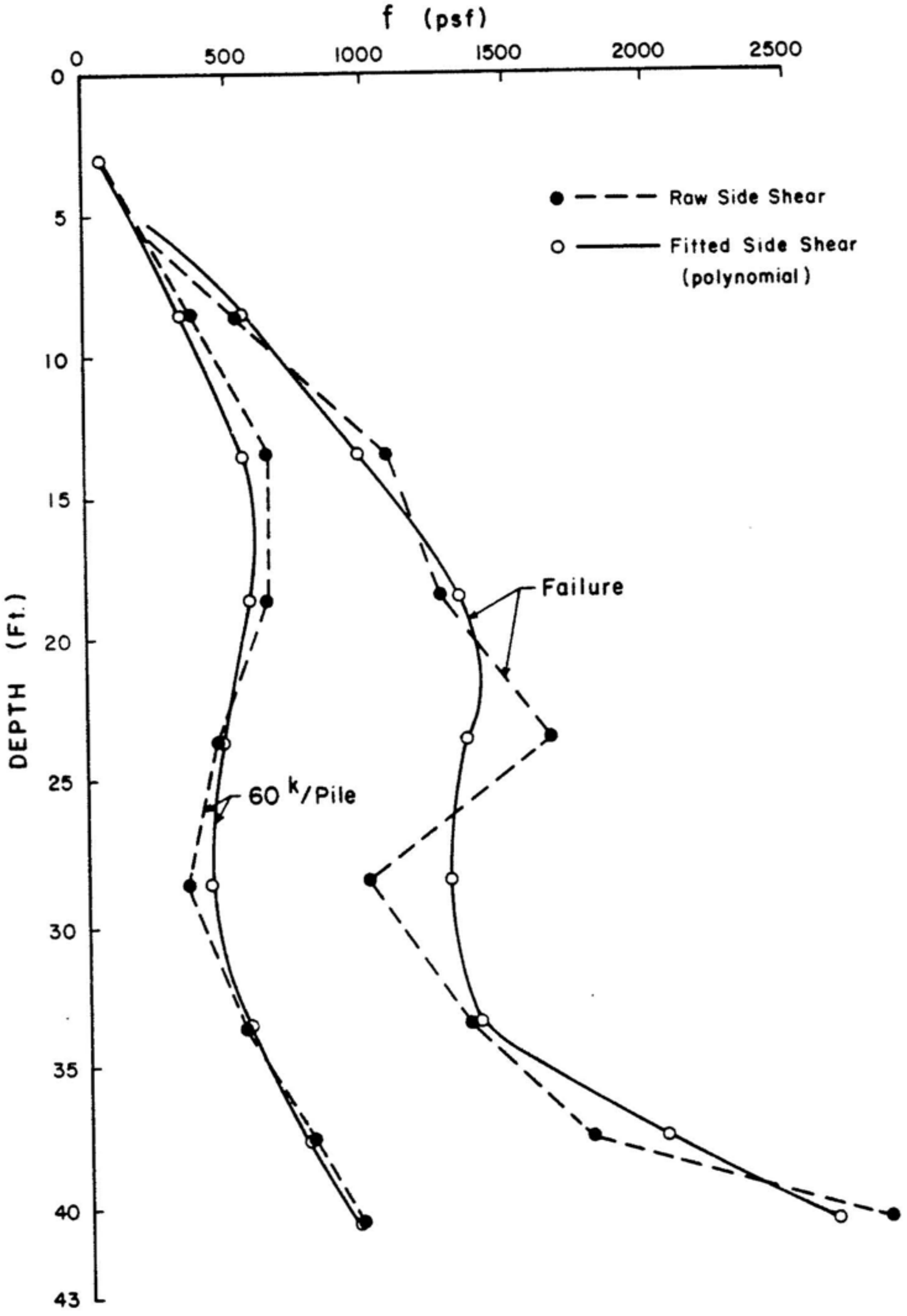


FIGURE E16. COMPARISON OF RAW AND FITTED UNIT SIDE RESISTANCES (1 ft = 0.305 m; 1 psf = 47.9 N/m^2; 1 k = 4.45 kN) had to be moved from point to point on the site during installation, and its temperature could not be regulated. Sets of residual stress readings were made prior to the first load test, during which the patchboard was placed within a sealed box whose temperature was controlled by means of a heater that kept the temperture of the box constant at approximately 23°C (the temperature during calibration). This box was permanently located near the piles for the remainder of the study.

This latter set of residual stress values still exhibited considerable scatter. It was not possible to ascertain whether the scatter was the result of real phenomena such as local bending in the wall of a pile which may have produced a spurious gage response, erratic depthwise variability in the residual side shear, or of zero shifts due to driving. One source of such zero shifts could have been differential stretching of lead wires between the dummy tab and the pile wall due to plastic rotation of the tab about its weld, although precautions were taken to minimize this effect by cradling the lead wire in epoxy, bringing the wire across the probable point of rotation, and close inspection of the quality of the welds between the tabs and the pile walls.

Another source could have been differential stretching of the lead wire between the gaging levels and the surface due to gross bending of the piles during installation. In any event, such scatter should have been essentially random, particularly since the bridge polarity was established in a random manner, so that average residual load distributions obtained for the reference piles and for the nine-pile group should have been valid, while less significance can be placed in the indicated distribution in any given pile.

Four of the 16 dynamic strain gages did not yield completely acceptable results. One circuit saturated electrically (an operational error), and three circuits failed during driving, possibly due to broken lead wire or to broken connections. Two of these three circuits did yield acceptable output traces for a considerable penetration before failing.

Observation of the dynamic gages, which were not bending compensated, indicated that measurable bending strains were developed in Piles 2 and 4 during the pile driving process.

Pile Lateral Pressure Cells

With the exception of the effects of temperature on the total pressure components, the performance of the pressure cells was generally satisfactory throughout the tests.

Prior to driving of the piles, a set of zero readings was taken on the total pressure cells at the site. The piles were stored in the sunlight, but the cell locations were locally shaded. The temperature of the piles was about 38°C during the zero readings, but the temperature was slowly changing. Because of the high temperatures in the piles, the total pressure zeros in the temperature-sensitive cells were very high. Four temperature sensors were not reading and one total pressure cell (Cell No. 4) did not stabilize during the on-site predrive zeros.

During driving, the piezometers lost saturation due to the high forces generated by pile driving. It was, therefore, not possible to obtain accurate pore pressure readings against the piles immediately after driving the piles. Fortunately, the piezometers had been outfitted with re-saturation lines, so the piezometers (and surrounding soil) were re-saturated and stable readings were realized within one to two days after re-saturation.

Some of the temperature sensors (or their connections with lead wires) were apparently damaged during driving, so an estimate of the temperature for several pressure cells had to be made using the measured temperature from another pile at the same level. Table E7 summarizes the condition of the lateral pressure instrumentation during the load tests. Note that the two lateral pressure cells at the bottom of Pile No. 3 were inoperative. The cause for this problem could not be ascertained.

During the pile load tests, total and pore pressure readings were taken before the beginning of the loading and at 5 minutes and 30 minutes after each load increment was applied. The total pressure cells were quite sensitive to temperature, and temperature readings at all levels varied over the course of a test. It was reasoned that most of the indicated variation of temperature had to be the result of the effects of ambient air temperature changes on the lead wire and readout device and of slight thermal gradients that may have existed between the points of attachment of thermal sensors and the total pressure cell fluid, which was separated from the soil by only the very thin sensor plate. To circumvent this problem, at least to a degree, temperature readings made as soon as a pile was uncapped prior to a test were taken as the applicable temperatures for the various cells throughout the test. The cells, temperature sensors, and sensor lead wire were all approximately at the same temperature as the pile and should not have been affected by ambient temperature fluctuation at that time.

The total pressure cell readings, after having been corrected for temperature effects, were extremely scattered. Part of this scatter may have been due to local variations in soil conditions. Undoubtedly, however, part of the scatter was the result of the design of the cell itself. Aside from the temperature effects already described in detail, geometric effects may have influenced the readings.

First, the cell face was flat, not curved, as was the surface of the pile. This shape results in a different stress field in an immediate vicinity of the cell face than exists around the pile surface in general. In particular, the effect of tangential, or hoop, stresses in the soil is lessened on the flat surface, so that arches that may have built up in the soil around the curved pile surface could have partially or fully broken down against the cell face, causing registered pressure to be variable but unrepresentatively high in comparison to the operative total pressures against the remainder of the pile.

Second, since the soil at the test site was very stiff, registration was apparently very sensitive to the exact orientation of the cell and to the presence of the irregularities along the cell documented previously.

TABLE E7. CONDITION OF LATERAL PRESSURE CELLS ON PILES

PILE NO.	PRESSURE CELL NO.	REMARKS
1	1	Temperature sensor did not respond during all tests.
1	8	Everything read properly for all tests.
1	9	" " " " " "
1	6	" " " " " "
2	2	" " " " " "
2	11	" " " " " "
2	15	Temperature sensor did not respond for all tests. Pore pressure cell inoperative after first group load test.
2	7	Temperature sensor inoperative for all tests.
3	3	" " " " "
3	12	" " " " "
3	16	Total and pore pressure cells inoperative for all tests.
3	10	Total pressure cell inoperative for all tests. Pore pressure cell inoperative after first load test.
4	4	Everything read properly for all tests.
4	13	Temperature sensor inoperative for all tests. Accurate pore pressure readings could not be obtained during Test #2.
4	18	Temperature sensor inoperative for all tests.
4	17	Everything read properly for all tests.
5	5	Temperature sensor inoperative for all tests.
5	14	Everything read properly for all tests.
5	20	Temperature sensor inoperative for all tests.
5	19	" " " " "

The pile piezometers apparently performed satisfactorily once they had been re-saturated. They were flushed periodically in order to purge air bubbles in the system. They were initially flushed under a pressure of 50 psi (345 kN/m^2) (during re-saturation) until all air was removed from the return line. The return line was then closed and the pressure was maintained on the flush line in order to force water into the ground. Pore pressure readings indicated an increase in pore pressure during piezometer flushing equal to the applied pressure. A rapid decrease in pore pressures to a stable value occurred within 48 hours after removing the pressure from the flushing line. There were small increases in the total pressure readings during ground saturation. This indicates that the piezometers and the ground were well saturated in the vicinity of the cells and the total pressure cells were sensitive to pore pressure changes. It also provided an indication that excess pore pressures dissipate rapidly in the soil around the piles at this site.

Ground Piezometers

The ground piezometers, as a whole, appeared to function satisfactorily throughout the test program. Anomalous behavior occured in seven of the 14 ground piezometers, however, as described briefly below:

1) P191: Apparently, one of the buried connections became partially clogged with soil which intruded during the processes of installing the piezometer, causing indicated pressures to be too high. The lines were successfully blown out by applying high pneumatic pressure to the return line prior to Test 1, and the piezometer functioned satisfactorily throughout the remainder of the testing program.

2) P192: This piezometer functioned properly during the pile installation process, but one or both the pneumatic lines apparently developed a leak during the period of subsequent reaction frame and cap construction, rendering the piezometer unusable for the remainder of the study.

3) P194: This piezometer yielded a flat response throughout the test program, even though return of air through the return line was evidenced. No explanation for this malfunction is offered.

4) P341: This piezometer apparently had a partially clogged connection and consequently registered inordinately high pressures, even though return of air was observed. Attempts to blow out the cell and reduce the pressures were unsuccessful.

5) P343: This piezometer never reached a steady state condition prior to installing the piles. However, the indicated pore pressures were unexplainably increasing, rather than decreasing, with time. Readings from this piezometer are not considered representative.

6) P503: This piezometer experienced the same problem as P343 but returned to a pressure value nearly equal to that registered by P501 and P502 by the time the final group test was conducted. Readings from this piezometer are considered representative only for that test.

7) P504: This piezometer experienced the same problem as P343 and P503. The pressure never stabilized completely during the approximately six months the cell was monitored. The proximity of this piezometer to the west anchor may have had some effect on the readings.

Ground Settlement Points

The ground settlement devices also appeared to perform satisfactorily. They (and the reference system) were very sensitive to ambient temperature changes, however, and, because the mechanical strains in the soil were small, success was achieved only by completely shielding the reference system and settlement points from the sun. One uncertainty does exist with respect to use of the system employed, and that is the lack of ability to locate the exact position of the anchor points in a horizontal plane. For purposes of analysis it was assumed that the ground settlement rods were perfectly vertical, as every attempt was made to impart a vertical push when the guide tubing was installed. In particular, the response of DSP1-25 appears to indicate that it may have been slightly closer to Pile No. 9 than assumed.

Inclinometer

The inclinometer used to measure the true alignment of the piles after driving performed satisfactorily. The only problem encountered with the system was that the 1-1/2 inch (38 mm) square inclinometer steel tubing was too small to allow the sensing element to pass at some joints, where tube alignment was apparently imperfect. The sensor used was 33 inches (840 mm) long, 1 inch (25 mm) in diameter, with two 1-inch (25 mm) spring-loaded guide wheels diametrically opposite one another. The wheels are 24 inches (610 mm) apart. The inclinometer sensing element could be lowered and raised the full length of the pile in Pile Nos. 1, 2, 3, 5, 7, 8, 9, and 10, and unencumbered readings were obtained on pile inclination. The inclinometer sensing element hung on Piles No. 4 and 6 at a depth of 26 feet (7.9 m) (at the location of the joint in the inclinometer tubing) and inclination readings were unable to be recorded below that depth. On Pile No. 11, the sensing element was lowered to the full depth of the pile in one orientation, but hung at the depth of 26 feet (7.9 m) on a perpendicular track. Apparently, bending was sufficient in Piles 4, 6, and 11 to produce some offset in the inclinometer tubes at the joint.

Inclination readings were made every two feet (0.6 m) in two orthogonal directions and in two perpendicular tracks in order to check the measurements. Close agreement was obtained on both tracks. Where readings could not be obtained below 26 feet (7.9 m), it was assumed that the pile was deflected according to an extrapolated tangent at 26 feet (7.9 m). Inclination results are summarized in Table E8.

TABLE E8. INCLINOMETER READINGS IN FEET EXPRESSED AS OFFSETS FROM PILE TOP

	PILE	1		2		3		4		5		6	
DEPTH FROM TOP OF PILE (FT.)		A	B	A	B	A	B	A	B	A	B	A	B
10		-.0590	-.0673	-.0790	-.0604	-.0341	+.0769	+.0578	-.0846	+.0912	+.0118	+.0185	-.1198
20		-.1665	-.1473	-.2035	-.1483	-.0559	+.1474	+.1837	-.1352	+.1737	+.0503	+.0358	-.2641
(26)								+.2460	-.1683			+.0457	-.3536
30		-.2411	-.1885	-.3265	-.2076	-.0867	+.2078	-	-	+.2559	+.1146	-	-
40		-.3460	-.1973	-.4471	-.2533	-.0456	+.3056	-	-	+.2893	+.1769	-	-
42		-.3670	-.1931										
48				-.5771	-.2998	+.0205	+.3706	+.4608	-.3162	+.3188	+.2233	+.0902	-.6459

Note: 1 ft.= 0.305 m.

PILE	7		8		9		10		11	
DEPTH FROM TOP OF PILE (FT.)	A	B	A	B	A	B	A	B	A	B
10	+.0161	-.1945	-.2443	+.0013	-.1675	+.1001	-.0004	+.0174	+.1248	+.1032
20	+.0298	-.3615	-.5126	-.0390	-.3409	+.1686	+.0075	+.0445	+.2546	+.1845
30	+.0564	-.5311	-.8176	-.0833	-.5337	+.2178	+.0402	+.1190	+.4030	+.2396
40	+.0673	-.7354	-1.180	-.0939	-.7742	+.2397	+.1348	+.1731	+.5947	+.3262
42									+.6445	+.3502
48	+.1125	-.8936	-1.506	-.0578	-.9685	+.1983	+.2206	+.2188		

"A" DIRECTIONS

PILE		AZIMUTH
1	—	41° West of North
2	—	45° East of North
3	—	41° East of North
4	—	38° West of North
5	—	48° West of North
6	—	31° West of North
7	—	28° West of North
8	—	43° East of North
9	—	73° East of North
10	—	56° East of North
11	—	9° East of North

"B" DIRECTIONS ARE 90° CLOCKWISE (IN PLAN VIEW) TO "A" DIRECTIONS.

Extensometers

The extensometers performed satisfactorily in a general way during all pile tests. On Pile 5, two of the aluminum measuring rods had been cut off (during installation into the reference head) at an angle that was not perpendicular to the rod. When reading these extensometers, the portable dial gage could not be seated properly on the rod ends, and a reliable reading was unobtainable. This happened at anchor depths of 0 feet (0 m) (ground level) and 20 feet (6.1 m).

The main purpose of the extensometers was to provide a backup in the event of strain gage failure. A typical comparison between values of pile compression obtained directly from extensometers and strain computed from gage output is shown in Table E9. It is observed that extensometer compressions in the indicated depth intervals tended to be somewhat smaller and more erratic than the compressions computed from the electrically measured strains. This effect is possibly due to resistance of extensometer rods rubbing against each other, as complete separation of all rods was not possible with the post-drive setting scheme used. As a consequence, the extensometers did not delineate the same patterns of strain (and therefore, of load) as the strain gages, although the gross compressions along an entire pile compare better. The electronic strain gage data were assumed as the correct data throughout the study.

Data Acquisition System

The components of the data acquisition system provided the necessary output as intended. Minor problems were encountered with the length of computation and output time during the acutal load tests, but no significant inconvenience or interruption in testing resulted. Most of the delays were associated with the slowness of the teletype printer.

It was not possible, with the data acquisition-gaging system used, to maintain the predrive zeros beyond about one month after driving. Some drift occurred in many of the circuits that could not be reasonably related to physical phenomena in the piles or soil and that therefore must be assumed to be electrical drift. As stated previously, part of this drift could have been caused by infiltration of moisture into lead wires. It is believed that at least some of the drift may have been due to slight electrical drift within the amplifier circuits.

Vertical Deflection Measurement

Two primary factors influenced the accuracy of the measurement of vertical displacement of the piles and the ground movement points:

1) The effects of temperature changes in the steel reference system, which caused small zero shifts, and
2) The effects of soil strains and resulting displacements of the reference system supports due to loading of the test piles and the reaction anchors.

TABLE E9. COMPARISON OF VERTICAL COMPRESSION (IN INCHES) BETWEEN STRAIN GAGES AND EXTENSOMETERS, NINE-PILE TEST 1.

	PILE	2		3		4		5		6		7		8		9		10	
DEPTH (ft)	NOM. LOAD	300	600	300	600	300	600	300	600	300	600	300	600	300	600	300	600	300	600
0-10		.019	.048	.020	.041	.021	.043	.019	.045	.020	.045	.018	.038	.021	.040	.019	.047	.021	.047
0-20		.036	.096	.039	.082	.040	.086	.037	.087	.037	.090	.035	.076	.040	.079	.038	.095	.040	.094
0-30		.048	.131	.053	.111	.053	.116	.049	.120	.050	.124	.047	.103	.053	.106	.052	.128	.054	.126
0-42		.057	.156	.063	.130	.062	.137	.058	.144	.059	.147	.057	.120	.063	.128	.061	.151	.063	.147

a. Strain Gage Data

Note: Nominal (Nom.) load expressed in tons.

	PILE	2		3		4		5		6		7		8		9		10	
DEPTH (ft)	NOM. LOAD	300	600	300	600	300	600	300	600	300	600	300	600	300	600	300	600	300	600
0-10		.012	.043	.023	.045	.021	.038	-	-	.018	.051	.019	.038	.020	.038	.019	.043	.023	.045
0-20		.033	.085	.033	.075	.029	.073	-	-	.034	.083	.031	.069	.036	.067	.034	.087	.038	.086
0-30		.031	.104	.048	.101	.047	.101	-	-	.035	.103	.042	.093	.030	.092	.048	.116	.049	.109
0-42		.046	.129	.052	.116	.051	.115	-	-	.053	.124	.049	.109	.049	.109	.051	.136	.054	.140

b. Extensometer Data

Note: 1 ft.= 0.305 m.
1 ton= 8.90 kN.
1 in.= 2.54 cm.

In order to minimize the effects of the former factor, the entire reference system was shielded from direct sunlight at all times during testing by a large tent-like shroud, and most tests were conducted on overcast days during which temperature effects were at a minimum. Nonetheless, a significant ambient temperature drop (approximately 8°C) occurred during the first nine-pile group test, which was caused by the passage of a cold front.

In order to evaluate the effect of temperature changes on deflection measurements, dial gages were set up on fourteen of the ground settlement points during a 6-hour period on a day when the piles were not tested and the test site was shaded as it was during the tests. The various dial gages were read at each ambient temperature change of two degrees Fahrenheit (one degree Centigrade). The results of this monitoring are tabulated in Table E10.

The mean excursion of the fourteen gages monitored was 0.008 inches (0.2 mm), discounting the large changes that occurred in SSP1 and DSP1-43 at the 46° reading, which were apparently the result of mechanical disturbance. If the readings on the remaining gages at 46° are discounted, the average excursion was 0.005 inches (0.13 mm). Since spurious readings of this kind (e.g., due to obvious bumping of reference beams) were discounted or corrected when interpreting the data, it is reasonable to state that the apparent error in dial gage readings during an 8°-10°F (4°-5°C) change in ambient temperature was in order of 0.005 inches (0.13 mm). This temperature differential was typical of most tests, except for the first test on the nine-pile group.

Because of the complexity of the design of the reference system, it was not possible to develop a correction factor which could be applied mathematically to the raw readings. Because of the combination of twisting, flexure, and foreshortening of the various components of the reference system, each gage responded differently to a temperature change, with some readings increasing, some decreasing, and some appearing to cycle.

While no temperature effect study was made for the pile and cap deformation gages, similar accuracy would be expected in the readings for those components.

Observation of data from the microhead level system indicated a probable error of about 0.02 inches (0.5 mm) in each measurement. Errors increased during periods of rain when the instrument could not be read clearly.

The effects of soil strains induced by the reaction anchors could not be studied experimentally; therefore, the problem was addressed analytically by the use of Mindlin's equations for a point load in the interior of an elastic halfpsace. The approximate error in any vertical displacement reading on the group due to this effect was obtained by calculating the upward displacement at the tips of the test piles [43 feet (13 m) below grade] and at the tips of the reference anchor piles [15 feet (4.6 m) below grade] induced by upward directed forces from the two main anchors. The error in deflection measurement is then approximately equal to the relative movement between these two points.

TABLE E10. VARIATION OF GROUND SETTLEMENT READINGS UNDER NO LOAD CONDITIONS AND VARIABLE TEMPERATURE (23 JAN 1980).

TEMP. (°F)	DIAL GAGE READING (in.)						
	SSP1	SSP2	SSP3	SSP6	SSP5A	SSP7A	DSP1-2
42	-0.094	0.013	0.003	0.004	0.012	0.002	0.007
44	-0.093	0.015	0.003	0.004	0.010	0.002	0.008
46	-0.174*	0.018	0.005	-0.001*	0.012	0.003	0.019*
48	-0.169	0.017	0.005	0.000	0.009	0.006	0.013
50	-0.181	0.017	0.008	0.001	0.012	0.010	0.014
52	-0.178	0.018	0.009	-	-	-	-
	DSP1-25	DSP1-43	DSP1-30	DSP2-2	DSP2-25	DSP2-43	DSP2-50
42	0.014	0.215	0.015	0.006	0.007	0.010	0.009
44	0.015	0.216	0.015	0.005	0.006	0.007	0.008
46	0.027*	0.128*	0.026*	0.012	0.013	0.016	0.015
48	0.013	0.116	0.016	0.004	0.006	0.007	0.007
50	0.014	0.118	0.019	0.005	0.007	0.007	0.007
52	-	-	-	-	-	-	-

(*) Possible mechanical anomaly at 46° reading (e.g.,reference bumped)

Note: 1 in.= 2.54 cm.
°F = 1.8(°C)+32

For purposes of calculation, it was assumed that the mean depth of load transfer in the reaction system anchors was 90 ft (27.4 m) below grade, allowing for load transfer in shaft friction as well as upward bearing on the bells. Using an elastic modulus of 15,000 psi (103,400 kN/m^2) for the soil, which is based on deep-seated pressuremeter test results and E/c correlations, the upward displacement at the level of the test pile tips was computed to 0.000083 in./ton of applied load (0.000047 cm/kN). The upward displacement at the level of the reference anchor pile tips was computed to be 0.000065 in./ton (0.00004 cm/kN). The net error was, then, 0.000018 in./ton (0.00001 cm/kN), which, because the pile tips were being lifted more than the reference anchors, caused the settlement reading to be about 0.000018 in./ton (0.00001 cm/kN) too low. Expressed as a percentage, the error in settlement measurement due to this effect was about 6%.

The effect of uplift on the H-pile anchors for the reference pile tests on the movement of the reference system was essentially theoretically counterbalanced by the downward displacement produced by loading of the test pile, as each reference anchor was situated approximately seven widths of the H-pile anchors from the center of the uplift. It may therefore be assumed that the reference pile settlement readings were essentially unaffected by loading of the ground from the test piles or reaction anchors.

Finally, a similar elastic analysis of the settlement of the reference anchors induced by the downward loading of the test piles, assuming the test piles act as friction piles, yields a downward vertical movement of the reference anchors of 0.00012 in./ton (0.00007 cm/kN), or to produce a further theoretical error in the measurement of group settlement of about 39% (on the low side).

Thus, as an upper limit, the group settlement measurements could be in error by as much as 45% on the low side (that is, the measured values should be multiplied by 1.45) when the two conditions described above are combined.

This also leads to the conclusion that reported settlement ratios should be multiplied by as much as 1.45 to obtain an upper limit to the true settlement ratio, unaffected by movements of any reference system.

In point of fact, induced movements of unloaded piles by loaded piles on the test site during the subgroup tests were found to be considerably less than that predicted by elastic theory, possibly because of pile reinforcement of the soil. As a lower bound to the error in measured settlement (and settlement ratio), the settlement induced in the reference system anchors by compressive load in the group piles [0.00012 in./ton (0.00007 cm/kN)] may be multiplied by the ratio of observed displacement in unloaded piles during the subgroup tests to displacement of those piles predicted by elastic theory. Such an operation yields induced settlements of 0.00004 in./ton (0.00002 cm/kN) and a resulting error factor of 1.19, instead of 1.45, assuming that the displacement value obtained for the effect of deep anchors uplift remains valid. The true error is within these limits. It is suggested that the proper correction factor to be applied to the data within the elastic range is about 1.20. This factor, of course, decreases as inelastic settlement of the piles begins.

Analysis of the microhead level readings on the first and third nine-pile group tests revealed an average settlement factor of 1.09 with a probable error 0.25. Data from Test 2 were excluded since the cap tipped considerably toward the instrument in that test, introducing a systematic error in the settlement readings.

CONCLUSIONS

1) The strain gage system performed adequately. Some long-term attrition occurred that was apparently due to moisture intrusion resulting from small breaks in the lead wire produced during welding. It is believed that the nitrogen environment was effective in limiting this attrition, although stability adequate to maintain the pre-drive zeros could not be maintained past the first test.
2) The piezometers performed adequately, except that the pile piezometers lost saturation due to impact forces during driving. This required re-saturation through a separate flushing system that had been installed, making the assessment of immediate post-drive pore pressure impossible, but allowing accurate measurement of pore pressures for the remainder of the program. Some small amounts of soil may have become lodged in the ground piezometer tubes during installation that affected the piezometer response, but in general the ground system performed well.
3) The total pressure measuring system was too sensitive to temperature effects to be of practical future use without modification. Furthermore, geometric modifications, including provision of a curved sensing surface (for pipe pile tests) and assurance of a zone free of irregularities around the cell is believed to be necessary. The data obtained did yield trends in total pressure development when careful thermal calibration and temperature effect corrections were made. Approximately one half of the thermal sensor circuits used to correct total pressure readings became inoperative after driving, which increased the uncertainty of the measurements.
4) The pile extensometer system proved to be relatively easy to install and yielded gross pile compressions that approximated pile compressions obtained from the strain gages. Analyses of each individual reading difference, however, revealed scatter sufficient to make the system of questionable use with respect to determining the correct shapes of the load distribution curves.
5) The ground movement system performed as intended. The only significant difficulties in interpreting the data from this system resulted in the uncertainties with regard to positioning of the deeper anchor points in a horizontal plane and in the errors associated with temperature-generated movements in the reference system. The importance of shielding the reference system from the direct sun was evident.

6) Settlement measurement in the pile group was also affected by movement of the reference system due to the several effects described. Errors in group settlement are not thought to be greater than 20%. Relative movement between the piles and the ground settlement points are thought to be essentially correct, since the movements of both systems were measured off the same reference frame.

7) The inclinometers performed satisfactorily in determining the true pile orientation. Slightly larger inclinometer tubes would have facilitated the measurements.

8) The data acquisition system served its intended purpose. A more ideal system would be one in which every electronic instrument (i.e., load cell or strain gage bridge) would have a dedicated circuit (so as to read all circuits simultaneously at failure and to eliminate switching) and in which hard copy is obtained through a line printer or other device faster than a teletype printer. For tests in which long term electrical stability is needed, it may be desirable to use a system, such as a null balance system, which is less sophisticated than the system used in this study.