TEXAS
TRANSPORTATION
INSTITUTE

TEXAS
HIGHWAY
DEPARTMENT

COOPERATIVE
RESEARCH



# EVALUATION OF PRESSURE CELLS USED FOR FIELD MEASUREMENTS OF LATERAL EARTH PRESSURES ON RETAINING WALLS

in cooperation with the
Department of Transportation
Federal Highway Administration

RESEARCH REPORT 169-1
STUDY 2-5-70-169
RETAINING WALL DESIGN

# EVALUATION OF PRESSURE CELLS USED FOR FIELD MEASUREMENTS OF LATERAL EARTH PRESSURES ON RETAINING WALLS

By

David A. Corbett
Research Assistant

Harry M. Coyle
Associate Research Engineer

Richard E. Bartoskewitz
Engineering Research Associate

and

Lionel J. Milberger
Research Associate

Research Report No. 169-1

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

Sponsored by
The Texas Highway Department
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

September 1971

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the Federal Highway Administration.

ABSTRACT

Commercially available total earth pressure cells and gaging systems are investigated. The principles of operation for nine commercially available pressure cells are presented, and the manufacturers performance ratings are summarized. The performance characteristics of four types of pressure cells selected for this preliminary study are determined by lab calibration. The four pressure cells selected include the Geonor vibrating wire, Carlson unbonded strain gage, Terra-Tec pneumatic, and Gloetzl hydraulic types. Installation of the four types of pressure cells in a cantilever retaining wall is described. Wall movement and measured earth pressures are presented graphically. Theoretical earth pressures on the instrumented retaining wall are determined by the Rankine and Coulomb theories and a comparison is made with the measured lateral earth pressures. The relative merits of each cell is summarized and problem areas are identified.

SUMMARY

This test program was conducted during the first year of a five-year study on "Determination of Lateral Earth Pressure for Use in Retaining Wall Design." The objective of the Research Study is to develop the most economical design procedure for retaining walls.

The limited objective for this first year of study was to investigate the performance of commercially available total earth pressure cells, and select the type of pressure cell which is best suited for measuring lateral earth pressures on typical cantilever retaining walls.

The principles of operation for nine types of total earth pressure cells are described. Four types of commercially available cells, namely, Geonor vibrating wire, Carlson unbonded strain gage, Terra-Tec pneumatic, and Gloetzl hydraulic, were obtained for installation in a cantilever retaining wall. The results of laboratory calibration tests on these four types throughout the range of temperatures expected in the field are presented.

The installation of the pressure cells and thermocouples for temperature determinations is described. Relative merits of each cell are discussed and problem areas are identified. Wall

movements during and after backfilling were measured. Graphs of lateral earth pressure and wall movement versus time are presented. The theoretical earth pressures are computed by the Rankine and Coulomb theories. A comparison of the theoretical and measured lateral earth pressures is made.

## IMPLEMENTATION STATEMENT

Research Report 169-1 is a technical progress report which presents the results of an investigation which was conducted to evaluate several types of commercially available total earth pressure cells for the measurement of lateral earth pressure on a retaining wall. This work was accomplished during the first year of a five-year study to develop the most economical design procedure for retaining walls.

Four types of pressure cells were obtained and installed in a cantilever retaining wall. Measurements of lateral earth pressures have been and are continuing to be made. However, the work accomplished during the first year is preliminary in nature. Implementation of any results derived therefrom are not intended. No attempt has been made to revise or modify the "classic" earth pressure theories or present design procedures currently being used by THD. The results of this year's work will be the determining factors in the selection of the most suitable pressure cell (or cells) to be used during the second year of study to develop a more accurate pressure distribution profile.

TABLE OF CONTENTS

LIST OF TABLES

## LIST OF FIGURES

# INTRODUCTION

## Nature of the Problem

One of the most important problems encountered by civil engineers involved in the design of retaining walls is the determination of the magnitude and distribution of the lateral earth pressure acting upon the retaining wall. The lateral earth pressure must be known if the engineer is to design an adequate, yet economical, retaining wall. The use of retaining walls in highway construction in Texas is increasing rapidly, especially in the larger urban areas, but present procedures used to determine lateral earth pressures are not considered adequate in some cases by the Texas Highway Department Engineers. All the customary methods of earth pressure computation can be traced back either to Rankine's or to Coulomb's theory of earth pressure (15).* Both of these theories contain several simplifying assumptions which decrease their accuracy and restrict their application. The assumed conditions are generally not fulfilled in nature. Consequently, the extent to which this disagreement will affect the validity of the theoretical design is indefinite. The determination of actual stress distribution in full scale structures would provide both a positive check on the validity of the assumptions made in the design procedure

---

*Numbers in parentheses refer to the references listed in Appendix I. (The citations on the following pages follow the style of the Journal of the Soil Mechanics and Foundations Division, ASCE.)

and a source of empirical data for use in further development of the design theory.

Present Status of the Question

A literature survey has revealed that little research work has been done during the past 25 years in connection with determination of lateral earth pressures through field measurements. Terzaghi (16) obtained some experimental data concerning the relation between the lateral yield of the wall, the location of the center of pressure, and the hydrostatic pressure ratio as a result of some large scale earth pressure tests at Massachusetts Institute of Technology in 1929.

An extensive soil mechanics fact finding survey which included an investigation on soil pressure cells was conducted by the Waterways Experiment Station, Corps of Engineers, U. S. Army, in the early 1940's. The consultant, D. W. Taylor, concluded that the amount of useful data that had been obtained by earth pressure measurements was limited - it could not be classified as sufficiently dependable for use in checking existing theories or in developing improved methods (22).

Most subsequent research has been concerned with the development of more nearly mechanically perfect pressure cells. However, in recent years, engineers have adopted the use of long term instrumentation in order to verify classical design theories for structures other than retaining walls. This approach involves the instrumentation of real structures in the field in order to measure the performance of the structure under real loading conditions. Similarly, long term instrumentation on retaining walls can produce actual measurements of lateral earth pressure based on field loading conditions.

Objectives of the Research

The findings reported herein were obtained during the first year of a five-year study, the ultimate objective of which is to develop the most economical design procedure for retaining walls. The total research effort has been subdivided into three Phases. During Phase I, which includes the first two years of the study, lateral earth pressures will be measured on a standard cantilever retaining wall in the Houston urban area. Phase II of the study extends through the third and fourth years, during which time pressures will be measured on a new design retaining wall involving pre-cast panels supported by drilled shafts. In Phase III, the final year of study, researchers will evaluate present design theories and procedures, including surcharge loads, for determination of lateral earth pressure for use in retaining wall design.

The specific objectives of the work accomplished during the first year were:

a. Determine which types of total earth pressure cells are commercially available and obtain the pertinent information regarding cost, performance characteristics, etc.

b. Select and purchase a variety of the most promising cells for calibration and installation.

c. Obtain measurements of the lateral earth pressure on a typical cantilever retaining wall.

d. Based on data obtained from the field measurements, select the pressure cell (or cells) which is most adequate for measuring the earth pressures commonly encountered on typical cantilever retaining walls. The type of cell selected will be used in further research work throughout the remaining four years of the study.

e. Sample and test the soil which was used for backfill material on the Houston retaining wall project.

f. Estimate lateral earth pressures by existing theories (Rankine and Coulomb methods) for comparison with the field data.

# PRESSURE CELLS

## General

Attempts to measure lateral earth pressures against a retaining wall have usually been made by means of pressure cells embedded in the wall in such a manner that the contact face between the soil and the cell is flush with the face of the retaining wall. Hamilton (5) gives an excellent summary and discussion of different types of earth pressure cells. He describes three basic types of earth pressure cells and four basic types of gauging systems used in earth pressure cells:

a. Types of cells

   1. Direct acting. In this type of cell the soil acts directly on the portion of the cell carrying the gauging system.
   2. Indirect acting. In a cell of this type the soil acts via a fluid on a second pressure-responsive element.
   3. Counteracting. In this type of cell a counter fluid pressure is applied to the pressure-responsive element to balance the soil pressure.

b. Types of gauging systems.

   1. Mechanical gauging systems. These systems include levers, extensometers, friction-tapes, and friction plates.

2. Hydraulic gauging systems. Hydraulic gauging systems include manometers and Bourdon gauges.
3. Acoustic gauging systems. A vibrating wire is an example of an acoustic system.
4. Electric gauging systems. Electrical resistance, reluctance, inductance, and capacitance systems are examples of electric gauging systems.

Since the contact face between the soil and the cell is flush with the face of the retaining wall and the cell is entirely embedded in concrete, the shape of the cell is irrelevant. However, any displacement of the contact face between the cell and the soil changes the pressure on the contact face. The error becomes excessive if the ratio of diameter to displacement is less than 1000 (22).

## Specific Pressure Cells

Before discussing the selection of specific cells for use in this study and subsequent calibration and installation, it is desirable to have as clear an understanding as is possible of the basic functioning of the better known pressure cells. Therefore, this section deals briefly with the early development of pressure cells and then the better known pressure cells suitable for use in measuring lateral earth pressures against retaining walls are discussed.

a. Earliest pressure cells. The earliest cells consisted of flat circular boxes filled with a liquid (17). The contact face was a flexible membrane and the liquid pressure was measured with an ordinary Bourdon gauge. Although the absolute deflection of the membrane was small, it was still large enough to cause an important change of pressure. In addition, the cells were very sensitive to changes in temperature.

b. Goldbeck cell. The next stage in the development of pressure cells is represented by the Goldbeck cell. It was reported in the literature in 1916 by Goldbeck and Smith (4). A sketch of the gauge is shown in Fig. 1. This cell is basically a counteracting type of cell employing a pneumatic-electrical contact gauging system. A piston is attached to a cylindrical casing by means of a flexible diaphragm. Pressure acting on the piston stretches the diaphragm allowing the piston to make contact with a button in the base of the cell which closes an electric circuit. Compressed air is then admitted to the cell causing the electric circuit to be broken by forcing the piston away from the button. The air pressure necessary to break the contact or open the circuit was assumed to be equal to the earth pressure acting on the piston.

There are several disadvantages to this type of cell. Chief among these is the outward movement of the contact face required to break the electric circuit. Therefore, the indicated pressure is too large. On one field installation, the pressure observed by means of Goldbeck cells was 80% in

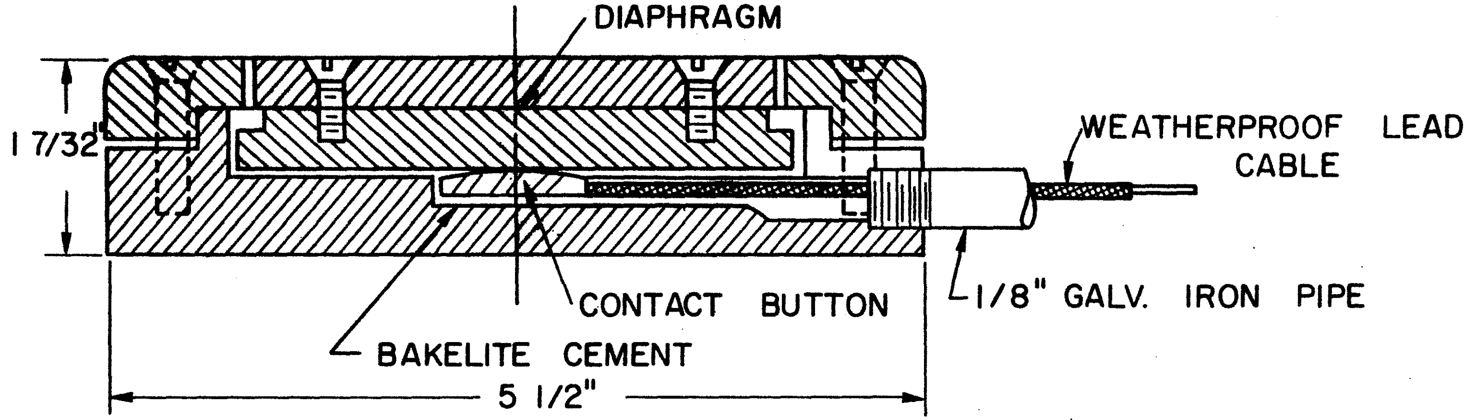


FIG. 1 – GOLDBECK PRESSURE CELL

excess of the load determined by more accurate methods (17). In many cases, the break in the electrical circuit is not sharply defined, but consists of a gradual diminution of current corresponding to a considerable range in pressure.

c. Carlson cell. The Carlson cell is an indirect acting type of cell using an electrical resistance gauging system (5). A sketch of the Carlson cell is shown in Fig. 2. Earth pressure acting on the flat circular plate is transmitted by confined mercury to a metal diaphragm. The deflection of the diaphragm actuates the strain meter. The strain meter consists of two electrical resistance wires coiled between insulators attached to a steel frame. The deflection of the diaphragm increases the tension in the wires of one coil and reduces the tension by the same amount in the other. The changes in tension causes a change in the ratio of the electric resistances of the two coils, which can be measured by means of a Wheatstone bridge. A precise bridge is required since the resistance changes are very small compared to the total circuit resistance. The change in resistance ratio is a measure of the deflection of the diaphragm, and hence of the contact pressure against the cell.

The entire strain meter is housed in a stem and may be read by electrical means from a remote point. Theoretically, temperature changes have no effect upon the resistance ratio since a change in temperature either increases or decreases

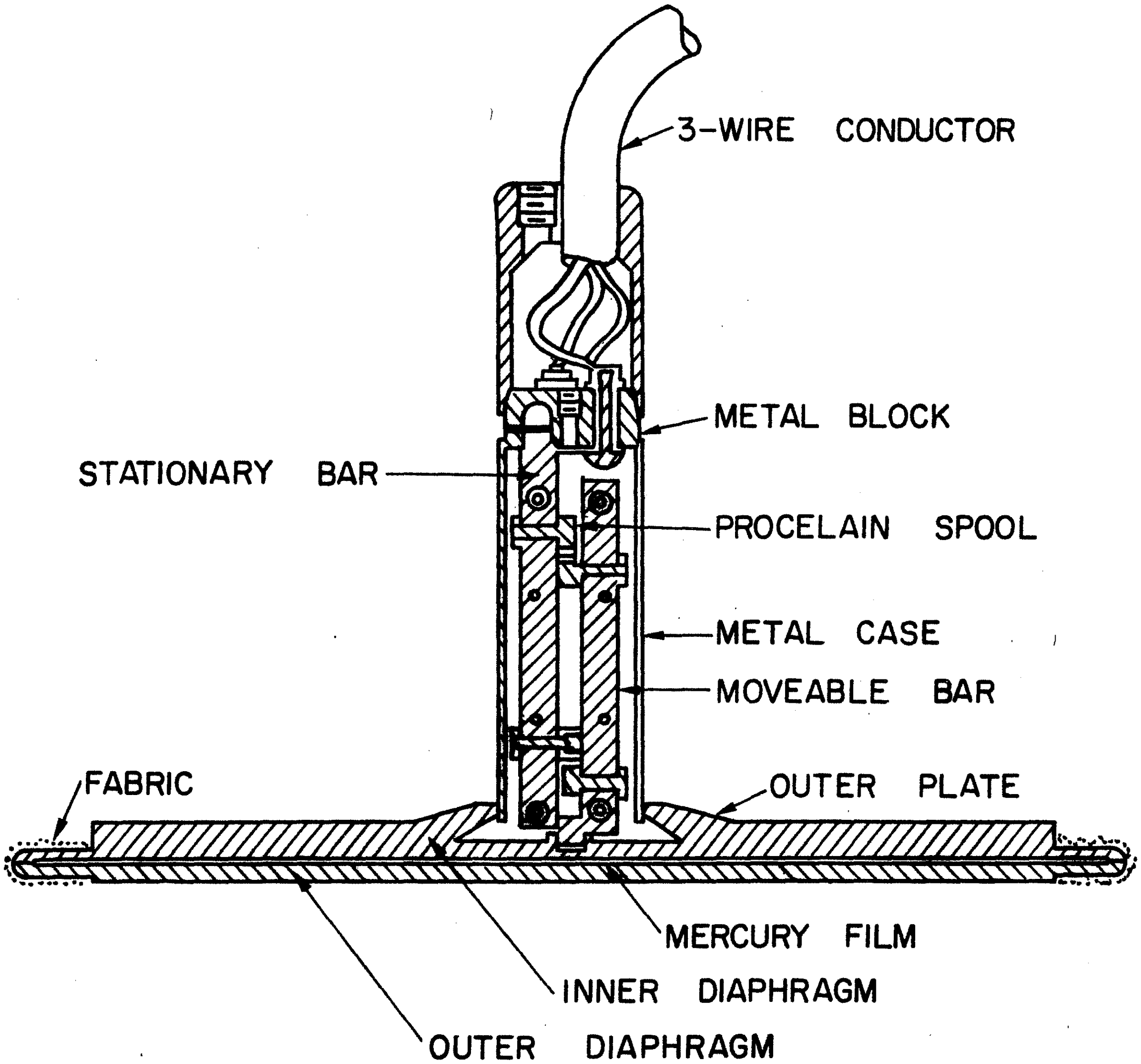


FIG. 2 — CARLSON PRESSURE CELL

the tension in the wires of both coils by the same amount. However, small resistance changes in the connector cables or splices may cause erroneous pressure indications or total failure of the meter. Successful use of these cells mounted flush in the face of rigid structures was reported in a progress report of the Soil Mechanics Fact Finding Survey, Corps of Engineers, Waterways Experiment Station (22).

d. WES cell. This cell is the result of studies by the Waterways Experiment Station (21), and a sketch of the cell is shown in Fig. 3. It is similar in principle to the Carlson cell, except that the deflection of the diaphragm that constitutes the contact face is measured by means of SR-4 electrical resistance strain gauges bonded to the inside of the diaphragm (17).

Early installations of WES cells showed numerous mechanical and electrical defects, most of which have been eliminated in revised designs of the cells. The tendency of bonded resistance strain gauges to long-term creep and zero drift must still be considered. A resistance change occurs in pressure cell cables when the cables are subjected to various degrees of tension. Extreme care must be taken in the choice, installation, and maintenance of connector cables.

e. Geonor vibrating wire cell. This cell was originally developed to be mounted flush with the outer surface of sheet piling driven into soft clay (5). A sketch is shown in

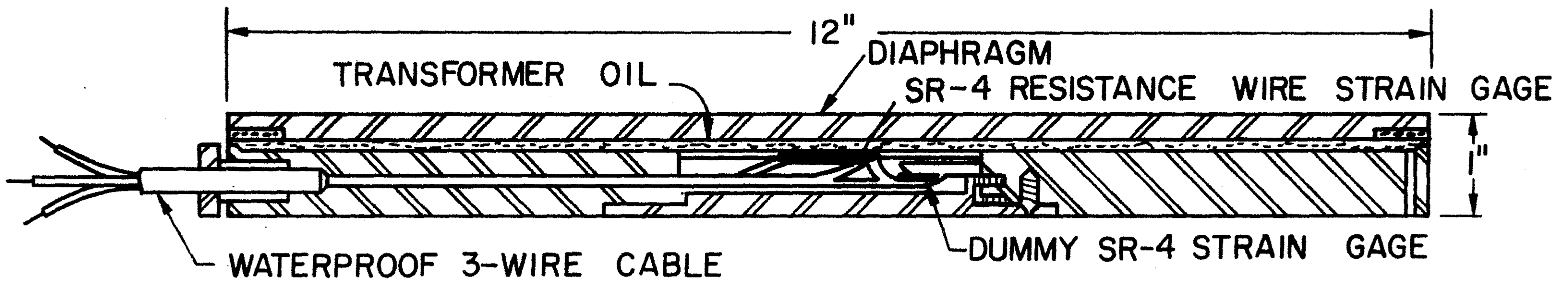


FIG. 3 - WES PRESSURE CELL

Fig. 4. The cell operates on the principle that the deflection of the diaphragm changes the tension in an elastic wire stretched between two posts affixed to the diaphragm, and thereby causes a change of the natural frequency of vibration of the wire. A combined permanent magnet and electromagnet is mounted near the wire. To make an observation, an electrical impulse is sent through the electromagnet which causes the wire to vibrate. The vibration of the wire in the field of the permanent magnet sets up an electromotive force in the coils of the electromagnet with a frequency equal to that of the vibrating wire. The electromotive force is amplified and its frequency determined by means of a portable frequency-measuring instrument. The deflection of the diaphragm is proportional to the change in the square of the frequency. Theoretically, temperature changes require no compensation because they produce the same strain in the diaphragm as in the vibrating wire. The vibrating wire cell has an advantage over strictly electrical strain gauges in that any change in the properties of the electrical circuit does not alter the gauge and its frequency (12). The readings are independent of fluctuations in the power input, current, capacitance, change in electrical resistance of the circuit, or induction from ground circuits. The cells are particularly useful in field work where

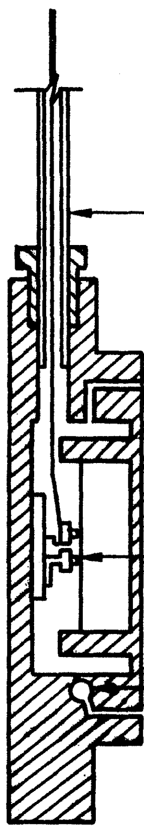


FIG. 4 GEONOR VIBRATING WIRE PRESSURE CELL

electrical circuits are prone to damage and deterioration. The durability and long-term performance of vibrating wire cells has been very satisfactory (2).

f. Gloetzl cell. This cell consists of a bypass valve assembly, an input (pressure) tube, and a discharge tube. A sketch of the cell is shown in Fig. 5. The Gloetzl cell acts as a pressure actuated bypass valve in a hydraulic circuit. External earth pressures acting on a cell maintain it in a "closed" configuration. To determine the magnitude of the external pressure, internal pressure is increased in the cell circuit until it equals the external pressure. At this point the cell valve assembly opens, bypassing hydraulic fluid to a separate return path of the circuit.

g. Terra Tec cell. This is a newly developed and promising cell, but no field test data are available at this time. The pressure cell consists of three basic parts: cell, control unit, and flexible connecting tubing. A sketch is shown in Fig. 6. The cell is constructed of two 9-inch diameter steel plates welded together at the circumference. The plates are coated with a film epoxy to prevent corrosion. The void between the plates is filled with an incompressible, non-corrosive fluid which transmits the applied pressure to the sensing unit; the sensing unit consists of a double-bellows assembly. Air pressure from the control unit is applied through a closed loop system inside the bellows to

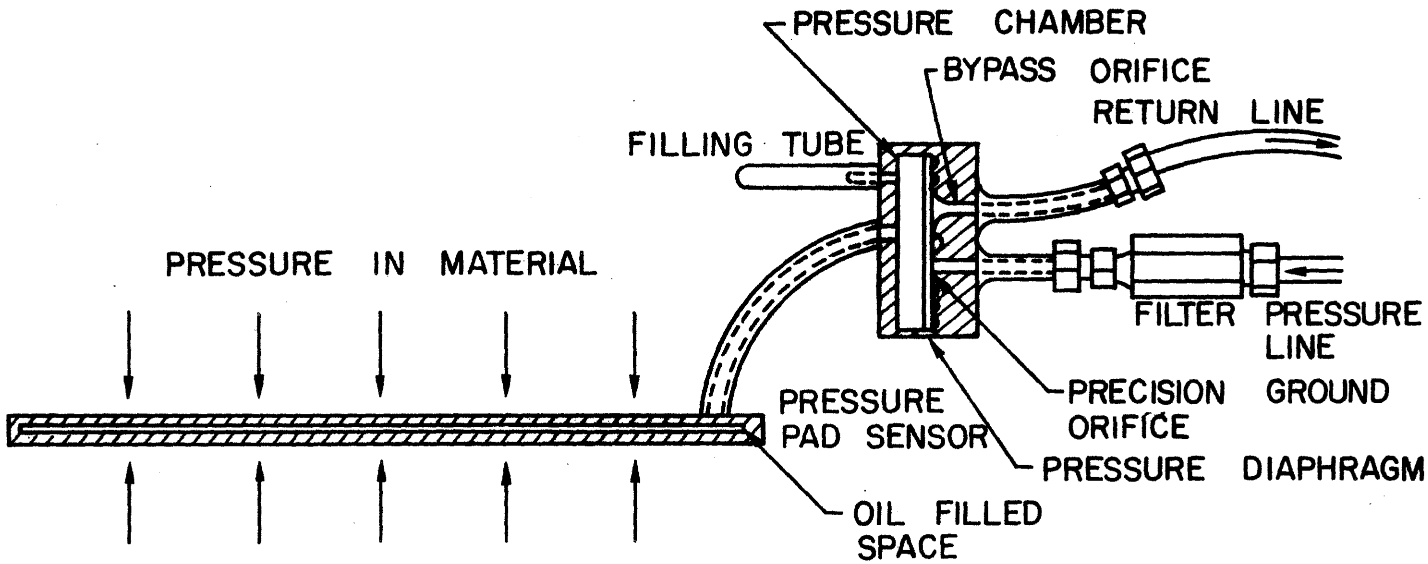


FIG. 5 – GLOETZL PRESSURE CELL

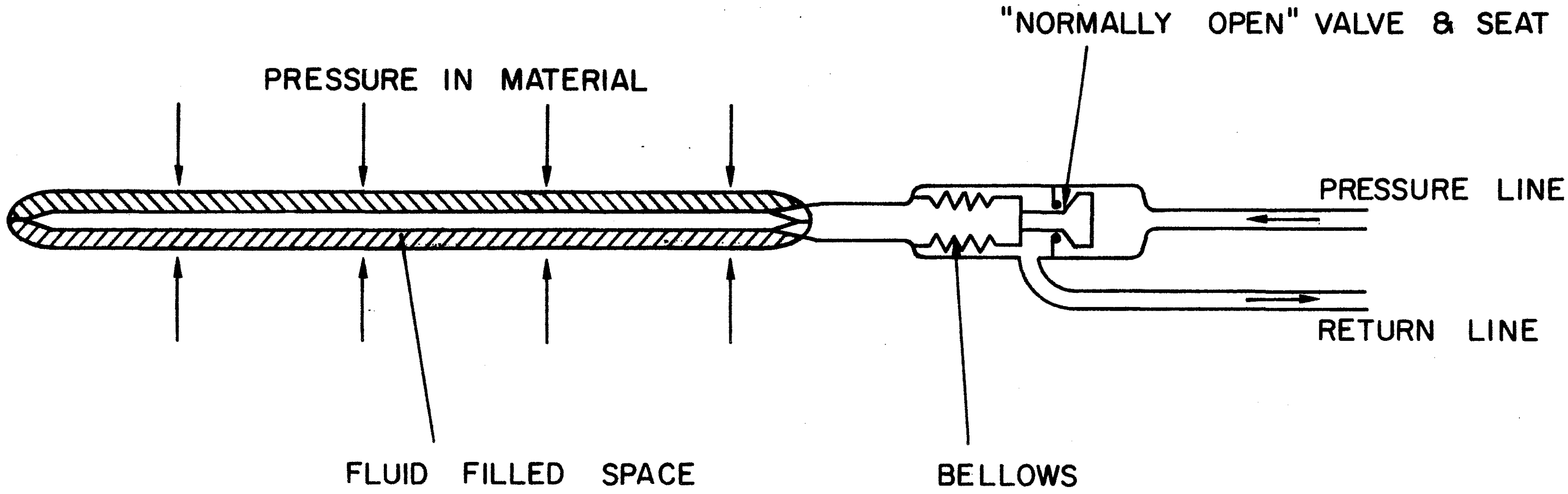


FIG. 6 - TERRA TEC PRESSURE CELL

balance the external total pressure. This pressure is read directly on the gauge in the control unit. The unique bellows assembly design allows the pressure balance operation to occur with null displacement.

h. LVDT pressure cell. This is a pressure cell developed recently by the Slope Indicator Company. The cell has a linear variable displacement transducer for a sensor. Very little information on this cell is available at this time.

Selected Pressure Cells

In the selection of pressure cells for use in measuring lateral earth pressures against retaining walls, several factors must be considered. In an approximate order of importance, the factors include:

a. the accuracy and consistency of the unit,

b. its durability, or resistance to failure,

c. simplicity of operation under field conditions,

d. auxiliary equipment necessary for operation,

e. ease of installation, and

f. cost.

The first requirement is paramount; if accuracy is not achieved, the cell has not served its purpose.

After considering the principles of operation of the basic pressure cells, along with their inherent advantages and disadvantages, a number of "brand-name" pressure cells were investigated. These included:

a. Geonor vibrating wire cell

b. Soil Instruments LTD vibrating wire cell

c. Perivale vibrating wire cell

d. Maihak vibrating wire cell

e. Soiltest pressure cell (has a bonded strain gauge and is believed to be identical to the WES cell).

f. Gloetzl hydraulic cell

g. Terra Tec pneumatic cell

h. LVDT cell

i. Carlson cell

j. Goldbeck cell

Of these cells, the Goldbeck cell was immediately eliminated since it apparently is no longer available commercially. Gloetzl pressure cell equipment which had been originally purchased by the Texas Highway Department for use in drilled shaft studies at the University of Texas were obtained at no expense for use in this research project.

The characteristics of the previously mentioned "brand-name" pressure cells (with the exception of the Goldbeck cell) are summarized and compared in Table 1.

As a result of the survey conducted to ascertain the most effective yet economical type of pressure measuring device on the commercial market, two each of the three most promising pressure cells were ordered as follows:

a. Two Geonor vibrating wire pressure cells. A read-out unit was rented initially.

TABLE 1. - CHARACTERISTICS OF PRESSURE CELLS FOR USE IN RETAINING WALLS

| BRAND NAME | GEONOR | CARLSON | TERRA TEC | GLOETZL |
|---|---|---|---|---|
| TYPE | Vibrating Wire | Unbonded Strain Gage | Pneumatic | Hydraulic |
| Manufacturer's Stated Accuracy | ± 0.1 psi | N/A | ± 0.6 psi | N/A |
| Manufacturer's Stated Pressure Range (psi)[(a)] | 0 - 71 | 0 - 25 | 0 - 250 | 0 - 30 |
| Active Diameter (in.) | 3 | 7 1/4 | 8 1/2 | N/A |
| Available Through U.S. Distributors | Yes | Yes | Yes | Yes |
| Cost of Readout | $1,300[(b)] | $495 | $695 | N/A |
| Power Requirement | 120/240 VAC or battery & inverter | Battery | Compressed Air | Compressed Air [(c)] |
| Cost per Cell | $450 | $230 | $248 | N/A |
| Expected Accuracy | Good | Good | Fair | Fair |
| Expected Durability | Excellent | Good | Good | Good |
| Expected Simplicity of Operation | Excellent | Excellent | Excellent | Fair |
| Expected Ease of Installation | Excellent | Good | Excellent | Good |

(a) Other ranges available; stated ranges are based on requirements of this study.
(b) Cost of locally constructed readout is approximately $400.
(c) After TTI modification.

TABLE 1. (Cont.) - CHARACTERISTICS OF PRESSURE CELLS FOR USE IN RETAINING WALLS

| BRAND NAME | SOIL INSTRUMENTS LTD. | PERIVALE | MAIHAK | SOILTEST [d] | SLOPE INDICATOR |
|---|---|---|---|---|---|
| TYPE | Vibrating Wire | Vibrating Wire | Vibrating Wire | Bonded Strain Gage | LVDT |
| Manufacturer's Stated Accuracy | N/A | N/A | N/A | N/A | N/A |
| Manufacturer's Stated Pressure Range (psi) [a] | 0 - 100 | 0 - 100 | 0 - 28 | 0 - 20 | 0 - 25 |
| Active Diameter (in.) | N/A | N/A | N/A | N/A | N/A |
| Available through U.S. Distributors | No | No | Yes | Yes | Yes |
| Cost of Readout | $1,030 | $1,400 | N/A | $540 | N/A |
| Power Requirements | 120/240 VAC or battery & inverter | 120 VAC or battery & inverter | 220 VAC | 45 V battery | N/A |
| Cost per Cell | $384 | $585 | $975 | $370 | $450 |
| Expected Accuracy | Good | Good | Good | Fair | Fair |
| Expected Durability | Excellent | Excellent | Excellent | Good | Good |
| Expected Simplicity of Operation | Excellent | Excellent | Excellent | Good | Excellent |
| Expected Ease of Installation | Excellent | Excellent | Excellent | Excellent | Excellent |

(a) Other ranges available; stated ranges are based on requirements of this research study.

(d) This cell is believed to be similar to the WES cell.

b. Two Terra Tec pneumatic pressure cells and one read-out unit.

c. Two Carlson unbonded strain gauge pressure cells and one read-out unit.

Consequently, eight pressure cells (the six above and two Gloetzl cells from the University of Texas) were available for calibration and subsequent installation by mid-May 1971.

Calibration Procedures

It is necessary that all pressure cells which are to be used in earth structures have long-term calibration stability. This requirement is obvious, since the cell is to be placed below ground surface and must function reliably for several years. The normal calibration methods used employ pneumatic, hydrostatic, or dead-weight loading. Calibration factors derived by the different methods usually differ (21), and it is probable that all of these differ somewhat from in situ conditions. The simplest and perhaps most frequently used method is the pneumatic method. This is the method being used initially in this study.

Calibration should at least extend through the maximum expected pressure range, both for loading and unloading conditions, and should be repeated several times. The effect of temperature changes on the cell characteristics must be taken into account. Calibration at the temperature range that is expected in the field should suffice. Calibration for the eight cells used in this phase of the research was conducted over a range of temperature from 50°F to 100°F. Each cell had a total of nine calibration tests run on it; three tests on each cell were run at three different temperatures: 50°F, 73°F, and 100°F. The connector leads on all the cells during calibration were the same length as they would be when the cells were installed in the retaining wall. A summary of the data obtained by calibration of the eight cells are shown in Table 2.

After the cells had been installed in the retaining wall and just prior to the backfilling operations, field "zeros" were obtained for each pressure cell. The field zero for each cell was the average of two or three readings taken at similar temperatures. A better procedure would have been to take at least two or three "zero" readings at each extreme of the available temperature range; for example, readings at night when the temperature is lowest and readings in the early afternoon when the temperature is highest.

TABLE 2. - ACTUAL PRESSURE CELL CHARACTERISTICS DETERMINED BY LAB CALIBRATION

| BRAND NAME | GLOETZL | | TERRA TEC | |
|---|---|---|---|---|
| CELL NUMBER | 1 | 3 | 501 | 502 |
| Nominal Zero Offset (psi) | 6.8 - 8.8 | 9 - 10.1 | 5.2 - 6.5 | 5.3 - 6.7 |
| Zero Stability Range (psi) (50°F to 100°F) | 2.0 | 1.2 | 1.35 | 1.4 |
| Calibration Factor (psi per unit gage reading) | 0.959 | 0.970 | 0.962 | 0.984 |
| Resolution (psi) | 0.05 | 0.05 | 0.2 | 0.2 |
| Hysteresis (psi) | 0.19 | 0.32 | 0.25 | 0.23 |
| Linearity (psi) | 0.12 | 0.20 | 0.18 | 0.17 |
| Accuracy* (psi) | ± 1.1 | ± 0.8 | ± 0.8 | ± 0.8 |

* 1/2 zero stability range + 1/2 hysteresis.

TABLE 2 (Cont.) - ACTUAL PRESSURE CELL CHARACTERISTICS
DETERMINED BY LAB CALIBRATION

| BRAND NAME | GEONOR VIBRATING WIRE | | CARLSON | |
|---|---|---|---|---|
| CELL NUMBER | 17 | 18 | 1 | 2 |
| Nominal Zero Offset (psi) | 124.4 - 125.0 | 141.8 - 143.1 | 9.3 - 10.5 | 18.4 - 20.2 |
| Zero Stability Range (psi) (50°F to 100°F) | 0.6 | 1.3 | 1.3 | 1.8 |
| Calibration Factor (psi per unit gage reading) | 0.0888 | 0.1009 | 8.83 | 10.21 |
| Resolution (psi) | 0.1 | 0.1 | 0.1 | 0.1 |
| Hysteresis (psi) | 0.29 | 0.22 | 0.22 | 0.25 |
| Linearity (psi) | 0.16 | 0.16 | 0.15 | 0.19 |
| Accuracy* (psi) | ± 0.4 | ± 0.8 | ± 0.8 | ± 1.0 |

* 1/2 zero stability range + 1/2 hysteresis.

## INSTALLATION OF CELLS

### Test Site

The test site for this study is located along U. S. Highway 59 near the intersection of Interstate Highway 45 and U. S. Highway 75 in Houston. The footing of the retaining wall panel chosen for instrumentation is sitting on piles. A typical cross section of the retaining wall is shown in Fig. 7. The groundwater table was below the retaining wall at all times during installation of cells. Weepholes are provided in the wall to relieve any seepage or hydrostatic pressures which might otherwise build up in the backfill.

### Instrumentation

The back face of the retaining wall panel was instrumented with eight earth pressure cells. Cell locations are shown on the retaining wall cross section in Fig. 7. The two cells from each manufacturer were arranged in a vertical row. A thermocouple was placed beside each pressure cell and, in addition, two thermocouples were placed just above the top of the footing. The instrumentation layout is depicted in Fig. 8.

### Method of Installation

One of the most important factors in the measurement of lateral earth pressures against retaining walls is that of installation. There are several conditions which are essential for a high grade

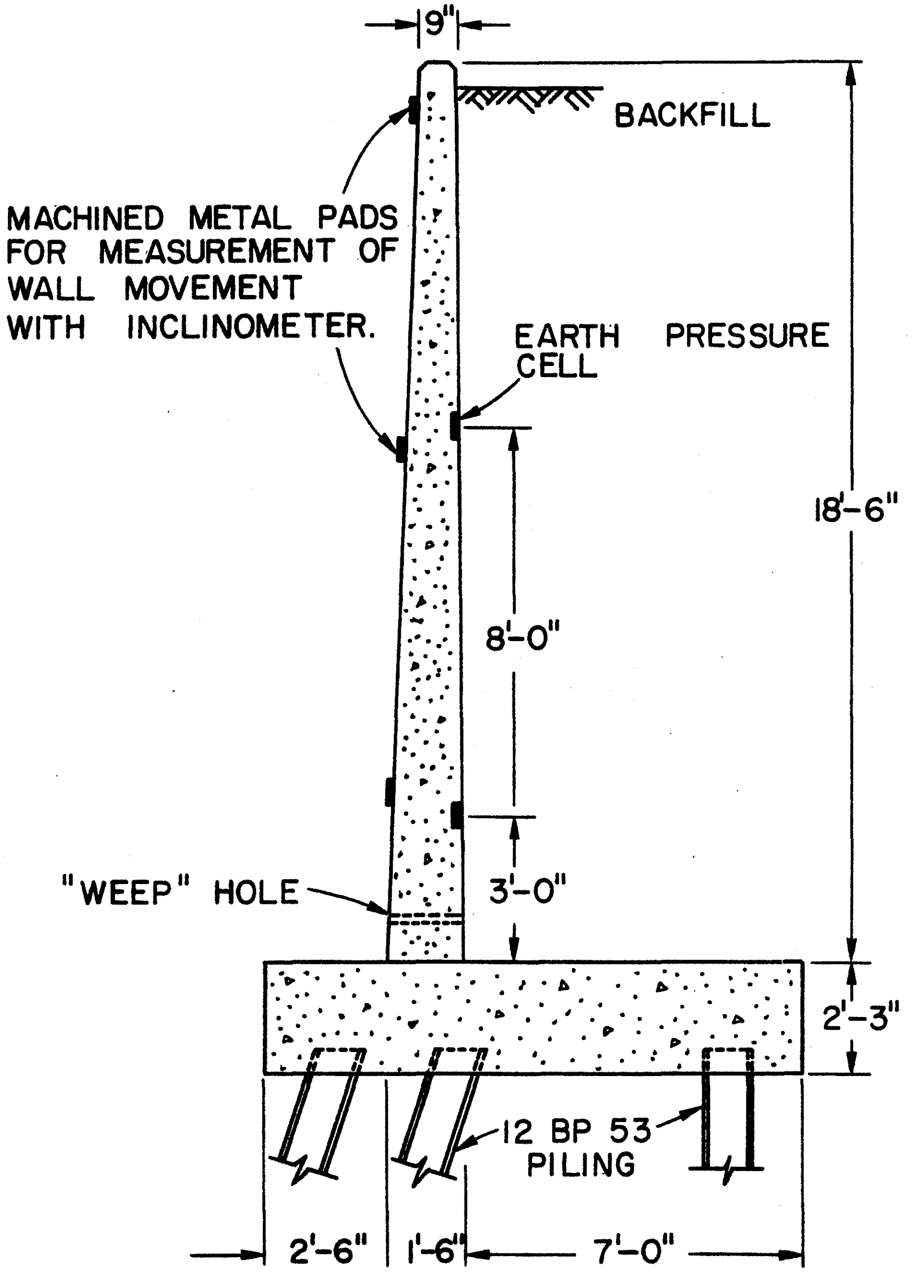


FIG. 7 - CROSS SECTION OF INSTRUMENTED RETAINING WALL PANEL.

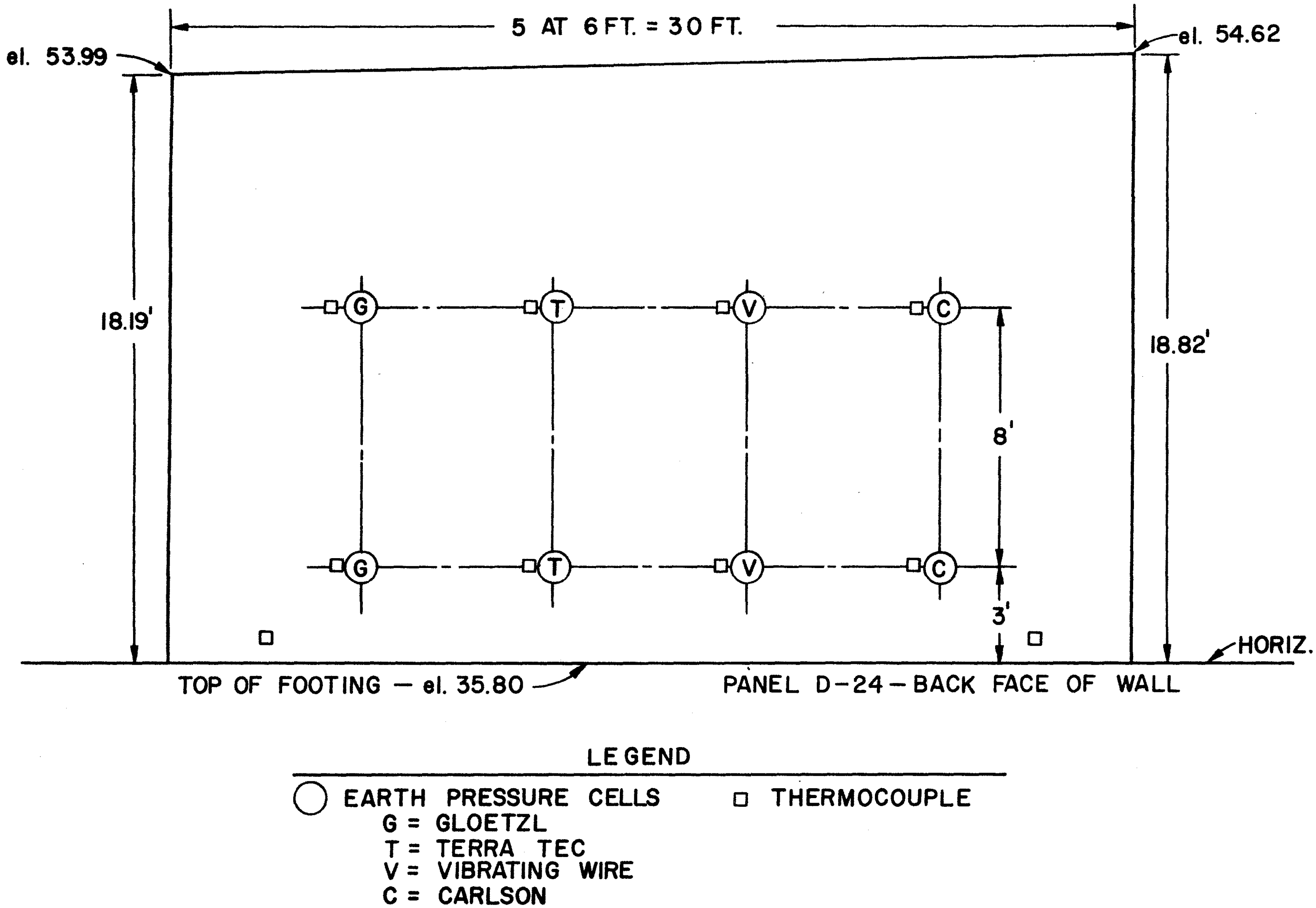


FIG. 8 - INSTRUMENTATION LAYOUT

installation. These include: cells and cables which are mechanically sound; favorable weather; the opportunity for careful preparation of every phase of the installation; well trained personnel; and sufficient time to properly carry out all the details.

If the wall to be instrumented has not been constructed, it is desirable to construct "block-out" boxes to attach to the forms for the retaining walls. These boxes create temporary cavities or working spaces in which the pressure cells are to be placed. If an existing wall is involved, as was the case in this research, the cells may be cemented into a cavity cut in the wall. This cutting involves considerably more effort.

After appropriate cavities had been cut out, each pressure cell was cemented in its desired location with an epoxy grout manufactured by the Dewey Supply Company known as "Patch All Special" in such a manner that the face of the cell was flush with the wall. It was also very important that uniform, intimate contact with the seating surface be achieved.

To install the thermocouples, a coat of epoxy was first placed at the desired locations. Then the thermocouples were glued down with a waterproofing compound, and finally another coat of epoxy was placed over each thermocouple.

All connector cables and wires for the pressure cells and thermocouples were run into a central location, and all of them were secured throughout to the retaining wall with a large strip of raw tread rubber. At the central location, a waterproof, securable terminal box was constructed. Inside the terminal box, all thermocouple wiring was connected to a plugboard.

On the front face of the retaining wall panel, three steel plates were bolted onto the wall in a single vertical row with approximately seven feet between each plate (See Fig. 7). These plates served as references from which any movement of the wall could be checked by means of an inclinometer or transit. Typical curves obtained by means of a transit are shown in Fig. 9. The reference point for the transit is on the footing of the wall and may be moving also, causing some apparent translation. However, the general shape of the wall movement curves are believed to be correct.

## Soil Properties of Backfill Material

The soil used as backfill material at the retaining wall test site is a tan fine sand with a small percentage of silt. Based on the Unified Soil Classification System, the soil is classed as a SP (poorly-graded sand).

The results of a sieve analysis performed on a representative sample of the backfill material are contained in Table 3.

TABLE 3. SIEVE ANALYSIS OF BACKFILL MATERIAL

| Sieve No. | % Finer by Weight |
|---|---|
| 4 | 99.2 |
| 10 | 97.4 |
| 20 | 93.9 |
| 40 | 92.9 |
| 80 | 50.8 |
| 200 | 3.8 |

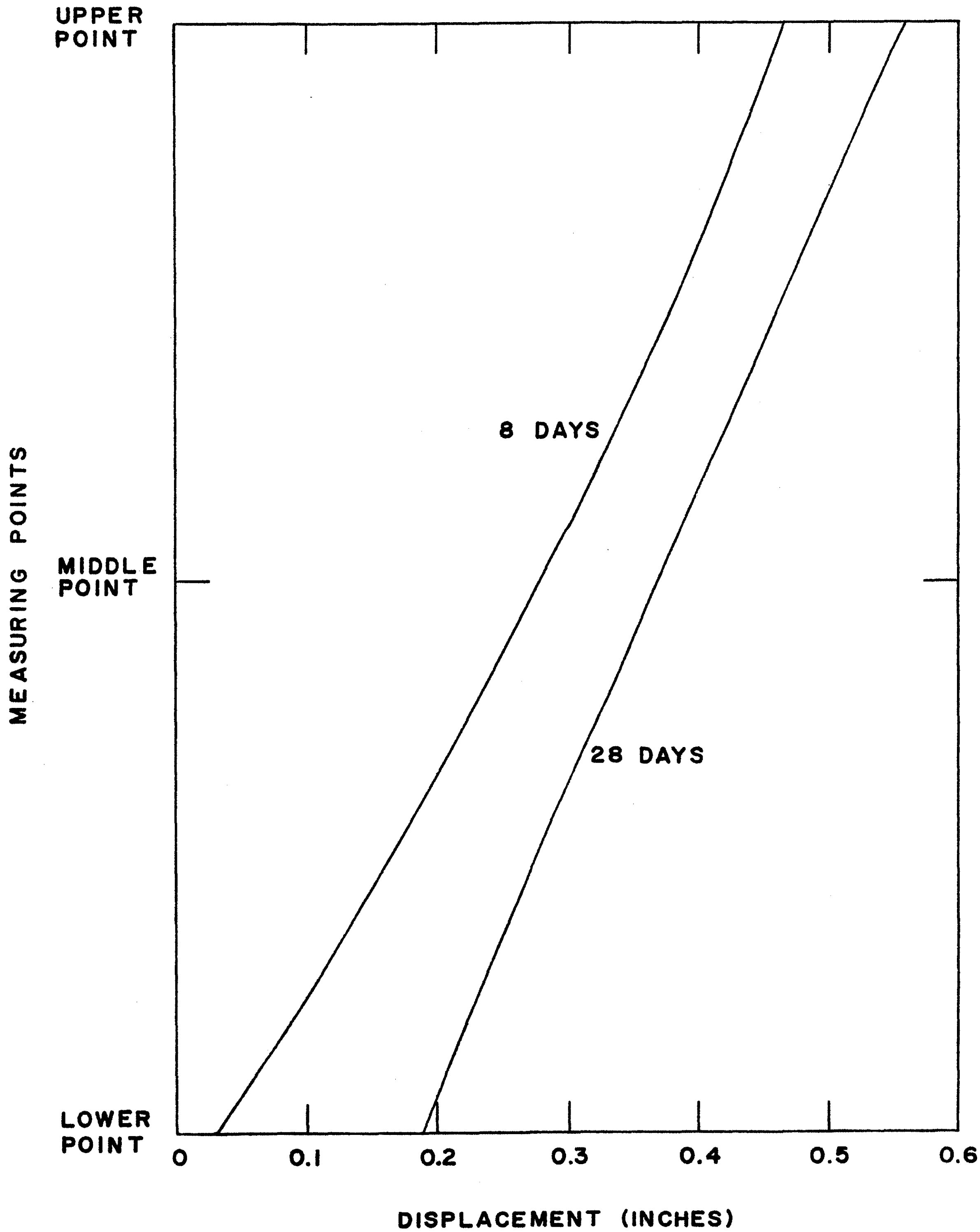


FIG. 9 – WALL MOVEMENT CURVES

Triaxial tests are scheduled to be run on soil samples in the near future to determine the internal friction angle, $\phi$. At the present time, $\phi$ for the soil used as backfill material is assumed equal to 32° (7). Wet unit weight next to the retaining wall averaged 96.2 pounds per cubic foot, and at greater distances from the wall, wet unit weight averaged 110 pounds per cubic foot. Average moisture content was 15.4%. The specific gravity of the soil, as determined by laboratory test, is 2.68.

It is planned to monitor the density of the backfill material by means of a nuclear density probe meter. Three 20-foot long aluminum pipes (two inches in diameter) have been installed in the backfill material, and in the future, density readings will be made at all depths to determine if a correlation exists between any changes in density and changes in lateral earth pressure.

## Backfilling Procedures

The backfill material for the retaining wall test panel was completely placed within a period of three days. The material was placed in approximately eight-inch compacted lifts. Compaction was achieved by means of a heavy scraper dumping material, and a dulldozer making approximately three passes on each lift before the next one was placed.

Research personnel were on hand to insure that none of the instrumentation on the test panel was damaged by the earth-moving equipment. Also, a close check was specifically made on the backfill material that was placed adjacent to all instrumentation to insure that no clay pockets or any other objectionable material would be in a position to influence pressure cell readings.

## COMPARISON OF THEORETICAL AND MEASURED EARTH PRESSURES

### Theoretical Pressures According to Coulomb

The basic assumptions (1) for the earth pressure theory proposed by C. A. Coulomb in 1776 are as follows:

a. The soil is ideal and possesses both internal friction and cohesion.

b. The rupture surface is a plane surface. (Coulomb realized this was not true, but it greatly simplifies computations.)

c. The friction forces are distributed uniformly along the plane rupture surface.

d. The failure wedge is a rigid body.

e. There is wall friction. (That is, soil in the failure wedge develops friction forces along the wall boundary.)

f. Failure is a two-dimensional problem: a unit length of an infinitely long body is considered.

g. There are no seepage pressures.

h. Wall is free to move.

The main deficiencies in the Coulomb theory are in the assumptions of an ideal soil and a plane rupture surface. These deficiencies, along with the uncertainty of the value of the angle of wall friction, prevent the failure wedge from satisfying the statics of the system since the computed force vectors will not generally intersect at a point.

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

$$p_a = \gamma_T \; H \; K_a \qquad (1)$$

where

$$K_a = \frac{\text{Sin}^2 (\alpha + \phi)}{\text{Sin}^2 \alpha \; \text{Sin} (\alpha - \delta) \; [1 + \sqrt{\frac{\text{Sin} (\phi + \delta) \; \text{Sin} (\phi - \beta)}{\text{Sin} (\phi - \delta) \; \text{Sin} (\alpha - \beta)}}]^2} \qquad (2)$$

and

$K_a$ = active earth pressure coefficient,

$H$ = vertical height of retaining wall

$\gamma_T$ = unit weight of the soil

$\phi$ = angle of internal friction

$\alpha$ = angle of back of retaining wall from horizontal

$\delta$ = angle of wall friction

$\beta$ = angle of slope to horizontal

Theoretical pressure along the upper row of pressure cells is computed from the following data:

$\gamma_T$ = 110 pcf

$H$ = 7.5 ft

$\phi$ = 32°

$\alpha$ = 90°

$\delta$ = 0.88 $\phi$ = 28.2° (19)

$\beta$ = 0°

Based on the angular values above, $K_a$ = .276 (1). Therefore, $p_a = \gamma_T \; H \; K_a$ = (110) (7.5) (.276) = 228 psf = 1.58 psi. In other words, 1.58 psi is the pressure we would expect to be acting along the upper row of pressure cells, according to Coulomb's theory.

Theoretical pressure along the bottom row of pressure cells is computed from the same data as above except that H = 15.5 feet. Therefore,

$$p_a = \gamma_T H K_a = (110)(15.5)(.276) = 470 \text{ psf} = 3.26 \text{ psi}$$

Therefore, 3.26 psi is the pressure we would expect to be acting along the bottom row of pressure cells, according to Coulomb's theory.

Theoretical Pressures According to Rankine

Rankine's theory uses basically the same assumptions as Coulomb, except that he assumed no cohesion or wall friction, which simplifies the problem considerably (1).

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

$$p_a = \gamma_T H K_a \tag{3}$$

where

$$K_a = \cos\beta \left(\frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}}\right) \tag{4}$$

When the ground surface is level ($\beta$=0), the above equation simplifies to:

$$p_a = \gamma_T H K_a \tag{5}$$

where

$$K_a = \tan^2 (45° - \phi/2) \tag{6}$$

Theoretical pressure, according to Rankine's theory, is computed from the same data as was used in Coulomb's theory, except that $K_a$ = .307 (1). Thus, along the upper row of cells,

$$p_a = \gamma_T H K_a = (110)\ (7.5)\ (.307) = 253 \text{ psf} = 1.76 \text{ psi}$$

and along the bottom row of pressure cells,

$$p_a = \gamma_T H K_a = (110)\ (15.5)\ (.307) = 523 \text{ psf} = 3.63 \text{ psi}$$

Measured Earth Pressure

The earth pressures measured by each pressure cell from the initial readings on June 29, 1971, through readings on July 29, 1971, are shown in Fig. 10 and Fig. 11. The measured pressures of each cell seem to follow a general trend as to whether the pressure is increasing, decreasing, or holding steady. For the upper level of pressure cells, pressure increases to an initial maximum by the third day and then starts dropping off; from the sixth day on, pressure remains relatively steady. The pressure holds around 3.7 psi for the Terra Tec, Carlson, and Geonor vibrating wire cell, while the Gloetzl holds about 2.4 psi. For the lower level of cells, pressure increases to a maximum by the third day and then drops off. However, there is considerably more variance among the different cells. The approximate average pressure maintained on each cell after the peak pressure is passed is as follows: Terra Tec, 4.5 psi; Gloetzl, 1.5 psi; Carlson, 9.0 psi; Geonor vibrating wire, 3.0 psi. The Gloetzl appears to be excessively low and the Carlson excessively high.

Discussion

It is at once obvious that the theoretical and measured earth pressure data are apparently not compatible at this point. For

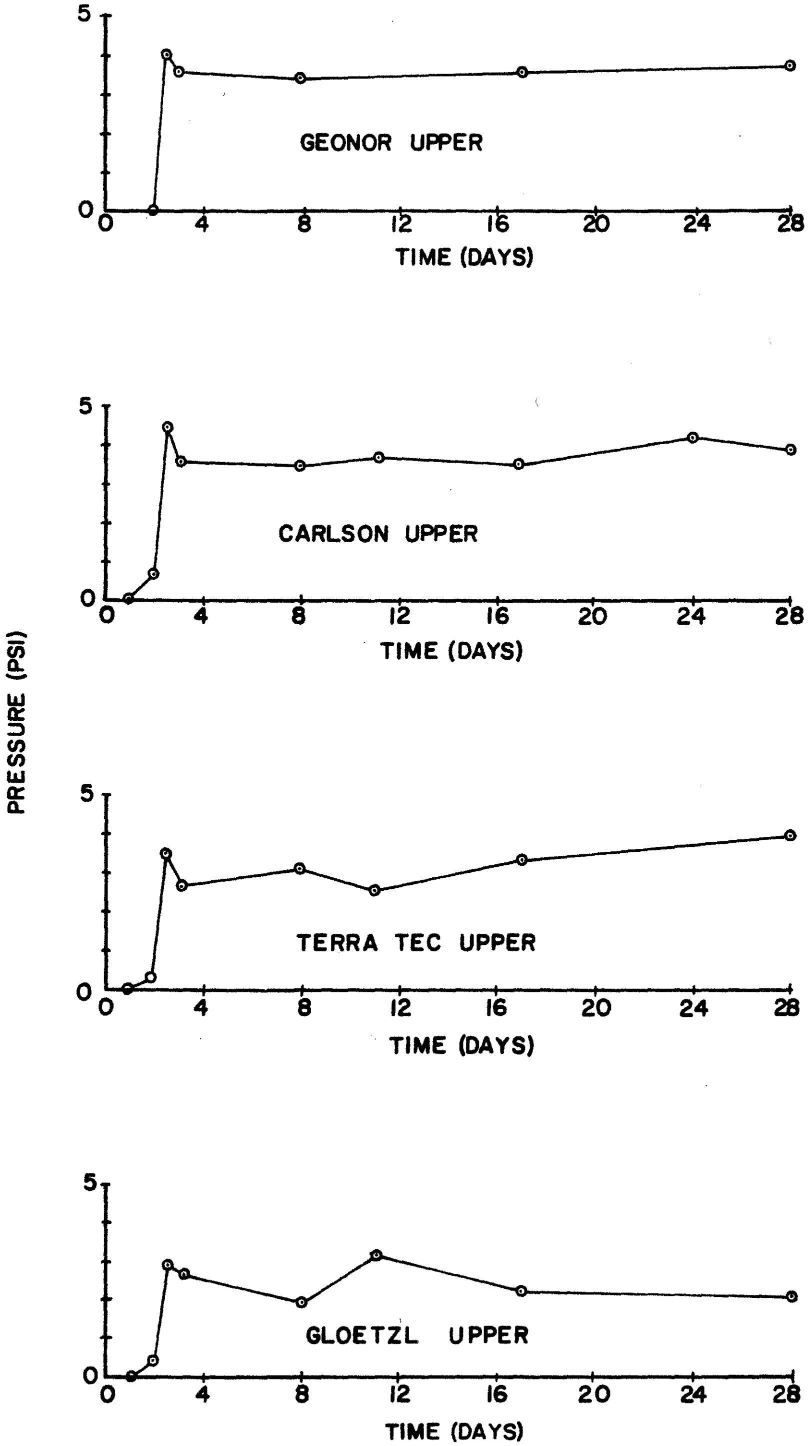


FIGURE 10. MEASURED EARTH PRESSURES. ZERO ON TIME SCALE REPRESENTS BEGINNING OF BACKFILL.

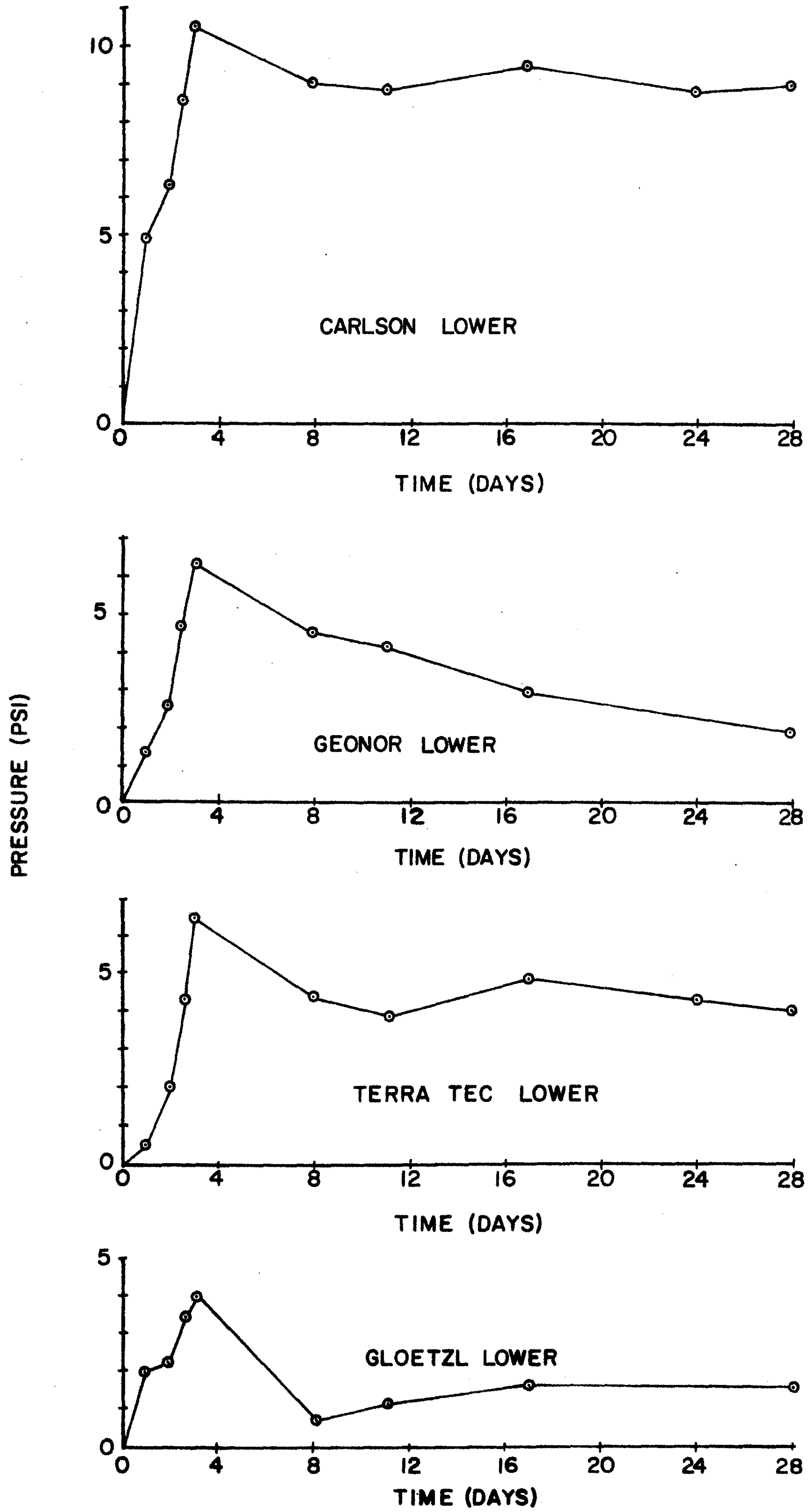


FIGURE II. MEASURED EARTH PRESSURES. ZERO REPRESENTS BEGINNING OF BACKFILL ON TIME SCALE.

the upper level cells, measured pressures are approximately twice as high as theoretical. For the lower level cells, the measured pressures of the Terra Tec cell and the Geonor vibrating wire cells seem to be reasonable. However, it was not expected that the data obtained at this stage would be adequate to check existing theories; rather it was anticipated that by considering the data measured by each type of cell in relation to measured data from the other cells and theoretical data, a basis might exist for selection of one or two types of cells for continued research.

There are several factors which could result in measured earth pressures not reasonably coinciding with theoretical earth pressures.

First, the arching effect may exist. According to Taylor (22), "arching is the action wherein certain zones, which are more rigidly fixed or are more resistant to compression than surrounding zones or which have been displaced toward the stresses acting on them, are caused to carry more than their proportionate share of load, whereas zones which are less securely fixed or which yield more readily under the stresses acting on them carry less than their proportionate share of load." If a wall yields by rotating about a point near the base a relatively uniform strain occurs in the backfill and an approximately triangular pressure distribution occurs. If, however, the top of the wall yields only a limited amount, there are relatively small pressures on the lower portion of the wall because of arching.

Terzaghi's large-scale tests in the late 1920's established that a movement of approximately 0.001 times the height of the wall is required for the lateral thrust to drop to its theoretical active value (7). As noted above, to get an approximately triangular pressure distribution, the wall needs to yield a certain amount by rotating about a point near the base. Terzaghi's tests further showed that the distribution of the lateral pressure of sand on a retaining wall does not agree with theory unless the yield of the wall exceeds in every point the value determined that the wall must move. The more the yield departs from a straight line through the foot of the wall, the more important the departure from the hydrostatic pressure distribution is likely to be.

It appears that the arching effect does exist in the data thus far obtained. The yield of the wall (See Fig. 9) has not been merely a linear rotation about a point near the base, and the pressures measured on the lower portion of the wall are relatively small compared to those measured on the upper portion of the wall.

One basis for variations in pressure readings at individual points and the general average pressure in the surrounding soil is a local fluctuation from the general average state of density or compressibility (inherent scattering). This could account for part of the variance among the different cell readings.

# SUMMARY AND RECOMMENDATIONS

## Summary

The broad objective of this study was the "Determination of Lateral Earth Pressures for Use in Retaining Wall Design." However, achievement of the broad objective will not be possible until a later phase of the study. The specific objectives of this initial investigation covering the first half of phase I have been met.

The four types of pressure cells used during this initial investigation were the Geonor vibrating wire cell, the Terra Tec cell, the Carlson cell and the Gloetzl cell. A summary of the relative merits of each type of cell follows:

a. Geonor vibrating wire cell - Field measurements by the Geonor cells seem reasonable and consistent. Pressures obtained by means of these cells are about the median of pressures obtained by means of the other three types of cells. Readings from the upper level Geonor cell have been more consistent than those from any other cell. Readings from the other Geonor cell have steadily declined (but not at an excessive rate) since the maximum pressure read on the third day. Both Geonor cells are still functioning, and this type of cell has a good durability record. Initial installation is relatively easy and subsequent operation in the field is simple. The pressure cell's connector cables can easily be connected to a small, portable readout unit (which requires only a battery and inverter) and pressure cell readings can be obtained within a few minutes. The Geonor cell is slightly more expensive than the other types of cells used in this study.

b. Terra Tec cell - These cells have produced reasonable and consistent earth pressure readings also. There has been slightly more scatter in the pressure readings of the Terra Tec cells than in the pressure readings of the Geonor cells. The earth pressures registered by the Terra Tec cells are near the median of pressures registered by the other types of cells. Both Terra Tec cells are still functioning; no information is available concerning past field durability. Initial installation of this type of cell and subsequent operation is relatively simple. To take a reading, connector cables are hooked up to a portable readout unit (which contains a small bottle of compressed air) and readings can be made within a few minutes. The Terra Tec cell costs less than the Geonor cell, but slightly more than the Carlson cell.

c. Carlson cell - The pressures registered on these cells have been very consistent. However, the accuracy is questionable. Readings from the upper level cell seem reasonable and correspond to readings from the other types of cells, but the other Carlson cell has registered excessively high pressures - more than twice as much as the other types of cells at a similar depth. Both Carlson cells are still functioning, and this type of cell has a good field durability record. Because of its shape, initial installation of the Carlson cell is more difficult than for the other types of cells used. Field operations are simple; connector cables are connected to a portable readout unit and readings can be obtained within a few minutes. The Carlson cell is less expensive than the Geonor and Terra Tec cells.

d. Gloetzl cell - Pressure readings obtained from both of the Gloetzl cells have been considerably lower than those obtained from any of the other types of cells, and there has been some scatter in the data obtained. Both Gloetzl cells are still functioning; no field data are available concerning durability. Initial installation of the Gloetzl cell is less difficult than the Carlson cell, but slightly more difficult than the Geonor and Terra Tec cells. Field operation of Gloetzl cells is a cumbersome process. The hydraulic readout unit is awkward to move around and is difficult to operate. It takes considerably longer to get readings from the Gloetzl cell than it does to get readings from all of the other cells combined.
The Gloetzl cells were obtained at no expense and the basic cost is unknown.

Three major problem areas have been identified during the course of this year's work. These areas may be outlined briefly as follows:

a. A method of calibrating the earth pressure cells in a manner which simulates the field loading condition as closely as possible must be developed. Several methods of accomplishing this were considered prior to installation of the pressure cells. Time limitations precluded this type of calibration for this year's work.

b. Wall movement is one of the factors which influences the type of earth pressure, i.e., active, neutral, or passive, acting on a retaining wall. In most retaining wall situations the active pressure is achieved and this is due to very small deflections of the wall which are on the order of approximately 0.001 H for cohesionless backfills, where H is the height of the wall. The methods used to measure the motion of the wall during and after backfill in this study have not been completely satisfactory. Other methods which will yield greater accuracy are being studied.

c. The commercially available earth pressure cells investigated thus far have, in general, performed satisfactorily. They do, however, have two inherent characteristics which render them less than ideal for measurements of earth pressures on the order of magnitude commonly encountered on most THD retaining walls. Briefly these characteristics are:

1. The cells have a substantial "zero offset," or initial gage reading at zero applied stress, which tends to drift or shift with both time and temperature. Thus, the overall accuracy of the cell is reduced.
2. Commercially available cells are generally designed and manufactured for pressure ranges which are substantially greater than those encountered on most THD walls.

Recommendations

The following recommendations are made concerning further research in this area:

a. Discontinue use of the Gloetzl cell. The difficulties involved in field operations, along with the questionable accuracy of readings obtained, are sufficient reasons to eliminate this type of cell from further use.

b. Use of Geonor vibrating wire cells and Terra Tec cells should be expanded. Based on the data obtained thus far, these two types of cells appear to be best suited for measuring lateral earth pressures on retaining walls.

c. Continue readings of the Carlson cells in use, but do not expand usage of this type of cell as long as any question of accuracy remains.

d. Improved methods for calibrating earth pressure cells should be developed. Particular attention should be given to the following three items of importance:

1. The pressure cells should be calibrated in contact with a material which closely resembles the material to be used for the backfill, and in a manner which simulates the field loading condition as nearly as possible.
2. The effect of temperature on the pressure cell calibration and performance characteristics should be determined.
3. The tendency of the pressure cell reading at zero applied stress to drift with time and temperature should be thoroughly investigated in order to allow appropriate adjustments to be made in the field readings obtained after backfilling.

e. An accurate method for determining the small but extremely significant deflections of the wall, which occur both during and after backfill, should be developed.

f. Take lateral earth pressure readings as the backfill material is being placed. After the backfill has been placed and earth pressure readings have been obtained for an extended period, surcharge loads should be added and their effect on the earth pressure should be investigated.

## APPENDIX I. - REFERENCES


1. Bowles, J. E., Foundation Analysis and Design, McGraw-Hill, New York, 1968, pp. 265-365.

2. Cooling, L. F., "Field Measurements in Soil Mechanics," Geotechnique, Vol. 12, No. 2, 1962, pp. 77-103.

3. Coyle, H. M., Hirsch, T. J., Lowery, L. L., Jr., and Samson, C. H., Jr., "Field Instrumentation For Piles," Conference on Design and Installation of Pile Foundations and Cellular Structures, Lehigh University, April 1970.

4. Goldbeck, A. T. and Smith, E. B., "An Apparatus for Determining Soil Pressures," Proceedings, ASTM, Vol. 16, No. 2, 1916, pp. 310-319.

5. Hamilton, J. J., "Earth Pressure Cells - Design, Calibration, and Performance," Technical Paper No. 109, Division of Building Research, National Research Council, Canada, November, 1960.

6. Huntington, W. C., Earth Pressures and Retaining Walls, John Wiley and Sons, Inc., New York, 1957.

7. Lambe, T. W., Soil Mechanics, John Wiley and Sons, Inc., New York, 1969, pp. 29-39, 145-150.

8. Lee, I. K., Soil Mechanics, Selected Topics, American Elsevier Publishing Company, Inc., New York, 1968, pp. 322-340.

9. Leonards, G. A., (ed.), Foundation Engineering, McGraw-Hill, New York, 1962, pp. 1025-1065.

10. Peattie, K. R. and Sparrow, R. W., "The Fundamental Action of Earth-Pressure Cells," Journal of Mechanics and Physics of Solids, Vol. 2, 1954, pp. 141-155.

11. Plantema, G., "A Soil Pressure Cell and Calibration Equipment," Proceedings, Third International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, Switzerland, 1953, pp. 283-288.

12. Scott, J. D., "Experience with Some Vibrating Wire Instruments," Canadian Geothchnical Journal, Vol. IV, No. 1, February 1967, pp. 100-123.

13. Taylor, D. W., "Field Measurements of Soil Pressures in Foundations, In Pavements, and on Walls and Conduits," Proceedings, Second International Conference on Soil Mechanics and Foundation Engineering, Vol. VII, Rotterdam, 1948, pp. 84-89.

14. Taylor, D. W., Fundamentals of Soil Mechanics, John Wiley and Sons, Inc., New York, 1948, pp. 480-531.

15. Terzaghi, K., "Earth Pressure of Sand on Walls," Proceedings, Purdue Conference on Soil Mechanics and Its Applications, 1940, pp. 240-258.

16. Terzaghi, K., "Large Retaining Wall Tests," Engineering News-Record, Vol. 112, February 1, February 22, March 8, March 29, 1934.

17. Terzaghi, K. and Peck, R. B., Soil Mechanics in Engineering Practice, Second Edition, John Wiley and Sons, Inc., New York, 1968, pp. 649-660.

18. Thompson, L. J., "The Effect of Height of Highway Fills on the Design of Culverts, Phase I - Pressure Gage," Bureau of Engineering Research Final Report CE-4, University of New Mexico, February 1966.

19. Tomlinson, M. J., Foundation Design and Construction, John Wiley and Sons, Inc., New York, 1963.

20. U. S. Army Corps of Engineers, EM 1110-2-4300, Instrumentation for Measurement of Structural Behavior of Concrete Gravity Structures, September 1958, pp. 1-32.

21. Waterways Experiment Station Technical Memorandum 210-1, "Soil Pressure Cell Investigation (Interim Report)," Vicksburg, Mississippi, July 1944.

22. Waterways Experiment Station, "Soil Mechanics Fact Finding Survey Progress Report - Triaxial Shear Research and Pressure Distribution Studies in Soils," Vicksburg, Mississippi, April 1947.

## APPENDIX II. - NOTATION

The following symbols and abbreviations are used in this report:

°F = degrees Fahrenheit

ft = feet

H = vertical height of retaining wall, in feet

$K_a$ = active earth pressure coefficient

LTD = limited

LVDT = linear variable displacement transducer

No. = number

$p_a$ = active pressure

pcf = pounds per cubic foot

% = percent

psf = pounds per square foot

psi = pounds per square inch

SP = poorly graded sand

SR-4 = a type of strain gauge

WES = Waterways Experiment Station

$\alpha$ = angle of back of retaining wall from horizontal, in degrees

$\beta$ = angle of slope to horizontal, in degrees

$\gamma_T$ = unit weight of soil, in pounds per cubic foot

$\delta$ = angle of wall friction, in degrees

$\phi$ = angle of internal friction, in degrees