INSTRUMENTATION FOR MEASUREMENTS OF LATERAL EARTH PRESSURE IN DRILLED SHAFTS

by

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Soil Properties as Related to Load Transfer Characteristics of Drilled Shafts

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PREFACE

This, the second in a series of reports produced by Research Project 3-5-65-89 of the Cooperative Highway Research Program, describes the development and evaluation of pressure gages to measure lateral-earth pressures on the drilled shaft. Subsequent reports will give specific details and findings of other phases of the research including results of field load tests using these gages. In time a report will be submitted with design recommendations in final form based on the combined results of several field tests.

This report is the product of the combined efforts of many people. Technical contributions were made by Dr. W. R. Hudson, James N. Anagnos, Clarence Ehlers, John W. Chuang, V. N. Vijayvergiya, and Mike O'Neill. Preparation and editing of the manuscript were done by Art Frakes, Don Fenner, Joye Linkous, and Marie Fisher.

The Texas Highway Department Project Contact Representatives Messrs. Horace Hoy and H. D. Butler and District No. 14 personnel have been helpful and cooperative in the development of the work. Thanks are due them as well as the U. S. Bureau of Public Roads who jointly sponsored the work.

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LIST OF REPORTS

Report No. 89-1, "Field Testing of Drilled Shafts to Develop Design Methods," by Lymon C. Reese and W. Ronald Hudson, describes the overall approach to the design of drilled shafts based on a series of field and laboratory investigations.

Report No. 89-2, "Instrumentation for Measurements of Lateral Earth Pressure in Drilled Shafts," by Lymon C. Reese, J. Crozier Brown, and Harold H. Dalrymple, describes the development and evaluation of pressure gages to measure lateral-earth pressures on the drilled shaft.

ABSTRACT

This project involves the design, construction, and testing in the laboratory and field of instrumentation capable of measuring the lateral earth pressure along a drilled shaft.

A good deal of work has been done concerning the development of pressure transducers designed to measure stresses in an earth mass. Consequently, these studies have produced theories which set design criteria for soil pressure measuring devices based on soil behavior.

This project pulls these theories together, assimilates the present knowledge concerning transducers, and produces a pressure cell designed to measure lateral pressures against a drilled shaft up to 50 psi. Design "maps" based on Timoshenko's theory of a clamped-edge, circular, thin plate are given. These "maps" allow the investigator to arrive at the thickness of a pressure-sensitive diaphragm knowing the desired pressure to be measured, the allowable diaphragm deflection to diameter ratio, and the desired sensitivity of the cell. The beryllium copper cell is 2-3/4 inches in diameter and 1/2 inch thick.

This cell has been used to measure the pressures exerted against a drilled shaft under curing and loading conditions. Additional work will be necessary in order to evaluate completely the lateral-earth-pressure distribution and load transfer from the shaft to the soil. What is felt to be a satisfactory gage for making the necessary measurements in sands and clays has been developed and is recommended for these studies.

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NOMENCLATURE

Symbol	Typical Units	Definition
A_i	sq ft	Area over which a given point load acts
A_{total}	sq ft	Total loaded area
a	ft	Radius of diaphragm; radius of plate
D	ft	Sensitive diameter
E_r, ϵ_r	ft/ft	Unit radial strain
E_t, ϵ_t	ft/ft	Unit tangential strain
e_p	percent	Percent of over or underregistration
F_i	lb	Force applied at a given point i
F_{total}	lb	Total force applied to surface of sand
H	--	When used as a subscript, denotes horizontal
h_d	ft	Diaphragm thickness
K_a	--	Coefficient of active earth pressure
K_o	--	Coefficient of earth pressure at rest
M_t	lb-ft	Tangential moment
M_r	lb-ft	Radial moment
P_1	lb/sq ft	Pressure at a given level in sand sample
P_o	lb/sq ft	Applied pressure
P_{base}	lb/sq ft	Pressure on base of sample

Symbol	Typical Units	Definition
q	lb/sq ft	Maximum design pressure; normal pressure
R_d	ft	Radius of diaphragm
$\overline{R}$	--	Desired ratio of diameter to maximum centerline deflection
r	ft	Radial distance from center of diaphragm to point of interact
r_1	ft	Inner radius, linear radial gage
r_2	ft	Outer radius, linear radial gage
r_3	ft	Inner radius, spiral tangential gage
r_4	ft	Outer radius, spiral tangential gage
S_r	lb/sq ft	Radial stress
S_t	lb/sq ft	Tangential stress
X	ft	Distance from center of diaphragm to point of inflection
δ	ft	Centerline deflection
ε_{tm}	ft/ft	Total measured strain

CHAPTER 1. INTRODUCTION

A previous report on this project (Ref 25) outlined research aims and described the theory of interaction of drilled shafts and the supporting soil. Some aspects of the behavior of drilled shafts are reviewed in order to indicate the importance of knowing the lateral earth pressure between the shaft and the soil.

Load transfer from a shaft to the supporting soil is accomplished in two ways, as shown in Fig 1. First, the sides of the shaft will transmit a portion of the load to the soil through side resistance; second, load will be transferred by the bottom of the shaft into the soil through point resistance. Side resistance may be evaluated by subtracting the shaft load at any point from the applied load at the top of the shaft.

The curve in Fig 2(a) shows that the amount of side resistance developed at a depth is a function of the downward shaft movement. If there is no downward movement, no side resistance will be mobilized. The development of a family of such curves, for shafts in clay, is discussed in a paper by Coyle and Reese (Ref 1).

The ultimate side resistance shown in Fig 2(a) may be equal to the soil shear strength. For the full shear strength to develop at a particular depth, the failure surface which occurs when the shaft is overloaded must occur within the soil rather than at the interface of the soil and the shaft.

If it can be assumed that the failure surface occurs in the soil, the ultimate load transfer value as a function of depth can then be obtained from the soil shear strength as determined for various depths below the ground surface. The shear strength needed is that which exists after placing the wet concrete and after concrete hydration has taken place. As stated in the previous report on this project (Ref 25), this shear strength determination may be a complex problem.

If the failure surface which develops when a shaft is overloaded is at the interface of the shaft and the soil, the ultimate shaft side resistance may not be equal to the shear strength of the soil but may be much less.

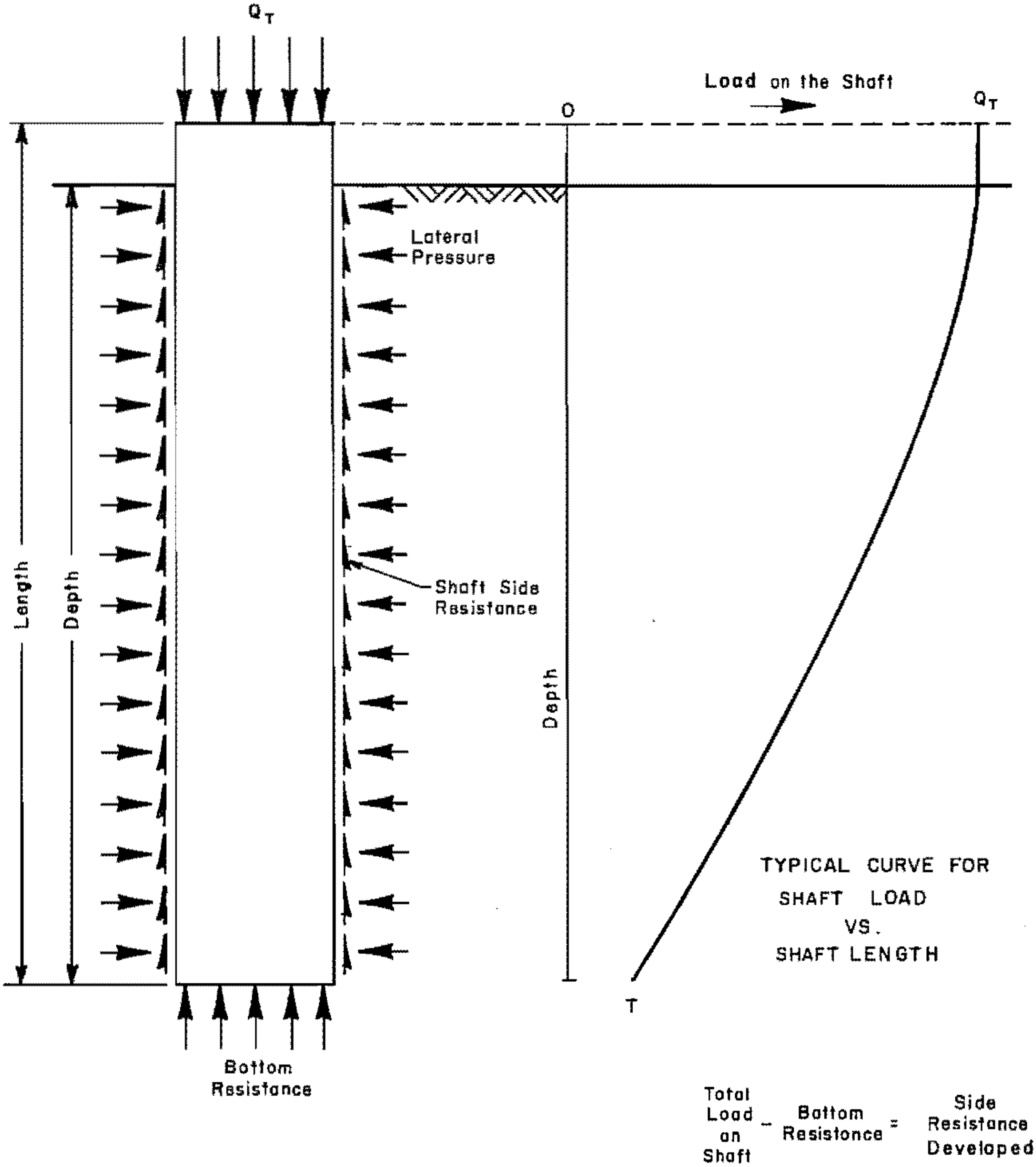


Fig 1. Typical load transfer curve for a drilled shaft.

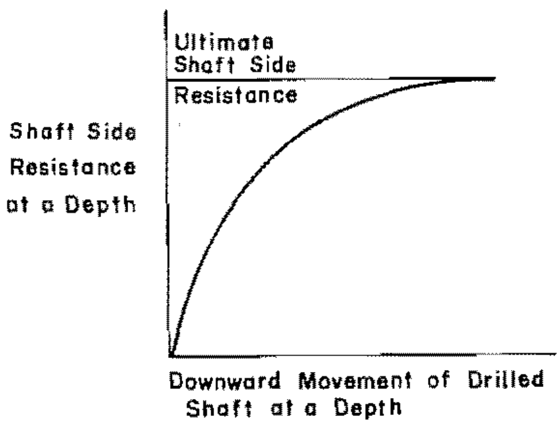


Fig 2a. Shaft side resistance developed at a depth as a function of shaft movement.

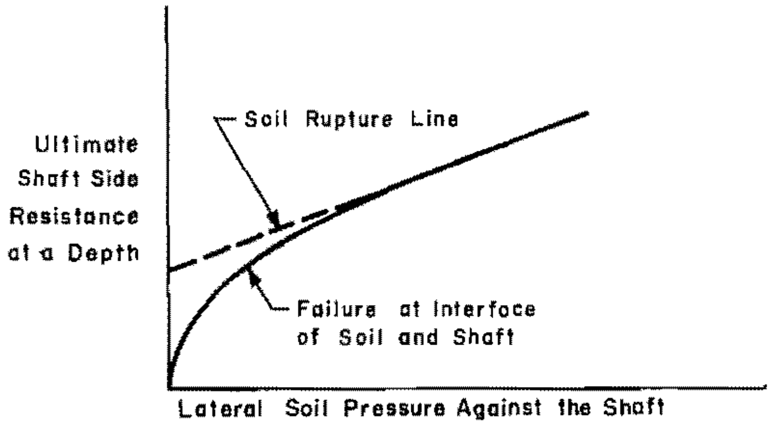


Fig 2b. Ultimate shaft side resistance at a depth as affected by the lateral soil pressure against the shaft.

Such a situation is illustrated for a particular point along the shaft by the early part of the solid-line curve in Fig 2(b). In the same figure the soil shear strength is plotted as a dashed line. This shear strength curve could be obtained in the laboratory by use of the direct shear machine or the triaxial machine. As may be seen in Fig 2(b), at some particular value of lateral soil pressure against the shaft, the full shear strength is developed. From this simple presentation, the importance of measuring the lateral pressure at the sides of a drilled shaft is apparent.

Not only is a knowledge of lateral earth pressure needed for computation of maximum load transfer along the periphery of a drilled shaft, but this knowledge is needed for insight into the problem of the interaction of the wet concrete and the soil (Ref 25).

In some areas the behavior can be affected considerably by climatic conditions. During dry seasons the soil may shrink away from the shaft causing a reduction in the amount of load which can be carried in side resistance. In wet seasons the soil may expand against the shaft and allow more load to be transferred through side resistance. The ultimate lateral earth pressure against the shaft which can be expected has been estimated to be approximately 90 percent of the vertical pressure (Refs 2 and 3).

Bored shafts in London clay were investigated by Skempton (Ref 4) at ten sites. Load tests were run, and the ratio of side resistance developed on the shaft to the average undisturbed shear strength was determined. Within a depth equal to the embedded length of the shaft in the clay, the ratio was found to be about 0.45. Skempton says that the value is low owing to water absorption by the clay during drilling and pouring of the shafts. According to Skempton this ratio can be as high as 0.6 under favorable conditions and with careful workmanship; however, under unfavorable conditions, the ratio may drop to as low as 0.35.

A knowledge of lateral earth pressure is fundamental to the development of any rational procedure for computing load transfer along the periphery of a drilled shaft. Accordingly, the purpose of this portion of the project was to design, construct, and test instrumentation for measuring the lateral earth pressure at points along a drilled shaft. The following chapters will describe the development of a lateral-earth-pressure cell for use in a drilled shaft. This cell was developed at The University of Texas and is designated as the UT cell.

CHAPTER 2. SOIL-PRESSURE MEASUREMENT

Since the earliest days of soil mechanics, stresses within a soil mass have interested engineers. By means of certain assumptions concerning the elastic properties of the soil mass and by using the Boussinesq expressions, theoretical stress distributions in soil have been developed (Ref 5). Some problems do not lend themselves readily to theoretical analysis; for example, the lateral pressures developed against a drilled shaft under loading conditions cannot be computed reliably. Therefore, the actual measurement of these pressures is desirable, but the majority of the work which has been done in measuring soil stresses concerns the vertical pressures in a soil mass. Much less work has been done concerning the measurement of lateral pressures within a mass of soil, or lateral pressures against a structure. The Waterways Experiment Station at Vicksburg, Mississippi, has been a leader in earth-pressure-measurement investigations.

Determination of soil pressure against a structure can be accomplished indirectly by measuring the stresses in the structure or the reaction between the structure and its supporting elements. Sometimes it is not possible to make measurements in this manner, and pressure cells must then be utilized to measure the pressure directly.

If pressure cells are used, the interaction of the soil and the cell is a problem which has received the attention of many investigators. Not as much emphasis has been placed on the influence of the cell on soil-pressure distribution as has been placed on the instruments used. In 1913, Goldbeck, a pioneer in the study of soil-pressure cells, discussed the soil-cell pressure distribution. Theoretical studies have also been made by Carlson, Hast, Kjellman, Taylor, Walen, and others (Ref 6). Laboratory testing has been carried out by Benkelman and Lancaster, Goldbeck, Hast, Kogler and Scheidig, and the Waterways Experiment Station (Osterberg and Taylor) (Ref 6). Additional laboratory studies have been conducted by the Royal Swedish Geotechnical Institute (Ref 6) and by Peattie and Sparrow (Ref 7). Full information concerning stresses, strains, and displacements in soil masses in typical foundation problems must be obtained if analyses and designs are to be developed to the highest degree possible (Ref 8).

Many of the design methods in foundation engineering are based on theoretical stress distributions which have not been checked by actual measurements. The scarcity of actual measurements is due to a lack of suitable earth-pressure sensing devices. Many devices have been produced and used in the past, but in most cases the results are inconclusive.

An earth-pressure cell is a device which provides an indication, at a remote point, of the soil pressure at the point of installation. Installation involves introducing into the earth mass a body with stress-deformation characteristics which may be radically different from the soil. The nonhomogeneity caused by the cell will produce redistribution of pressure in the vicinity of the cell, causing the true pressure distribution to be lost (Ref 7).

Two basic considerations are important in the development of an earth-pressure cell. First, the factors which control the functioning of the proposed device must be known. Second, the limitations within which the proposed device will perform with the specified precision must be known (Ref 9). These two basic considerations will be discussed later in this chapter.

In 1927, Kogler and Scheidig (as cited in Ref 7, p 142) first pointed out the inherent difficulties in obtaining accuracy with a soil-pressure cell. They observed that a cell which is more rigid than the soil around it will indicate pressures which are in excess of those existing in the soil before the cell was placed. Conversely, a cell which is less rigid than the soil will indicate pressures which are lower than the existing pressures. Therefore, the pressure indications of a cell will be free from error only if a cell has the same stress-deformation characteristics as the soil. However, the soil is a nonhomogeneous material, and its modulus varies with location and pressure. Furthermore, although the error is zero when the ratio of cell modulus to the soil modulus is equal to 1.0, the rate of change of error with any change in this ratio is very high. Thus, if the pressure cell is to be used in a material of varying modulus, such as soil, it is highly undesirable to construct the cell with nearly the same modulus as the material (Ref 7). As will be explained later, the solution is to maximize this ratio, thereby reducing the effect of changing soil modulus.

The Waterways Experiment Station has investigated a number of cells, and in fact has designed one of its own. Discussing cells which it has investigated, the Station says, ". . . because of the interrelated complexities of the physical laws and unpredictable variables that govern the performance characteristics of these apparently simple devices, perfection cannot be claimed for any of the cells." (Ref 10).

Basic Types of Action of Earth-Pressure Cells

For many applications it is essential that a device for earth-pressure measurement be capable of retaining its performance over 5 to 10-year periods. This requirement has a definite bearing on the selection of a pressure cell.

Most pressure cells employ changes in an electrical circuit, but a few use counterbalancing pressures with either electrical or constant-volume indicators. The three basic types of cell action as outlined by the Waterways Experiment Station (Ref 11) are

(1) countermovement of a part of the pressure cell against the soil by counterbalancing the soil pressure with air pressure,

(2) direct action of the pressure-responsive portion of the cell on the indicating gage, and

(3) application of the pressure to be measured through an equalizing, confined, incompressible fluid onto a second pressure-responsive element which acts on the indicator gage.

The Goldbeck cell is an example of countermovement action, the California State Highway Department cell is an example of action directly on the cell, and the Carlson Stress Meter and the Waterways Experiment Station cell are examples of action through a confined medium (Ref 11). Each of these gages will be discussed later.

The direction-action cell proved to be the most promising basic type which could be refined and adapted for use in this project. A direct-action hydraulic system was considered, but interest centered on an electrical gage owing to the ease of remote reading. Three basic types of electrical gages could have been used: (1) the inductance gage, (2) the capacitance gage, and (3) the resistance gage.

The inductance gage is loaded by pressure on a diaphragm. By changing the core of a coil of wire, the coil's impedance to alternating current is changed, and change in impedance is then measured as a change in voltage. An iron rod attached to the diaphragm serves as the core. The disadvantages of this cell are its insensitivity, the necessity of a coaxial cable connection, and its heaviness, bulkiness, and susceptibility to magneto-mechanical resonance. However, it has been used for miniature applications. The gage has the advantages of good temperature stability and simplicity of design.

The capacitance gage consists of a pressure-sensitive capacitor which is part of an electronic alternating-current generator. One plate of the capacitor is the diaphragm against which the pressure acts. When the diaphragm deflects, the distance between the plates changes, and hence the capacitance changes. The change in capacitance produces a change in the frequency of the alternating-current generator, which may be converted to voltage change and measured. The disadvantages of this gage are its high cost, poor temperature stability, necessity of using a coaxial cable, sensitivity to vibrations, mounting and clamping difficulties, and its complex electric circuit. The advantage of this gage is its high sensitivity.

The resistance gage is the remaining type of possible electric device. It consists of an electric conductor cemented to a diaphragm. As the diaphragm deflects, the conductor is strained, causing a resistance change. Current is sent through the conductor, allowing the resistance change to be measured. The conductor can be a metallic wire, foil, or a carbon strip. The carbon strip is highly sensitive to strain but is also sensitive to changes in temperature and humidity as well as to aging, which causes a zero shift. Foil conductors are less sensitive but are more easily temperature compensated, simple, and relatively inexpensive, as well as being more rugged (Ref 12).

The inductance, capacitance, and resistance gages have all been used, and limitations have been overcome by suitable techniques (Ref 13). However, the reistance gage was used in this project because of its simplicity, low cost, and compatibility with portable readout equipment. In addition, the inductance coil or capacitor would have had to be specially built, while resistance gages are commercially available.

In an electrical resistance gage, displacement is expressed as an electrical resistance change measured in ohms, produced by altering the size of a very fine electrical conductor. Several factors must be considered desirable for a high stability pressure measuring device. First, the sensitivity of the cell should be as high as possible to gain maximum output from the gage. The electrical leakage resistance to the ground of the gage should be as high as possible to prevent drift through unknown shunting conditions. The temperature coefficient of resistance must be as low as possible. Thermoelectric effects produced by the function of the gage and lead wires should be minimized. Lastly, the relationship between strain and resistance change should be linear up to high strains. High cell sensitivity and low temperature coefficient of resistance are the most important factors, but they do not occur simultaneously. Therefore, a compromise must be reached which involves careful selection of cell material and of the gages themselves.

Several factors which affect the resistance stability of a gage are (1) the technique used to fix the strain gage to the measuring device, (2) the temperature and humidity conditions, (3) the strain range, (4) the material used to bond the gage to the measuring device or diaphragm, and (5) the stability of the diaphragm structure itself. If these factors are ignored, there will be a lack of stability of the cell resulting in a zero drift with time, hysteresis under load, or creep under sustained load. Therefore, great care should be used in all aspects of the gage design and construction.

Humidity has some serious effects on the system. If excess humidity is allowed, a breakdown of insulation between the gage and the diaphragm material results. Also, electrochemical corrosion of the gage wire or foil due to electrolysis will take place, causing the gage resistance to change. Over a long period of time, humidity can cause a zero drift. Therefore, waterproofing must furnish a high degree of bond to the nonporous strain gage but must not be stiff enough to cause resistance to diaphragm movement. Waterproofing must be effective over the range of temperatures expected in the measurement application.

As has been stated, in order to measure a pressure change with a resistance gage, the resistance change induced by the strain acting on the gage must be measured. This change will necessarily be very small, and therefore the most sensitive and accurate electrical circuit available must be utilized. The circuit employed, the Wheatstone bridge, has four electrical resistors (arms) connected end to end, with a source of potential connected across any two opposite connections and an indicating meter across the other two opposite connections (see Fig 3). The fact that the meter "bridges" the midpoints of two potential paths accounts for the name. The resistances in the arms are adjusted to produce no current flow through the meter. This is known as the null method and can be used in quarter (one active arm), half (two active arms), or full (four active arms) bridge configuration. Temperature

C_1 and C_2 Are Compression Gages
T_1 and T_2 Are Tension Gages

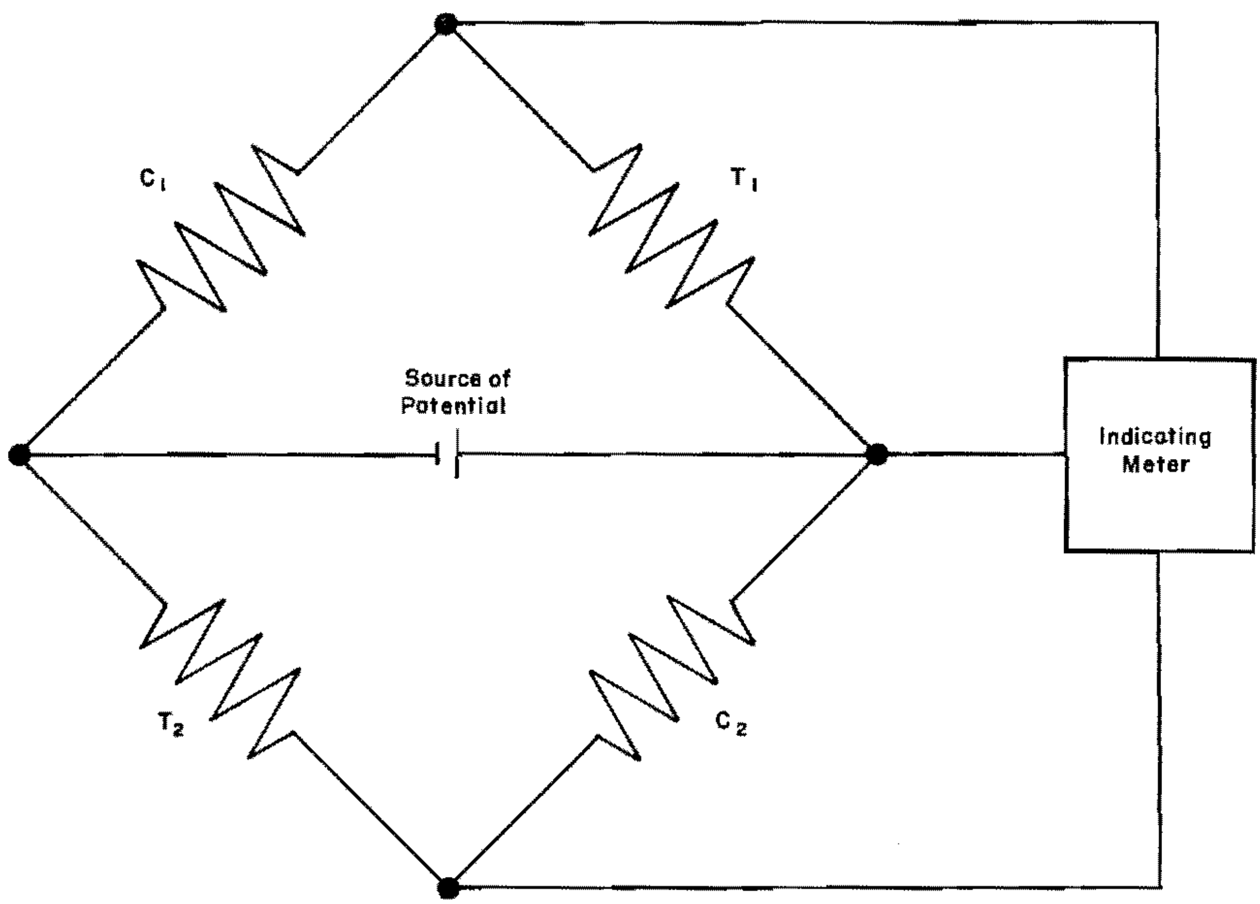


Fig 3. Wheatstone bridge.

compensation may be obtained automatically by maintaining opposite arms of the bridge at the same temperature. The full-bridge circuit provides certain advantages over the half-bridge circuit, even though both will provide temperature stability. Advantages include double sensitivity and elimination of adverse effects of extraneous resistance changes in cable conductors (Ref 10).

The bonded electric strain gages may also be subjected to instability under continuous loading by creep of the glue which bonds the gage to the cell. Careful checks should be made to determine whether this will affect a given gage (Ref 14).

Existing Pressure Measuring Gages

With the exception of the University of New Mexico gage, the cells to be discussed have been investigated or built at the Waterways Experiment Station. Most cells investigated, developed, or utilized at the Waterways Experiment Station use SR-4 electrical resistance strain gages, but one exception, a hydrodynamic cell, utilizes a linear differential transformer (Ref 10).

Information available to the station indicated that Carlson cells and Goldbeck cells could be expected to give satisfactory results on soil pressures against rigid walls. The major requirements were ruggedness and long-period stability.

Goldbeck Cell. The Goldbeck cell operates by measuring the pressure necessary to move a piston or diaphragm back to its initial zero position after an unknown pressure has been applied to the face of the diaphragm. The piston or diaphragm must move a short distance into the soil to break an electrical contact which indicates the null position of the face. This countermovement may have an important bearing on the pressure indicated by the cell. The motion acts against the passive resistance of the soil, which may be greater than the static pressure which acted prior to the movement. If the movement is small, the assumption is made that the pressure required to break the electrical contact is equal to the static soil pressure. This assumption is invalid for dense granular soils, and a serious problem exists for these soils because of "arching," which is explained in detail later. The Waterways Experiment Station has found that these cells gradually become inoperable in the field owing to short or open circuits preventing the determination of the null position (Ref 11).

Carlson Stress Meter. The Carlson stress meter contains a confined chamber of mercury which acts on a secondary diaphragm to which is attached an unbonded strain-gage element. The meter configuration requires that the insulation be particularly stable and that a precise Kelvin bridge be used. The principal problem with this gage is the maintenance of stable insulation resistance over long time intervals. Small resistance changes occurring in the connector cables or splices may cause pressure indications or total failure of the meter (Ref 11).

Waterways Experiment Station Cell. The Waterways Experiment Station soil-pressure cell operates on the same principle as the Carlson stress meter except that it utilizes bonded SR-4 strain gages. The first Waterways Experiment Station cells used a half-bridge in the cell, with one active arm and one dummy arm for temperature compensation and with the other two elements of the Wheatstone bridge in an external control box. Electrical insulation and cables proved to be a problem (Ref 11). Later models utilized a full-bridge on the diaphragm itself (four active arms) (Ref 10). The pressure applied to the face plate of this gage is transmitted to a light transformer oil and thence to a secondary diaphragm formed by boring out the back of the base-plate. The diameter and thickness vary according to pressures measured. The SR-4 strain gages are affixed to this diaphragm (Ref 8).

The Waterways Experiment Station cell measures the total pressure applied to the diaphragm, including both the solid and the liquid phase of the medium. This is also true of most other gages. Only the pressure component normal to the face of the cell is effective in operating the cell (Ref 10). The total pressure measured is the intergranular pressure plus the neutral or porewater pressure. Strains in the soil depend only on intergranular pressures, and neutral pressures have no direct effect on soil action. However, there is a large indirect effect of the neutral portion of the applied pressure because the portion of applied pressure carried by the water represents applied pressure not contributing to the strength of the soil (Ref 8).

Waterways Experiment Station Hydrostatic Pressure Cell. The foregoing indicates the importance of measuring the porewater or neutral pressure so that it may be subtracted from the total pressure to obtain the intergranular or particle pressure. The intergranular or particle pressure is the only effective component in providing shear strength. The Waterways Experiment Station earth-pressure cell which measures total pressure may be modified in one of two ways to allow measurement of porewater pressure. The first alternative is the installation of a perforated plate covered by a fine mesh screen in front of the diaphragm to allow only the water pressure to act on the diaphragm. The second alternative is the use of porous stone in front of the diaphragm to allow only the water pressure to act on the diaphragm. Otherwise, concepts used previously on the regular cell are followed. Assembly and calibration of this cell are rather straightforward.

The installation of this cell is the important part of its use. In clayey soils, the cells are usually bedded in a pocket of sand. Care must be used to avoid trapping air in front of the diaphragm and behind the screen or porous stone. This cell requires very little volume change and virtually no flow of water to make the required measurements. This method is expensive, however, compared to other available methods of measuring porewater pressure (Ref 10).

California State Highway Department Pressure Cell. This cell, used to measure subgrade pressures produced by pavement wheel loads, also operates on the fixed-edge-diaphragm idea. A layer of oil in front of the sensitive diaphragm carries the load to the diaphragm. The measuring system is operated by an electromagnet which changes the reluctance in a circuit so that it can then be balanced with a similar external system under no load and thus obtain the changes. This cell has produced useful data for pressures of short duration but has not been proven for long-period changes (Ref 12).

Carbon-Pile Cells. The carbon-pile cell was the earliest type of soil-pressure cell used. It utilizes a stack of carbon discs to which pressure is applied, thus decreasing the electrical resistance. This gage does not retain its calibration, however, and is not suitable for anything but laboratory use (Ref 12).

Acoustic Stress Meter. The basic principle of this cell is the dependence of the natural frequency of a freely vibrating string on the tension applied. A calibrated vibrating wire above ground is matched, through the use of audible tones produced by the frequency of vibration, with the frequency of a wire under tension behind a plate and free to move with pressure changes in the soil. This gage has given satisfactory service over several years beneath bridge piers and other structures. Apparently it is less susceptible to electrical circuit difficulties which affect other types of pressure cells, as well as being rugged (Ref 12). This cell was not used in the present project because it is difficult to construct.

University of New Mexico Cell. This cell operates by use of measuring strains induced in a short column of aluminum by the applied load. Solid-state strain gages are used to obtain the strain changes. Owing to the high sensitivity of the solid-state gages, very little strain is necessary to obtain pressure indications.

Advantages of this cell are numerous. They include linear gage response in a nonlinear medium, very slight pressure overregistration because of arching, little or no effect on gage response with zero gage cover of soil, and dynamic and static response of equal accuracy. Further advantages are negligible temperature effects, small response time, negligible electrostatic effects, and amenability to various methods of calibration (Ref 15). The University of New Mexico cell was not considered for this project, since it utilized solid-state gages which introduce time-stability problems and its design was not compatible with the necessary application.

Royal Swedish Geotechnical Institute Pressure Cell. This cell, used in soil-cell interaction studies, works strictly on the basis of the measurement of pressure in a hydraulic system by use of a Bourdon gage. Drawbacks to the cell are possible leakage of fluid, hysteresis in the cell proper, errors in the Bourdon gage, and the thermal expansion of the fluid. Electrical contacts immersed in oil are used to check the deflection of the diaphragm which applies the load. Good results with long time periods are claimed. However, the large diameter (some 10 inches) presents other difficulties. Use of bonded strain gages or the vibrating-wire readout system in place of the hydraulic system appears to be acceptable with this gage (Ref 6).

Design Considerations

The many design considerations and criteria vary somewhat with the purpose of the pressure cell, even though all of the cells just discussed have basically the same design criteria. First and foremost, the type of pressure to be measured and its expected magnitude must be considered. Materials must be found for construction of the cell, which must be designed within the practical limitations of shop practice and available facilities. Ruggedness and durability are necessities for a field cell. Stability must be very good, so that a calibration factor can be depended upon for some time. Installation must be easy and lasting. Durable connector cables must be used to withstand normal field pressures and rough handling. The cell must be simple, portable, and entail an easy, nondelicate observation procedure. The unit cost of the cell must be low, with quick installation and observation procedures a necessity (Ref 10). The cells must function reliably under adverse conditions for years after installation. Because of the many important factors involved, the success of pressure-cell development requires a perfectionist attitude (Ref 8).

Additional criteria include strain concepts, the operational environment of the cell, and the soil-cell interaction. Considerations of operational environment dictate that a gage designed for use in the soil must be insensitive to soil type and to soil moisture content. The soil-cell interaction presents a difficult problem. Ideally, a cell should match perfectly the characteristics of the soil it displaces. Practically, however, this cannot be done. The soil characteristics vary with the soil type, such as clays, sands, and silts; but variations occur within any one type, depending on moisture content and degree of compaction. The interaction effects can be minimized by designing the cell so that it is actuated with a minimum resistance to free movement of the soil (Ref 16).

From laboratory tests, Peattie and Sparrow (Ref 7) have determined that the gage should have a constant-thickness sensitive area on the face of the cell and that there should be a certain percentage of the cell face which is sensitive due to soil-cell considerations.

A diaphragm cell should be machined out of one piece of material and should have massive sides to serve as a clamping ring (Ref 17). The cell should produce a linear and reproducible calibration curve within design limits. There should be no bending in the cell body except in the sensing element. The modulus of the cell should be very much greater than the modulus of the soil (in lieu of a perfect modulus match). Cross-axis (axis parallel to cell face) sensitivity should be a minimum. Temperature effects should be controllable, or at least interpretable, and the gage should be rugged to insure reliability (Ref 15).

The instrument must be reliable in order to maintain accuracy under adverse conditions, which include difficulties introduced by soil conditions and the necessity of securing measurements at unpredictable times, regardless of the situation. This equipment cannot be protected, checked, and adjusted during field use as it is in the laboratory. Furthermore, only rarely can field tests be duplicated (Ref 10).

Cell-Soil Interaction

Cell-soil interaction must necessarily be one of the controlling bases for cell design. The action of the soil when the measuring cell is present must be determined in order to design a cell which will most nearly measure correctly the pressures present. An understanding of the cell-soil interaction will allow either measurement of correct pressure or the evaluation and qualitative correction of readings in light of known phenomena.

"Arching" of soil, one of the most important contributing factors in cell-soil interaction, may be defined as the action causing certain zones of soil to carry more than their proportionate share of load because some soil zones are more rigidly fixed or more resistant to compression than surrounding zones or because they have been displaced toward the stresses acting on them. Zones which are less securely fixed or which yield more readily under the stresses acting on them carry less than their proportionate share of the load.

Grain in a silo exhibits arching. Here the floor carries the weight of the grain only for a given height of grain. The angle of internal side resistance of the grain causes all weight above the critical height to be transferred to the walls of the silo and through the walls to the floor.

Terzaghi explained arching through the use of a "trap door action" experiment. He placed a rectangular trap door in the base of a bin filled with sand. The trap door could be raised or lowered as desired. A rapid change in load occurred when the door moved in either direction. As can be seen in Fig 4, as the trap door moved up, the pressure increased; and as it moved down, the pressure decreased (Ref 8). This is analogous to practical problems and may be applied to cell action.

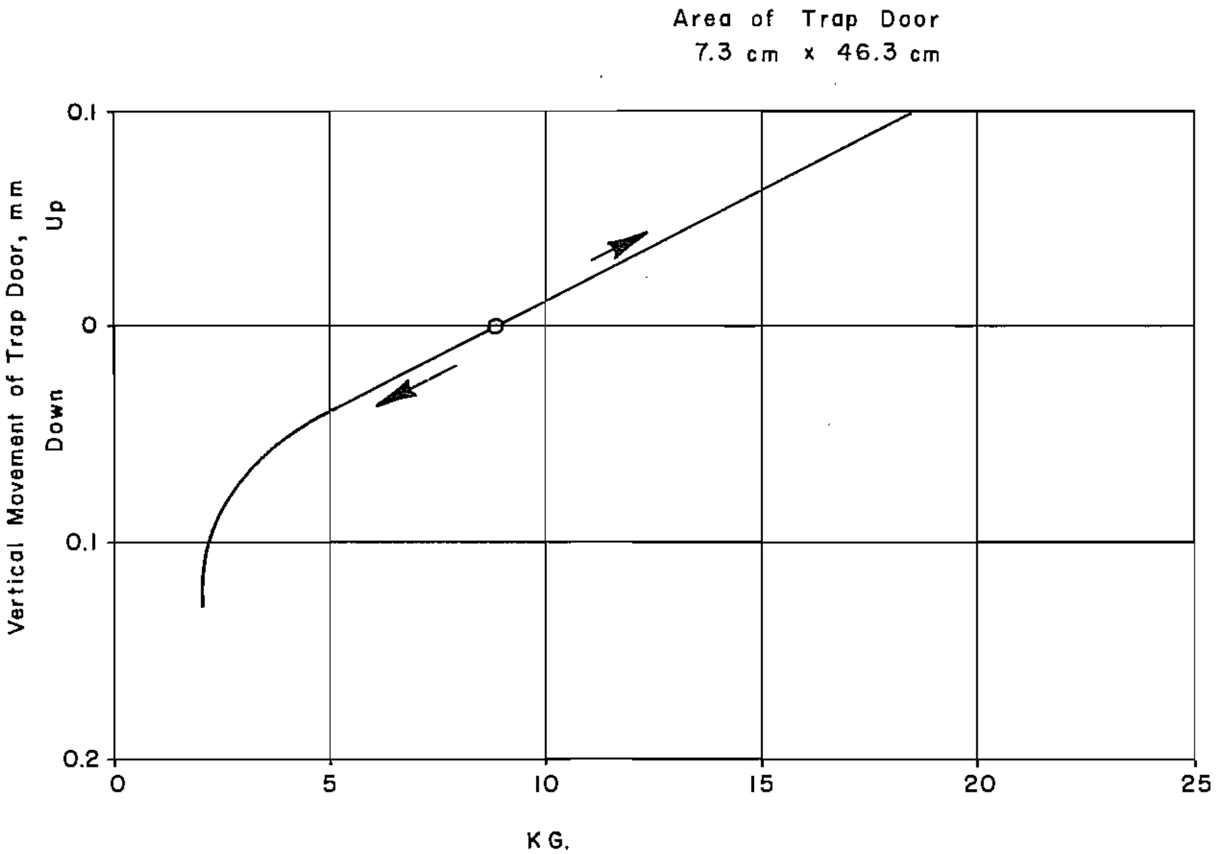


Fig 4. Trap door action.

Therefore, if the soil compresses more than the cell, arching will occur and the cell will carry more than its share of load. If the cell were more compressible than the adjacent soil, which is very unlikely, the cell would be protected by an arch and would therefore carry less load than the soil (Ref 5).

As has been shown, the modulus of elasticity of the soil has a great influence on the pressure measurements. Even if the soil-pressure cell is perfect, the results cannot be corrected any more reliably than the accuracy with which the soil modulus is known. Cells which project from a rigid surface may show some deviation, but they are as dependent on the soil properties as the cells which are flush with the rigid surface. Therefore, ideally, cells should be calibrated in contact with the actual soil and in the actual pressure range where they will be used. The necessary corrections resulting from boundary conditions and stresses can then be made (Ref 6).

Assuming that a cell is buried in the soil and a load is applied to the system, a "cell-action factor" can be defined as the ratio of measured stress to actual applied stress. This cell-action factor will vary with soil type, porosity, moisture content, particle-size distribution, particle shape, compressibility, stress ratio (σ_1/σ_3), and stress history (Ref 18). Most cells are in the shape of a disc and are gaged by the measurements taken from a flexible or rigid diaphragm which forms the cell face.

Slight deformations of the soil are caused by the diaphragm deflection, and arching may develop, thus modifying the stress distribution of the cell face and consequently the measured stress. To obtain the true stresses, the cell should be calibrated first in a hydraulic system and then in a soil subjected to known stresses. The cell-action factor can then be modified by the ratio of the response of the cell when embedded in soil to the response of the cell in a fluid.

Particle shape, mode of deposition, and the degree of packing will also affect the cell response. Therefore, reduction in the sensitivity of the cell-action factor to the changes in soil stiffness and stress changes is desirable. This can be done by increasing the diaphragm stiffness, but sacrifice in sensitivity must be made (Ref 18).

The Royal Swedish Geotechnical Institute has investigated the conditions governing the behavior of a soil-pressure cell fitted into the surface of a wall situated in a granular soil. The Institute found that when the soil-pressure cell cover moves away from the soil surface and the soil does not vibrate, the cell will indicate an underregistration of pressure, which can be corrected.

The dominating factors will be the magnitude of cell-cover travel, Young's modulus for the soil, the boundary conditions of the soil, and the type of cell-cover movement. Therefore, accurate measurements are highly dependent on accurate knowledge of the soil properties (Ref 6). Plastic clays, however, have been found to produce a much less significant deviation in pressure indications than more granular soils (Ref 9). Experimental work along these lines has been done by Peattie and Sparrow and will be discussed later.

Pocket and Cover Action

Pocket and cover action are closely tied to arching and cell action but are not identical. Basically, "pocket action" occurs when a pocket of soil surrounding the cell is different in compressibility from the soil mass as a whole. When the soil directly above or below a cell is different in compressibility from the soil mass as a whole, a slightly different action, known as "cover action," occurs. Both pocket and cover action occur in addition to cell action and are further sources of error.

The low compressibility of a pocket around a cell may lead to an appreciable overregistration, whereas high compressibliity of a pocket may lead to an appreciable underregistration. The underregistration is greater for loose soils than is overregistration for dense soils (Ref 8).

Plastic characteristics of cohesive soils will reduce considerably the cell action since, over a period of time, plastic flow near the cell may relieve arching and stress irregularities. There is no reason to believe that plastic flow would entirely eliminate cell, cover, and pocket action, but it should cause a considerable reduction (Ref 8).

Pressure Distribution

The static pressure acting horizontally against a vertical plane through a large soil mass is defined by

$$\sigma_H = K_o \gamma Z \tag{1}$$

where

γ = unit weight of the soil,

Z = depth of point in question,

K_o = coefficient of earth pressure at rest (ratio of lateral to vertical pressure).

If the soil stratum were deposited vertically and had never been subjected to lateral strains, K_o would be approximately 0.5 for sand and 0.9 for clay (Ref 8).

Calibration of Cells

The two basic methods available for calibration of cells are (1) the application of a known, evenly distributed pressure to the gage by means of some type of gas, hydraulic, or dead-load system; and (2) the application of pressure through a soil medium.

Eccentric loading will result in erratic pressure indications, and serious errors may be present in registrations in some types of cells. Eccentric loading may also result in damage to the cell; therefore, it should be avoided during calibration.

The Waterways Experiment Station cell, which has a range of 25 to 500 psi, was calibrated by both of the above methods. This cell has an indicator scale change of approximately 600 readable divisions for full load in cells with capacities of 50 psi or higher. In other words, the smallest pressure change which can be detected is about 1/600 of the maximum pressure capacity of the cell. The accuracy of this cell in the laboratory is about ± 0.5 percent at full load, as determined by repeated load tests. About 0.1 percent is due to strain gage inaccuracies. The balance of the 0.5 percent is due to gage bonding, imperfect diaphragm performance, mechanics of the flexural ring, and the fluid-transfer cavity behavior. Field accuracy is also affected by eccentric loading, unmatched soil-cell compressililities, and the technique of installation. Plus or minus variations may come from gage-wire aging, imperfect termperature compensation, and possible changes in the elastic properties of the adhesive film used to bond the gage to the diaphragm (Ref 10). These factors will apply to other cells of similar design.

Morse (Ref 19) reports using a dead-weight hydraulic tester to calibrate diaphragm gages. The Carlson cell is calibrated using a pneumatic application of load. Calibration curves were run to a maximum of 50 psi, using increments and decrements of 10 psi. Curves were plotted for increasing and decreasing pressures from which calibration constants were computed based on the average slope of the curve for increasing pressures. Application of calibration load evenly and symmetrically is essential. Creep was checked by maintaining a sustained load over a period of time (Ref 20).

Soil-Cell Calibration

Several methods are available for soil calibration of cells, depending on the size of cell, the use of the cell, and where it is to be located to make pressure measurements. Cells have been placed in triaxial sand specimens, embedded in a sand mass contained in a large pressure chamber, and placed at the bottom of a pressure chamber both flush and projecting somewhat from the base. The end results of soil calibration seem to be fairly consistent in all cases.

Dunn (Ref 18) placed a small cell in a triaxial sand specimen 18 inches high and 9 inches in diameter. He found that the cell-action factor (ratio of measured soil pressure to fluid calibration pressure) decreased with increasing pressure. Reloading of the sample reduced the cell response, but the third cycle agreed closely with the results of the second cycle. Curves were obtained similar to those found when loading the UT cell through sand.

The University of New Mexico cell (Ref 15) was calibrated using two soil containers. One was 30 inches in diameter by 16 inches deep, while the other was 22 inches in diameter by 48 inches deep. A greased membrane was used on the sides to reduce resistance and arching. Due to boundary conditions, gages were embedded to a maximum depth of only 8 inches in the first chamber and to 24 inches in the second. Pressure was applied through the use of compressed air. This testing evolved into determining the depths in the chamber to which the cell could be embedded and still measure virtually the correct applied load. However, it was still possible to use the method to determine overregistration and underregistration for static conditions. The percent of overregistration and underregistration was determined by

$$e_p = \frac{P_1 - P_o}{P_o} \times 100\ \% \qquad (2)$$

where

e_p = percent of overregistration or underregistration,

P_o = $\frac{F_{total}}{A_{total}}$ = applied pressure,

P_1 = $\sum^{i} \frac{F_i}{A_{total}}$,

= measured pressure at a given level in the sand sample,

A_{total} = ΣA_i = total area loaded,

F_{total} = total force applied to sand,

F_i = force applied at a given point,

A_i = area at a given loaded point.

Using this mathematical and experimental procedure, the cell was evaluated in soil.

Truesdale (Ref 16) developed a small inductance-type cell for use in the laboratory. He tested this cell statically by embedding two of the gages centrally in a 6-inch-soil specimen. Specimens were of kaolinite clay, illite clay, bentonite, and sand. Tests were run at varying moisture contents. Assuming the stiffness of the soil to vary inversely with moisture content, both cells recorded greater than average strain in stiffer soil and less than average strain under softer soil conditions. There were two reasons for this. First, the coil was very stiff in comparison with the soil. The effect of gage presence was lessened because the mismatch of moduli is smaller for stiff soils. Second, at higher moisture contents, the soil becomes sticky and adheres to foreign materials, thereby complicating the soil-gage interaction problem in clay. Tests in sand yielded results very similar to those for high-moisture-content clays. Truesdale claims that the gage-presence effect may be negligible in stiff soils but that it is of significant magnitude in sands.

Peattie and Sparrow (Ref 7) ran tests to study the effect of varying moisture contents and densities of clays and sands on a diaphragm-type pressure cell. Soil tests were conducted in a 30-inch diameter by 18-inch-deep pressure chamber loaded by use of water in a membrane with a back pressure. Diaphragms with a fully sensitive face and a partially sensitive face were used. The partially sensitive face in damp or wet clay produced the best performance, with errors on the order of 2 to 5 percent.

The Waterways Experiment Station has done a great deal of work dealing with soil-cell interaction. The testing was conducted in a soil chamber 28 inches in diameter and 10 to 12.5 inches in depth. By means of a membrane and a heavy bolted cover, air pressure could be used to apply static loads to the soil. Pressure cells of from 3 to 12 inches in diameter were used in the chamber, both embedded within the soil and set into the base, flush or projected. All tests were run using Ottawa standard sand. The purpose of the testing was to determine the accuracy of existing cell-pressure measurements embedded in the soil mass or in a rigid wall as opposed to the pressure which would be present if the cells were not included.

Side resistance became a major factor in this pressure-chamber test. Even though the pressure distributions were not uniform, the Waterways Experiment Station found it possible to obtain symmetrical and reproducible pressure distributions by carefully controlling the density at which the sand was placed. This method was satisfactory to obtain the results desired. Side resistance was found to cause decreases of pressure on the cell of up to 8 percent, and in tests where side resistance was negative, pressures increased as much as 30 percent. Therefore, the Station recommends that the reduction of side resistance would certainly be desirable.

The same report recommends that the sample depth should be twice the diameter of the cell and that the sample diameter should be at least four times the depth of the soil mass. Cells flush with the bottom plate should yield more consistent results and should permit the use of an apparatus somewhat smaller than that used for the embedded gages. There seems to be some question as to whether a reasonable estimate of overregistration can be obtained for cells measuring lateral pressures. There seems to be little question, however, about the estimation of overregistration in the vertical direction (Refs 8 and 11).

Pressure-Cell Hypothesis

The Waterways Experiment Station developed a working hypothesis for soil-pressure cells in an attempt to evaluate overregistration. This hypothesis attempts to evaluate the effect of cell dimensions, soil and cell moduli, compression of the cell, and soil properties for a cell protruding from a rigid wall. The original derivation relates overregistration to actual pressure for a rigid cell.

Laboratory testing by the Waterways Experiment Station was done in the soil calibration chamber previously described, using a 28-inch diameter by 10 to 12.5-inch-deep sand mass. This chamber was too shallow to allow pressure bulbs to develop above and below the cells, and too narrow to avoid large side resistance on the vertical boundaries of the mass.

Four important factors were determined from this testing. First, the modification in indicated pressure caused by the projection of the cell from a rigid surface was determined. The conclusion was that the effect is negligible if the ratio of diameter to projection is greater than 30. Ratios of 20, 15, 10, and 5 give overregistration values of 1, 4, 11, and 23 percent, respectively. Next, the effect of the compressibility of cells embedded flush with a rigid surface was determined. The effect was negligible when the cell diameter to cell compression ratio was greater than 1000. For ratios of 500, 200, 100, and 60 the percent of underregistration was 5, 19, 32, and 43, respectively. Third, the cell thickness to diameter ratio for a cell embedded in soil mass should be greater than 5, and fourth, the cell diameter to cell compressibility ratio should be greater than 2000 (Ref 8). (See Table I for a condensation of these criteria.)

Additional Origin of Error

The Royal Swedish Geotechnical Institute (Ref 6) gives several reasons for deviations in measurements resulting from the cell itself. In conflict with the Waterways Experiment Station, it recommends a minimum cell diameter to

TABLE 1. WATERWAYS EXPERIMENT STATION CRITERIA FOR PRESSURE-CELL DESIGN (REF 8)

Cell	WES conclusions on Requirements for Negligible Cell Effects	Overregistration According to Working Hypothesis for Previous Column
Rigid cell projecting from base	$\frac{\text{Diameter}}{\text{Projection}} > 30$	+ 3 %
Rigid cell within the soil	$\frac{\text{Diameter}}{\text{Thickness}} > 5$	+ 9 %
Compressible cells flush with the base	$\frac{\text{Diameter}}{\text{Compression}} > 1000$	- 9 %
Compressible cells within the soil	$\frac{\text{Diameter}}{\text{Compression}} > 2000$	- 9 %

deflection ratio of 10,000. The Institute also seems to suggest that a continuous deflection curve for the cell face as opposed to piston-like movement will reduce the scattering of results. If the cell surface is approximately as hard as the adjacent wall, there will be a minimum side resistance between the soil and the cell. The cell must also be able to take eccentric loads.

The Institute also enumerates deviations resulting from the soil properties. The first is that the modulus for a granular soil is not constant and changes with pressure. The nonisotropic condition of the soil is the main factor in this deviation. A change in unit weight of the soil close to the cell surface can influence the results. In addition, the stresses are not distributed uniformly, because of the nonhomogeneity of the soil. The remedy for this condition is to use large cells or a great number of cells. Vibrations will cause stress changes within the soil. These changes will cause the cell to pass from underregistration to overregistration in soils where vibrations occur.

The Geotechnical Institute used a test tank about 20 inches in diameter and about 14 inches in height. A series of separate rings 5 cm in height and separated by 1 mm spaces was used for the vertical support to permit axial compression on the soil without appreciable side resistance forces being developed if no stresses were transmitted between the rings. This worked reasonably well, but some nonuniform pressure distribution still resulted on the baseplate. This nonuniformity can be attributed to the nonhomogeneous soil and to arching caused by bending of the baseplate. Therefore, the results were affected by these boundary conditions.

Peattie and Sparrow (Ref 7) found that the error for a cell of a 1-1/2-inch-sensitive face on a 3-inch-diameter cell will be about 8 percent for loose and dense sand and moist clay. This finding agrees fairly well with the Waterways Experiment Station value of 9 percent. Sands with high water content and wet clays produced errors of approximately 2 percent.

The Waterways Experiment Station (Ref 11) observed that data for cells mounted in a rigid surface were fairly consistent and surmised that this would allow the results to be applied to other types of pressure cells. Tests show that the gage response relative to applied loads is good, but the absolute readings may be in error.

Cell Design Criteria

The function of a pressure transducer is to transform mechanical intelligence to electrical intelligence and then to transmit the electrical intelligence to a remote point in a manner suitable for communication. This route normally begins with a diaphragm which transmits information to an electrical strain gage. Then information is transmitted by cable to some type of remote readout system (Ref 10).

Several design criteria have been introduced previously, but some of them bear reiterating and expansion. The importance of the ratio of the cell modulus to the soil modulus has already been recognized. Peattie and Sparrow recommend a value for this ratio of at least 10. The proof for this is taken from Taylor for an embedded compressible cell. A value this high will avoid any dependence on the soil modulus. The maximum error due to the modulus mismatch will be produced, but at least it can be predicted for this case. An analysis by G. E. Monfore (as cited in Ref 7, p 144) gives the stress distribution over the face of an embedded cell. The analysis shows that infinite stresses are developed at the edge of a cell. Assumptions are that the material is elastic, homogeneous, and isotropic. These proofs must be applied with caution to soil, however, because of the assumptions. Peattie and Sparrow also explain that for a given modular ratio, the cell action will be a function of the ratio of the sensitive area of the cell face to the total area of the cell face.

Errors cannot be completely eliminated unless the modular ratio is equal to unity and the soil modulus is constant. If a few basic criteria are followed, however, the errors can be kept small and predictable. First, the thickness to diameter ratio or projection to diameter ratio must be small. Errors are directly proportional to these ratios. As previously stated, the error is also dependent on the ratio of the sensitive area to total area for the cell face. Recommendations on cells up to 4 inches in diameter have been made. For a cell which averages the pressure over the entire face (such as a fluid in front of a diaphragm), this ratio should be less than 0.25. A pressure-responsive diaphragm should have an area ratio of less than 0.45, and the modular ratio should remain above 10.

If the above criteria are fulfilled, variations in errors produced by changes in field pressure are unlikely to be important. Cells used in cohesive soils at a moisture content above the plastic limit will have small associated errors which can be neglected (Ref 7).

Cells 3 inches in diameter were used in the testing by Peattie and Sparrow. The optimum sensitive diameter was found to be 1-1/2 inches. The selection of unsuitable sensitive areas will make the cell sensitive to high edge pressures which will produce large cell error. The 1-1/2-inch dimension was found to be least affected by constant loads over a period of time (Ref 7).

In addition to these factors, Dunn (Ref 18) has mentioned several which should be considered in cell design. When measuring stress in a granular soil, the face of the cell must be large enough to have a sufficient number of contacts with the particles. The cell and connections should be shock resistant, waterproof, and resistant to corrosion. The output must be proportional to the applied pressure, unaffected by temperature change, and be stable with time. The measuring face must be unaffected by stresses in the direction parallel to the face.

The Waterways Experiment Station (Ref 8) has several points to add. There should be positive waterproofing on the inside of the gage, and the cables and the cable entrance to the cell should be waterproofed. A full-bridge strain gage should be included in the cell for maximum output and temperature compensation. The strain-gage resistance wires or foil may oxidize if not properly protected. Oxidation may be prevented by filling the cell with nitrogen or castor oil.

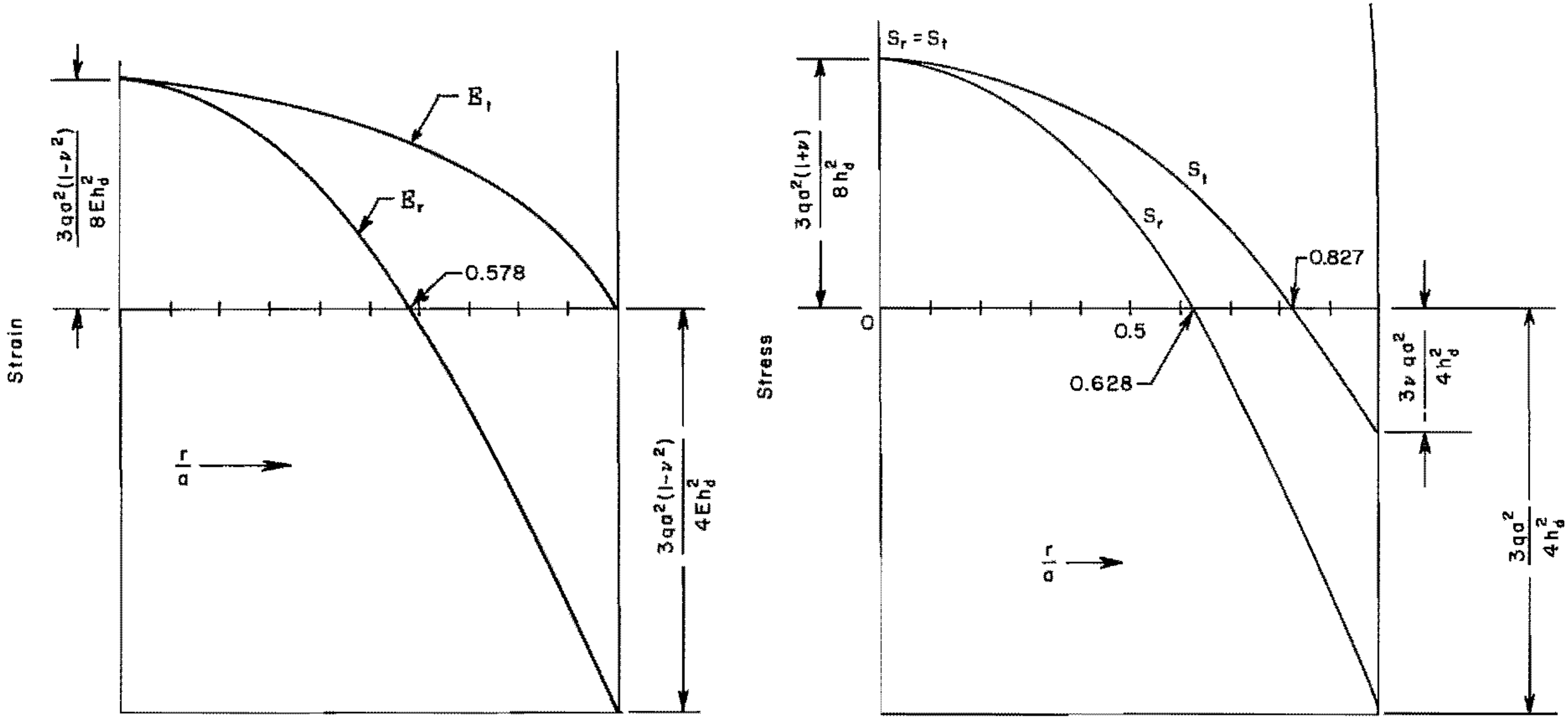
Recommendations on the diameter to deflection ratio range from 1000 by the Waterways Experiment Station to 10,000 by Mackey (Ref 5). Mackey constructed a cell with this ratio equal to 54,000 for a pressure of 1 psi. For the clay conditions encountered in the drilled shaft on the project being reported, a value of 1000 was used.

Design of a pressure cell is essentially a compromise between all of the requirements for an ideal cell. In particular, a compromise between cell stiffness and sesitivity must be reached (Ref 18). The use for which the cell is intended must be weighed against all of these factors and the best design possible prepared.

Material and Design of Diaphragm

The diaphragm cell consists of a circular thin plate which is clamped or fixed at the edges and which obeys certain laws of stress, strain, and deflection. Equations which define this behavior have been derived by Timoshenko (Ref 21) and appear in Appendix A. The primary factors in the design of this diaphragm consist of the dimensions of the diaphragm, maximum allowable stress in the diaphragm, and the composition of the metal or alloy to be used. If the dimensions of the diaphragm lead to a high stress, the material must have a correspondingly high elastic limit. The sensitivity of the gage depends on the elastic properties of the metal, the diaphragm dimensions, and the strain-gage sensitivity. The cell capacity is determined by the yield strength of the material and the diaphragm dimensions.

Curves for the theoretical behavior of the stresses and strains in a thin circular plate, fixed at the perimeter and under uniform surface load, are shown in Fig 5. The equations shown are based on two assumptions: (1) the thickness of the diaphragm is very small with respect to the diameter, and (2) the maximum deflection must be less than the diaphragm thickness. If the



Distribution of Radial and Tangential Strain on Uniformly Loaded Circular Diaphragm with Clamped Edges

Variation of Radial and Tangential Stresses Along Radius of Uniformly Loaded Circular Diaphragm with Clamped Edges

S_r = Radial Stress $\frac{6M_r}{h_d^2}$

S_t = Tangential Stress = $\frac{6M_t}{h_d^2}$

q = Maximum Design Pressure

M_r = Radial Moment = $\frac{q}{16}\left[a^2(1+\nu)-r^2(2+\nu)\right]$

M = Tangential Moment = $\frac{q}{16}\left[a^2(1+\nu)-r^2(1+3\nu)\right]$

a = Radius of Diaphragm

ν = Poisson's Ratio

r = Distance from Center of Diaphragm

E_r = Unit Radial Strain = $\frac{1}{E}$ = $(S_r - \nu S_t)$

E = Modulus of Elasticity

E_t = Unit Tangential Strain

Fig 5. Stress and strain in a thin circular plate with clamped edges.

deflection becomes greater than the thickness, the material will cease to act as a diaphragm and will begin to act as a membrane. The strain will then no longer be proportional to the load.

Design data necessary are the maximum desired pressure, the desired sensitivity, Young's modulus, Poisson's ratio, the yield strength of the material, and the dimensions and strain sensitivity of the cells (Ref 10).

By virtue of the long time reliability requirement, the cell material has been restricted to a metal. The choice of the metal is governed by its elastic and metallurgical qualities and its corrosion resistance. The entire gage must be made of only one metal to avoid differential thermal expansion which would change the calibration curve and distort the diaphragm. The strain is inversely proportional to Young's modulus, and consequently the modulus should be low. On the other hand, the yield strength must be high, since high strains will result in high stresses, particularly at the fixed edge of the diaphragm. Poisson's ratio does not vary greatly and hence is not a controlling factor (Ref 11).

A cell of metal will be rugged and permanent and should be easy to machine. The material must possess the proper elastic qualities. For instance, the deflection must be fully recovered on load removal and must take place nearly instantaneously. In most metals, a plastic deflection due to creep may occur, but this effect is semipermanent, and recovery does not take place when the load is removed. If this occurs, a continued application of load to the diaphragm will cause deflection to continue to increase slightly and ruin the calibration curve. The ideal metal exhibits no creep, hysteresis, permanent set, or change in stiffness with temperature, since all of these factors can affect the calibration of the cell (Ref 10).

The Waterways Experiment Station settled on Type 416 stainless steel after trying several types of steel and brass. Mild carbon steel and Tobin bronze had been used primarily in earlier cells. Experimental cells were made from beryllium cooper, aluminum, brass, and 18-8 stainless steel. The mild carbon steel and Tobin bronze machine easily, but the aluminum and brass are too plastic. The cold-rolled materials display hysteresis, for which the only correction is heat treatment. Stainless steel is difficult to machine. Beryllium copper was used in combination with Tobin bronze, and this, coupled with the lack of adequate facilities for heat treatment, probably accounts for the poor results achieved with beryllium copper by the Waterways Experiment Station (Ref 11).

If the proper cell fabrication techniques are not followed, the entire cell may be ruined. Proper heat treatment is necessary in order to obtain the desired elastic properties in a given material.

Extensive waterproofing is necessary with all pressure transducers. A filling or treating compound may be used to exclude air, moisture, and other deleterious agents. These compounds should have a very low thermal expansion rate. The surface of the cell must be protected if it is subject to rust. For example, stainless steel must have its surface oxidized.

The Waterways Experiment Station gages were welded and soldered in order to avoid using rubber gaskets or other uncertain sealing methods. This metal bonding produced a structurally sound and leak-proof unit. A good watertight connection must be used for the assembly of the cable to the transducer.

Careful control should be maintained during the fabrication and assembly of the cell. Great care should be taken in meeting dimensional tolerances and in checking the results of each operation. All welded and soldered joints should be pressure tested. Precision machining operations were adequate to produce the face plate and diaphragm plate for the Waterways Experiment Station cells. Particular care is necessary in making the final cuts on the gage chamber to insure the correct formation of the diaphragm section without bulging and with uniform thickness.

After the unit is fabricated it is gaged. The Waterways Experiment Station placed four active arms (full bridge) of a Wheatstone bridge on the diaphragm. The gage was then waterproofed and the chamber sealed and filled with dry nitrogen. The Waterways Experiment Station cell has a mercury-filled chamber in front of the diaphragm. This chamber is filled by evacuating the air and then sucking mercury into the chamber by means of the induced vacuum. The completed units, carefully tested and inspected, are then in good condition, electrically and mechanically, to be calibrated (Ref 10).

Summation

Zero shift and calibration should be determined by means of long-term tests. The effects of symmetrical nonuniform pressure patterns and pressure gradients across the face of the pressure cell, as well as eccentric loading, should be evaluated for field applications (Ref 10).

Claims of high accuracy in measurements may possibly be attributed to a favorable case of measurement or to underestimation of the difficulties connected with the disturbances of stress distribution in the soil (Ref 6). Cells can be justifiably condemned only when they are inoperable or become so erratic with time that performance is unquestionably faulty. The functional efficiency of the cell must be assessed after a long period of use to determine if it is in good operating condition (Ref 11). If the gage is in good operating condition and its resistance to ground is high, other explanations must be found for erratic data.

CHAPTER 3. DESIGN OF THE UT LATERAL PRESSURE CELL

Design Program

A development program for design of the UT soil-pressure cell was outlined in order to arrive at a suitable cell. The literature was surveyed to determine the design criteria, and the advantages and disadvantages of available cells were considered.

The development procedure which resulted is as follows:

(1) Select the most suitable material.

(2) Machine a prototype cell and consider the possibility of heat treating. If it is used, take final machine cuts after heat treatment.

(3) Gage the prototype cell with strain gage and wire.

(4) Take several sets of calibration data after loading and unloading the cell several times to release "locked-in" stresses. Plot the data and observe stability and sensitivity at room temperature. Keep a record of leakage resistance.

(5) Repeat No. 4 at temperatures above and below room temperature to establish temperature coefficient and drift.

(6) Calibrate the gage under various soil types, observing the effect of grain size on sensitivity and linearity.

(7) Proceed with fabrication of complete cell and check waterproofing in the bottom of the water tank over a period of time.

Characteristics considered in the evaluation of the UT pressure cell included small size, range and sensitivity, accuracy, cost, stability with time and temperature, ruggedness, good readability, compatibility with soil behavior, resistance to corrosion, and ease of sealing. Since the cell would be installed at the interface between a drilled shaft and the soil and would have to be placed between the shaft wall and the reinforcing cage, clearance would be only about 2 to 2-1/2 inches, and, therefore, the cell could not be very thick. Also, since the shaft wall is circular, the gage had to be small enough for the flat surface of its face to fit close against the wall surface and not be affected by the curvature of the wall. Ease of installation was also considered in determining the cell size. The cell had to be capable of the range of pressures expected, while at the same time producing sensitivity to small changes in pressure. Accuracy was, of course, considered in all phases of design. The cell had to be rugged, since installation under field conditions would very likely produce rough treatment for the gage. Also, the gage had to remain undamaged in an environment which would subject it to the pressures of concrete pouring and curing. Ease in reading the gage was another factor; the cell had to be quickly and accurately readable by a portable system. Compatibility with soil behavior (modular ratio, cell-action factor, etc.), as discussed in Chapter 2, was a very important consideration. To maintain its calibration, the cell had to be resistant to corrosion and rusting. Because of the initial saturated environment (wet concrete), the cell had to be capable of being sealed to keep the water out. Corrosion and grounding of the gage could occur if water were allowed to enter the cell. An additional problem in sealing involved protecting the cable leads and connections in the wet concrete. Because the cell would be buried in concrete, it could not be recovered. Hence, an effort was made to keep the cost of the cell as low as possible.

Types of gages considered were the quartz crystal, the bonded electric strain gage, the unbonded strain gage, the vibrating-wire gage, the linear-motion gage, and the hydraulic-pressure gage. All types of commercially available pressure cells were also considered. Despite its great sensitivity, the quartz-crystal gage was eliminated because of its instability. The unbonded strain gage, vibrating wire, and linear-motion gages were eliminated because of size, difficulty of construction, and associated problems. The hydraulic cell was considered a good possibility if an electrical gage could not be found. All commercial transducers found at the time of investigation proved to have extremely small measuring faces. One 100-psi Consolidated Electrodynamics Corporation (CEC) pressure transducer with a sensitive face 5/8 inch in diameter was purchased to place in the shaft on a trial basis. Owing to cost and small size, this cell will not be used for this application in the future. The UT cell is cheaper, easier to install, and gives equally good data. Apparently, the measuring system having the fewest problems in construction and meeting the design consideration was the bonded strain gage attached to a metal diaphragm. The Waterways Experiment Station cell and the Carlson stress meter were considered but were eliminated because of their bulk.

Design Criteria

Many of the design considerations were covered in the previous section, but some of the more critical details remain to be discussed.

The expected range of the pressures to be measured was from 0 to 100 psi. Static pressures with time as well as pressure changes during an axial-load test needed to be measured. Investigations and the literature indicate that the cell should be approximately the same rigidity as the concrete to record pressures accurately. The cell, being metal, has approximately the same rigidity with respect to the soil as does the concrete. In line with this consideration was the selection of the diameter-to-projection ratio. The projection mentioned in this ratio is the distance the cell protrudes from the shaft into the soil. The Waterways Experiment Station specifies that this ratio should not be less than 30 to obtain good measurements. The requirement for the ratio of diameter to centerline deflection of the diaphragm varies with the individual writer. All seem to agree that this ratio should have a value of at least 1000, but some recommend 10,000, and still others recommend even higher values. Since installation in clay and not in a granular material was anticipated, the value of 1000 was decided upon for use in design. The higher this value, the smaller will be the sensitivity and range of the cell.

For the particular cell being designed, a cell face with a sensitive face area smaller than the total face area was proposed in order to provide "massive" sides necessary to produce a clamped or fixed edge for the thin circular diaphragm. A recommended value for the ratio of sensitive area to total area is given by Peattie and Sparrow (Ref 7) for this type of cell. They have found that the ratio should be less than 0.45 and that the ideal sensitive area is about 1-1/2 inches in diameter. The UT cell has a sensitive face 1-33/64 inches in diameter and a total diameter of 2-3/4 inches (see Fig 6). These dimensions provided a sensitive-area to total-area ratio of 0.296, well within the design limit. A cylindrical steel case 1-3/4 inches in diameter was constructed to contain and protect the commercial cell in the concrete. Construction was such that the face of the cell protruded through one end of the steel case just enough to allow the cell face to be flush with the outside end of the protective case. The ratio of the sensitive area to the total area for this system was 0.128.

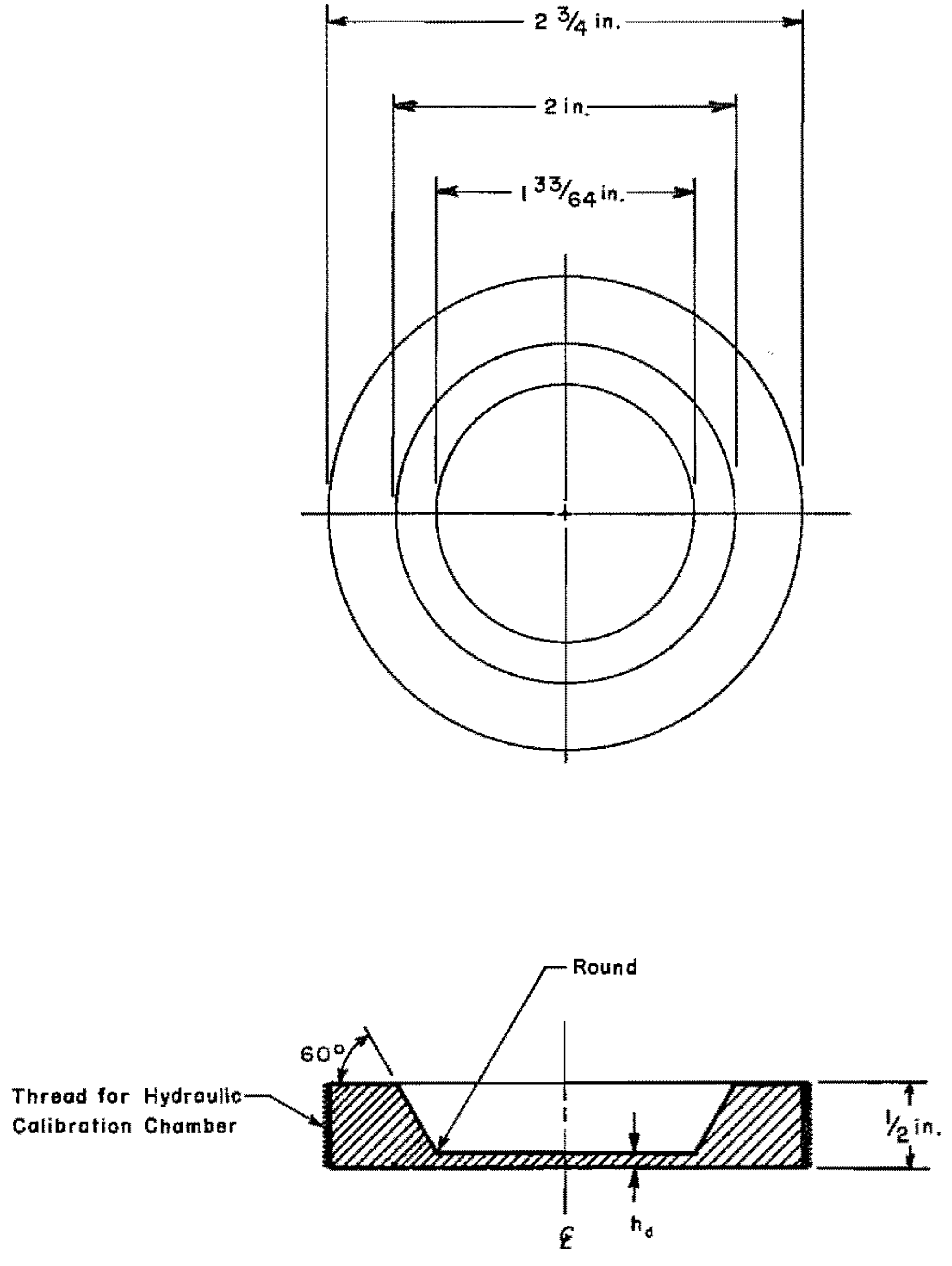


Fig 6. The UT lateral earth-pressure cell.

The basic behavior of the diaphragm is described by Timoshenko (Ref 21), and the equations for strain and deflection are found in Appendix A. The assumptions are that the slope of the diaphragm under pressure is zero at the center and outer edges of the diaphragm, that there is an even distribution of pressure across the diaphragm, that the diaphragm is thin with respect to its diameter, and that the deformation at the Center is small with respect to the diaphragm thickness. Figure 7 shows the deflected shape the diaphragm takes when loaded. The point where the radial strain changes from tension to compression is the point of inflection, denoted "P.I." on the diagram. This happens at 0.577 R_d from the center of the diaphragm, where R_d is the diaphragm radius.

The full-bridge strain gage utilized on the diaphragm and made by Baldwin-Lima-Hamilton is shown in Fig 8. The gage is so constructed that its diameter will be almost the same as that of the diaphragm. Some allowance in the diaphragm diameter was made for the epoxy backing of the gage to extend beyond the edge of the strain gage. This necessitated increasing the diaphragm diameter by 1/64 inch, producing the measurement of 1-33/64 inches rather than 1-1/2 inches. The strain gage is so proportioned that on a diaphragm of this diameter the P.I. of the radial strain which lies at 0.577 R_d will fall in the open space between the tangential and radial gages. Consequently, the two spiral gages measure the tensile strain in the diaphragm, and the two radial gages measure the compressive radial strains in the diaphragm. As can be seen in Fig 9, the gages are positioned and designed to measure the maximum strains on the diaphragm, so that this configuration produces the maximum output possible from a foil strain gage. The crosshatched areas of Fig 9 indicate the portion of the strains measured by the gage and constitute a graphical check of the strain equations in Appendix A which are used to determine sensitivity.

Using Timoshenko's equations for strain and deflection, design maps (Ref 22) for beryllium copper (Fig 10), steel (Fig 11), and aluminum (Fig 12) were constructed for given diameter-to-deflection ratios. The method for calculating the design maps is given in Appendix B. Knowing the pressure to be measured and the limiting diameter-to-deflection ratio, a diaphragm thickness h_d (see Fig 6) can be chosen which will give the maximum sensitivity for this cell for any of the three materials. Care should be used not to exceed the proportional limit of the material at small thicknesses and deflection

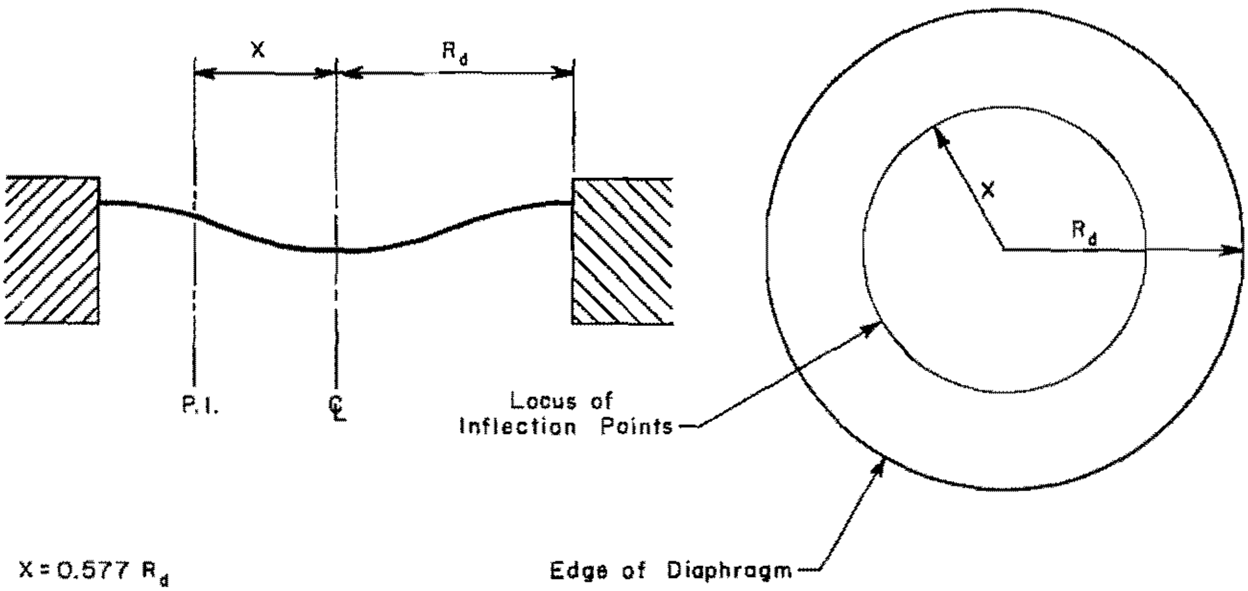


Fig 7. Clamped-edge-diaphragm behavior under uniform load.

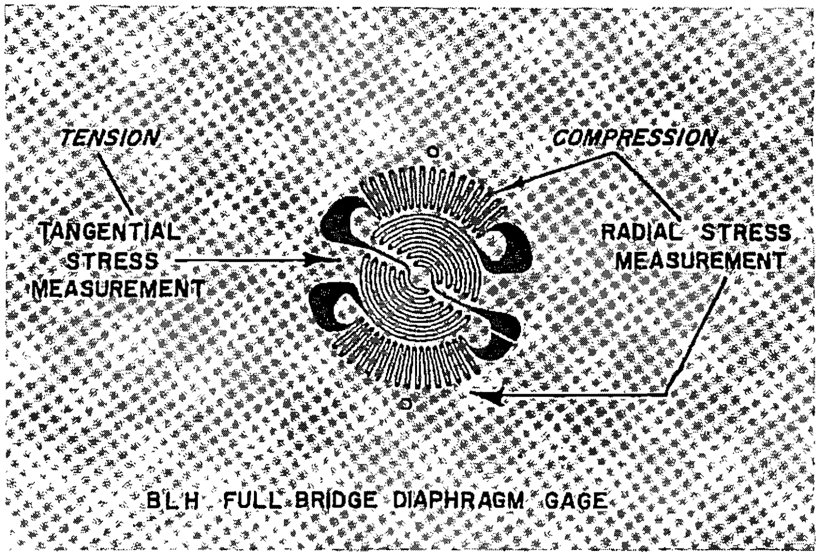


Fig 8. Full-bridge diaphragm strain gage.

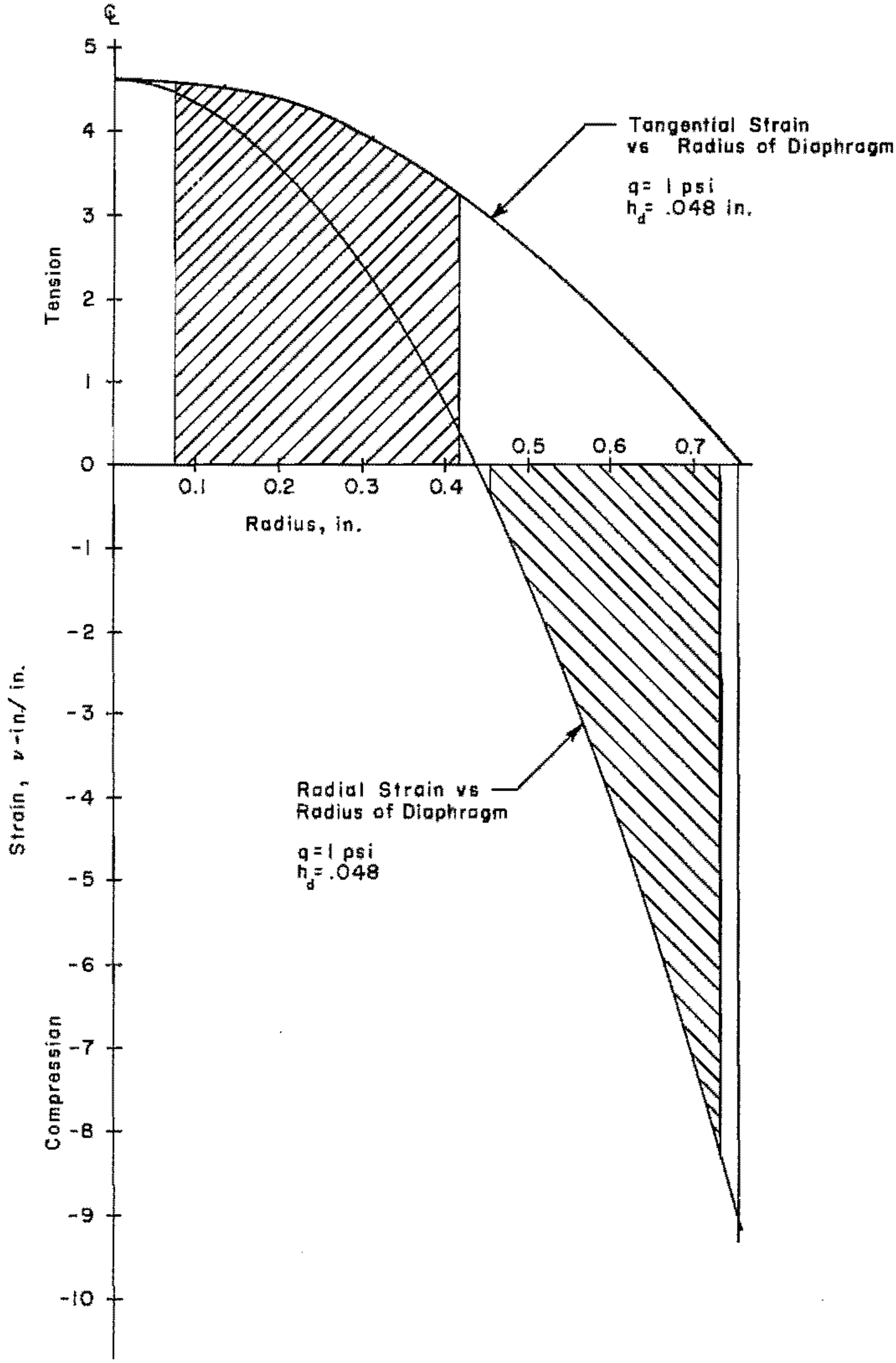


Fig 9. Graphical representation of strains measured by diaphragm strain gage.

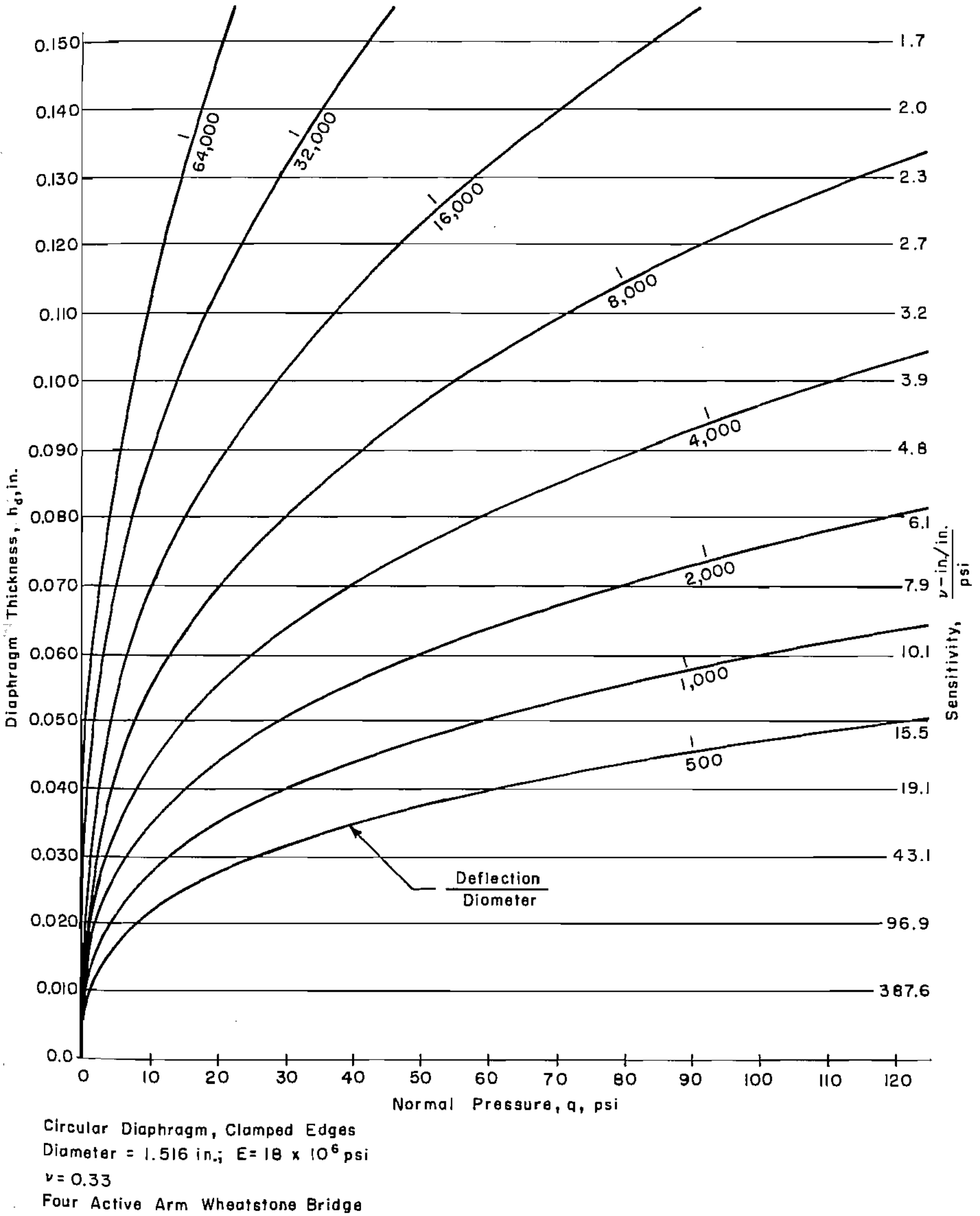


Fig 10. Design map for beryllium-copper cell.

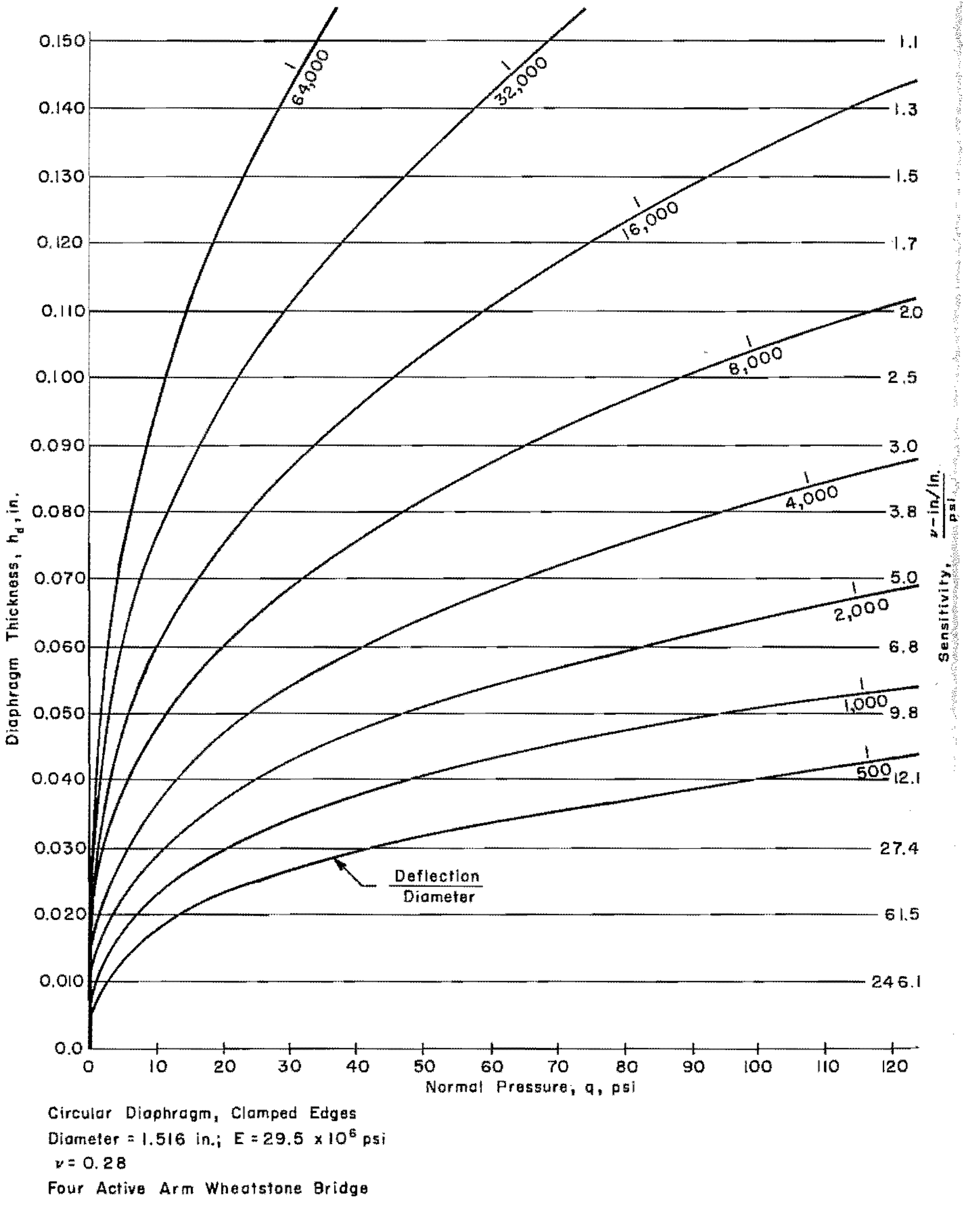


Fig 11. Design map for steel cell.

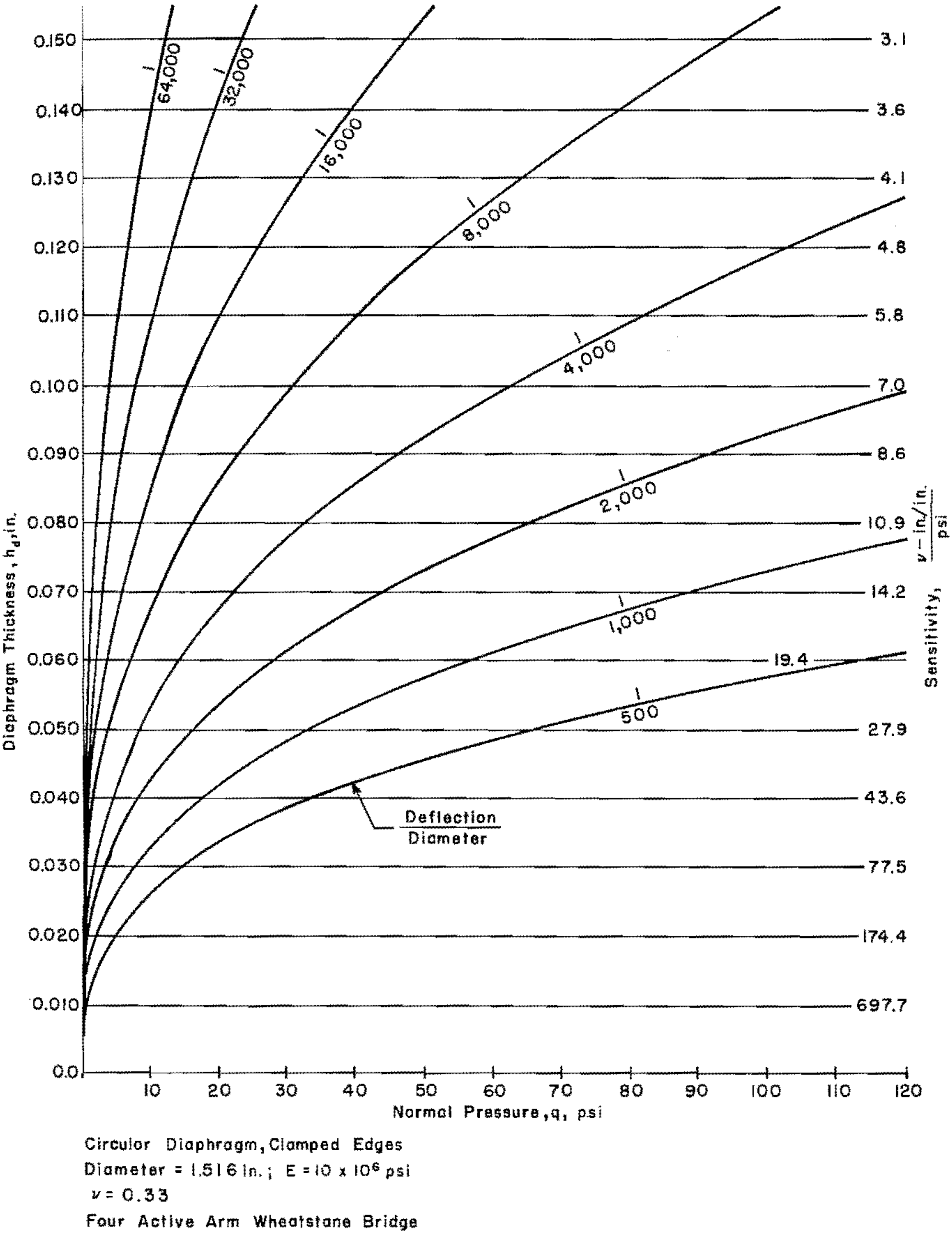


Fig 12. Design map for aluminum cell.

diameter ratios. The producer of the beryllium-copper map states that the proportional limit for this alloy is in the range of 100 to 125 ksi. Using 110 ksi for this value, a diaphragm 0.050-inch thick will be linear to 640 psi, and one 0.040-inch thick will be linear to 410 psi. Computer programs were used to calculate diaphragm thickness from diameter-deflection ratios and gage sensitivities for various diaphragm thicknesses.

Material of Construction

The importance of the type of material from which the cell is constructed has been pointed out. The important factors, again, are Young's modulus, Poisson's ratio, and the strength, machinability, and corrosion resistance of the material.

Several materials were considered for use in the cell. These included copper alloys, bronzes, aluminum alloys, and various steel alloys. Copper alloys considered were red brass, Silicon Duronze III (bronze), and beryllium copper.

Because carbon steel rusts in a moist environment and stainless steel tends to pit, a search for another material was made. Aluminum was eliminated because of its fairly low strength and severe reaction to the environment. The joining of aluminum to give a tight seal proved a major problem. A number of the copper alloys do not obtain a very high strength. However, one alloy, beryllium copper, was found to have many desirable qualities. A sample of this alloy, from which to build a prototype cell for testing, was obtained. The tensile strength of beryllium copper can approach 200,000 psi. Age hardening for two to three hours at 600° F followed by air cooling will produce high strength, good corrosion resistance, and fatigue resistance. Beryllium copper is recommended and used for springs, diaphragms, and non-sparking tools. This alloy, which has been developed in the last thirty years, has a corrosion resistance that practically equals that of a high purity copper (Ref 15). The material also exhibits low hysteresis and good creep resistance as well as a relatively low modulus of elasticity. The low modulus and high strength make possible accurate calibration over a wide range.

Another quality of beryllium copper is that it may be joined by several methods, including adhesive joining and soft soldering with lead-tin, antimony-tin, or lead-silver alloys. The relative ease of sealing was an important consideration in the selection of beryllium copper. Brush Beryllium

Company's alloy 25, which conforms to copper alloy No. 172 specifications (Copper Development Association's copper alloy designation), was obtained for use. This alloy consists of 1.80 to 2.05 percent beryllium (which is the additive that accounts for the highest strength imparted to any copper alloy), 0.02 to 0.30 percent cobalt, 0.20 percent minimum cobalt plus nickel, 0.60 percent maximum cobalt plus nickel plus iron, with the balance being copper. The certification received with the material stated that mechanical properties of this material were (1) ultimate tensile strength, 66,000 to 70,500 psi; (2) yield strength, 26,000 to 26,500 psi; (3) elongation in 2 inches, 50 to 60 percent; (4) Rockwell hardness, Rc 48; and (5) grain size, .070 mm. Information furnished by the supplier stated that mechanical properties after heat treating would be (1) ultimate tensile strength, 182,000 psi; (2) yield strength, 155,000 psi; (3) elongation in 2 inches, 5 percent; and (4) Rockwell hardness, Rc 40. As can be seen, heat treatment at 600° F for three hours produced a large gain in strength for the material. The modulus of elasticity for this alloy is about 18×10^{6} psi.

The previous data qualified beryllium copper as the ideal material for the UT cell. The low modulus of elasticity and high yield strength were of prime concern. The only drawback to beryllium copper was its high cost, which was in the neighborhood of $4.00 per pound in rod form, but this was not serious enough to override the advantages.

Prototype Test Cells

Two prototype cells were constructed for testing purposes. The plan was to construct and instrument one cell of steel and one of beryllium copper. The initial diaphragms were made fairly thick and then machined down in increments of .010 inch, testing the gages for sensitivity at each increment of diaphragm thickness. Originally the plan was to continue cutting the diaphragms down until membrane action became dominant, causing a nonlinearity in calibration curves. This plan was abandoned after trimming each of the cells three times, since sufficient data on sensitivity and linearity had been collected. The cell data are shown in Table 2. The thicknesses for each increment are approximate, since accurate measurement of the actual diaphragm was impossible because the strain gage was in place.

TABLE 2. THICKNESS AND SENSITIVITIES FOR STEEL AND BERYLLIUM COPPER NO. 1 PROTOTYPE TEST CELLS

Test	Original			No. 2			No. 3		
Gage	Original Thickness (in.)	Sensitivity ν-in/in/psi		Thickness (approx.) (in.)	Sensitivity ν-in/in/psi		Thickness (approx.) (in.)	Sensitivity ν-in/in/psi	
		Actual	Theory		Actual	Theory		Actual	Theory
Steel	.062	6.1	6.6	.052	8.5	9.1	.042	12.5	14.0
Beryllium Copper No. 1	.071	8.0	7.8	.061	9.6	10.5	.051	11.2	15.0

Test	No. 4		
Gage	Thickness (approx.) (in.)	Sensitivity ν-in/in/psi	
		Actual	Theory
Steel	.032	18.4	24.0
Beryllium Copper No. 1	.041	17.9	23.0

The gage factor for the diaphragm gages was taken as 2.00. The gage factor relates the percent of change in resistance of the gage to the inverse of the percent of change in its length. The equation for this relationship is

$$\text{Gage factor} = \frac{\Delta\ \text{resistance}}{\text{resistance}} \times \frac{\text{length}}{\Delta\ \text{length}} \qquad (3)$$

Owing to the configuration of the gage, the manufacturer does not give a gage factor for the strain gage. The theoretical strains given in Table 2 show that, for the steel gage, good agreement between Timoshenko's theory and the experimental values was obtained. The agreement was not quite as good for the beryllium copper, but the difference can be attributed to not knowing the actual thickness of the diaphragm after the first incremental cut was made and to not knowing the actual gage factor. Testing was begun using compressed nitrogen as the medium through which pressure was applied. Pressure was measured with a Bourdon gage. A problem developed because the actual pressure applied when using this system was not known. Therefore, a dead-load tester was employed for testing and calibration. The dead-load tester uses a dead weight acting on a piston in an oil-filled hydraulic chamber to produce a known pressure which was made to act directly against the diaphragm. The curves obtained for these tests may be seen in Figs 13 and 14.

Upon examination of these data, the design was determined to be acceptable from the performance standpoint, but one point should be made clear. The design for this diaphragm is based on the maximum allowable deflection of the diaphragm for any given pressure, and, therefore, the beryllium-copper diaphragm will have to be thicker than the steel diaphragm for the given pressure in order to maintain the maximum allowable deflection. This leaves the sensitivities virtually the same for either gage material at a given pressure. The sensitivities being equal, the beryllium copper will still have advantages over the steel, and therefore, construction of the beryllium-copper cells for use in measuring pressure against a drilled shaft was initiated.

Fabrication and Instrumentation of Cells

Dimensions used for the pressure cell are shown in Fig 6. Four cells were machined from beryllium copper, and several processes of fabrication

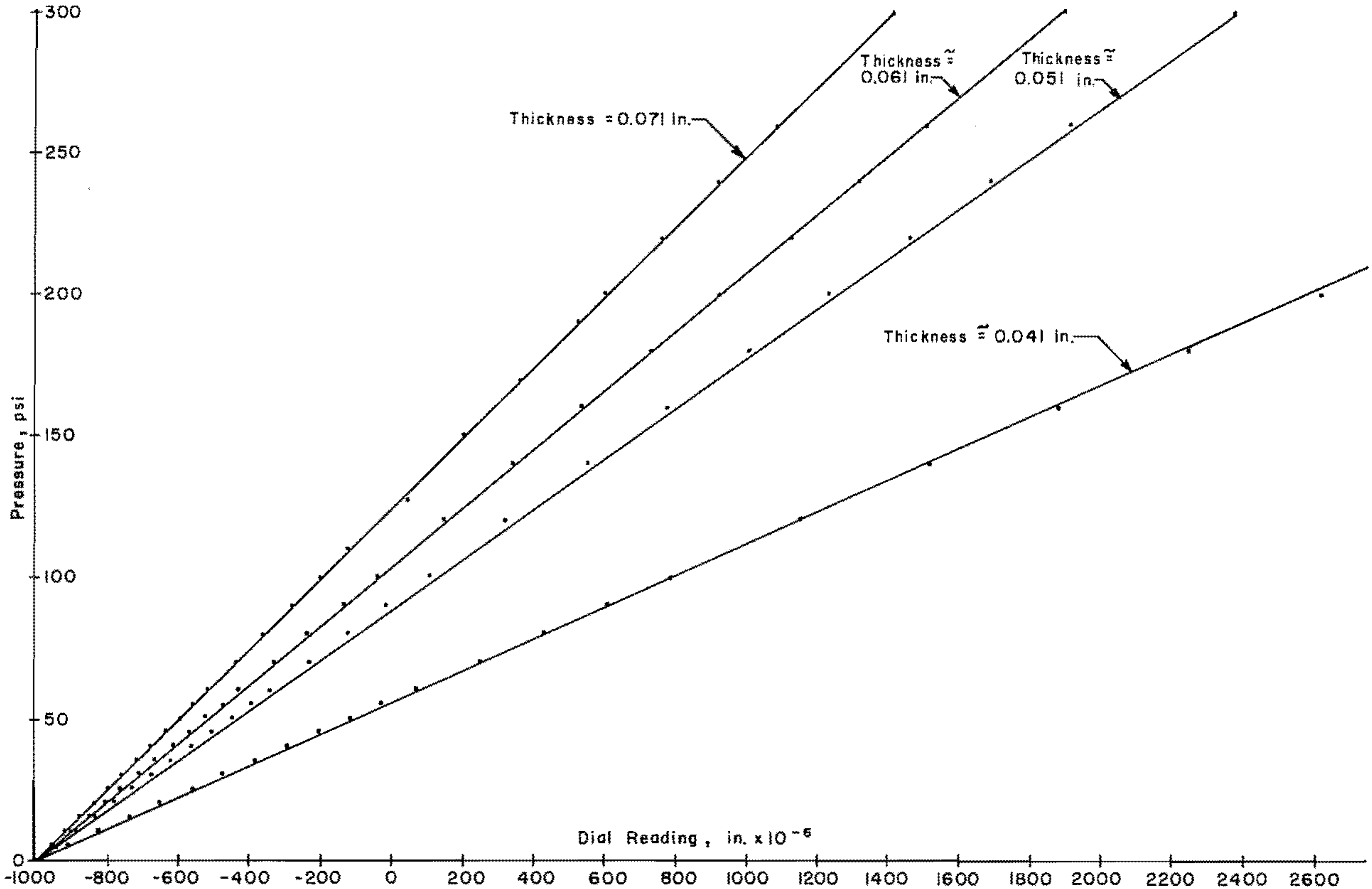


Fig 13. Calibration curves for beryllium-copper test Cell No. 1.

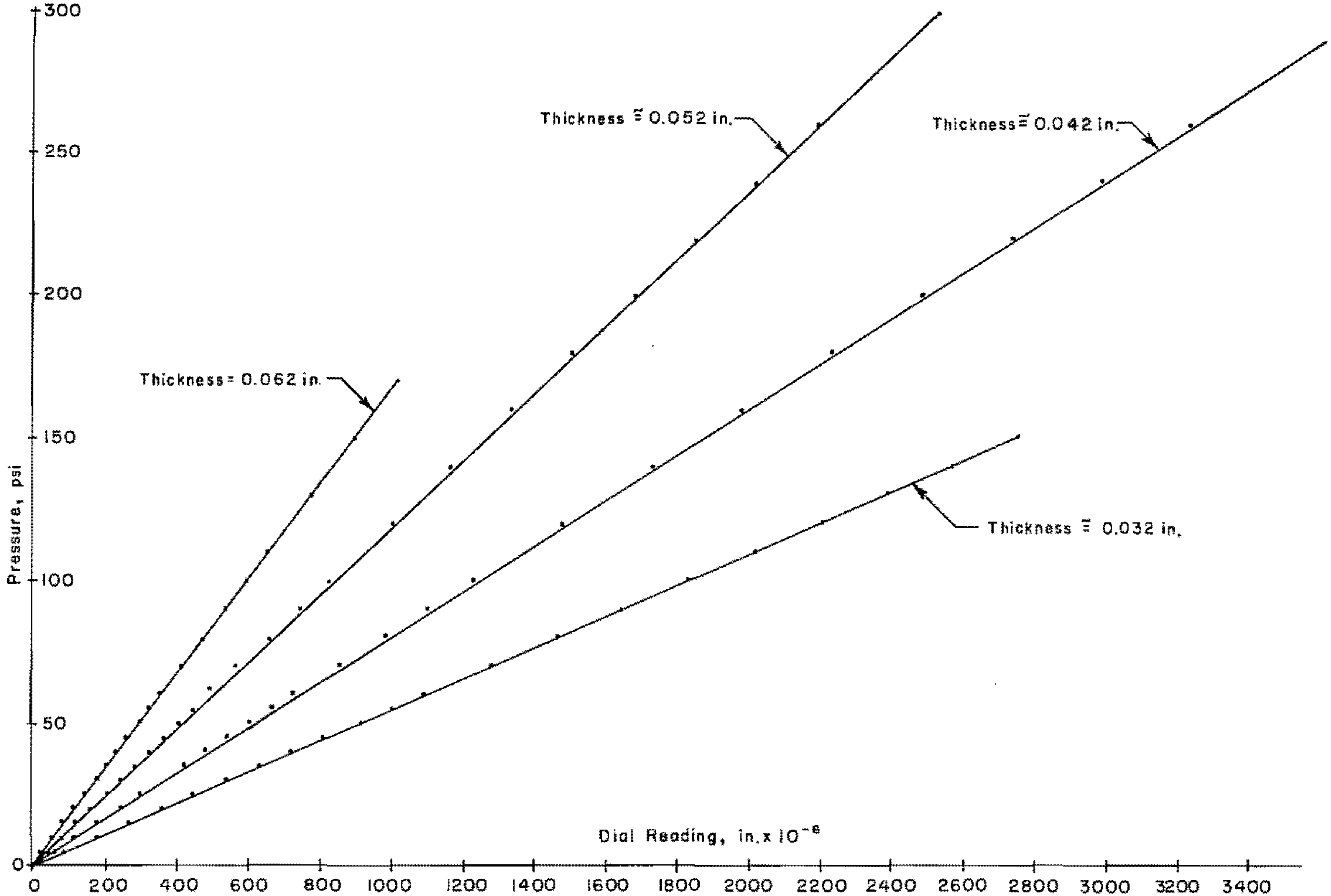


Fig 14. Calibration curves for steel test cell.

were tried to determine the most satisfactory one. Cell No. 1 was machined to final dimensions and then heat treated, while Cells No. 2, 3, and 4 were cut into cylindrical wafers, threaded for the calibration chamber, heat treated, and then cut to final dimensions. Problems developed with both methods. While the dimensional stability resulting from heat treatment was quite good, Cell No. 1 displayed a very slight amount of inward "bow" in the diaphragm face after heat treatment. Curvature was eliminated by trimming 0.010 inch from the face of the cell (this may have produced "thick and thin spots," however). The other cells were machined from the cylindrical wafers after heat treating. The material was somewhat more difficult to machine at this point owing to the increased strength properties, and there was the risk of inducing machining stresses into the material. Hence, thereafter, all cells were machined to within 0.010 inch of the final desired thickness, heat treated, and then the final cuts taken to reduce the diaphragm to the design thickness. This method had several advantages over the other two methods: (1) machinability was much better than when machining the entire rough wafer, (2) the risk of inducing machining stresses into the material was reduced though certainly not eliminated, and (3) the extra thickness prevented all but a small amount of inward bow.

Tests were conducted to determine the Rockwell hardness of each of the gages after heat treatment. If the hardness is within a reasonable deviation from the hardness of Rc 40, the desired mechanical properties should be present. Table 3 shows the Rockwell hardness for each gage.

Gaging of Cells

The strain gage was secured to the diaphragm with epoxy (BLH-Epy 150). The interior of all the cells was sandblasted before applying the strain gages. This was to insure good bond between the metal and the gage. The epoxy backing of the gage was rubbed with pumice powder to eliminate the slick, shiny surface. A small amount of epoxy was placed at the diaphragm center, and the gage was centered and pressed down. The epoxy was worked out under the epoxy backing of the gage by the use of a cotton-tipped applicator. After spreading the epoxy under the gage, a uniform pressure of about 6.5 psi was applied to the gage through a neoprene pad backed with metal. This pressure was allowed to remain on the gage for a minimum of two hours. The minimum

TABLE 3. ROCKWELL HARDNESS OF BERYLLIUM COPPER GAGES

Gage No.	Rc Value
1	-
2	37
3	38
4	36
7	40
8	40
9	40
10	40
L1	34
L2	37
C1	40
C2	40
C3	41

total cure time for the epoxy was 24 hours at 70° F. Curing at 140° F for two hours was used to accelerate the cure period in some cases. The same application pressure was used for all gages. After cure, wires were soldered to the tabs and calibration tests were run.

Calibration

Each of the beryllium-copper cells was calibrated by use of the dead-load tester. The cell was screwed into a calibration chamber which was attached to the dead-load tester. Figures 15 through 20 show the cell, the CEC commercial pressure transducer, a fixture to hold the commercial cell, and the calibration-test device. The cell shown has been waterproofed with silicone rubber.

Two CEC pressure transducers were purchased and calibrated. One was an 100-psi transducer intended for field use, and the other was a 50-psi transducer intended for use in the laboratory. Because these commercial transducers employed unbonded strain gages, the output was considerably higher than for the UT cell.

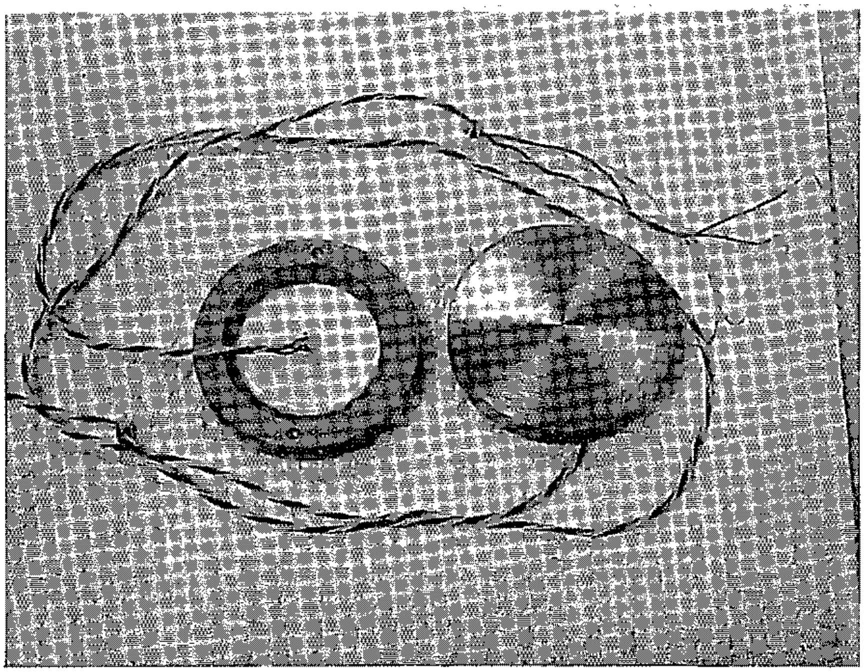


Fig 15. UT beryllium-copper cell with waterproofing in place.

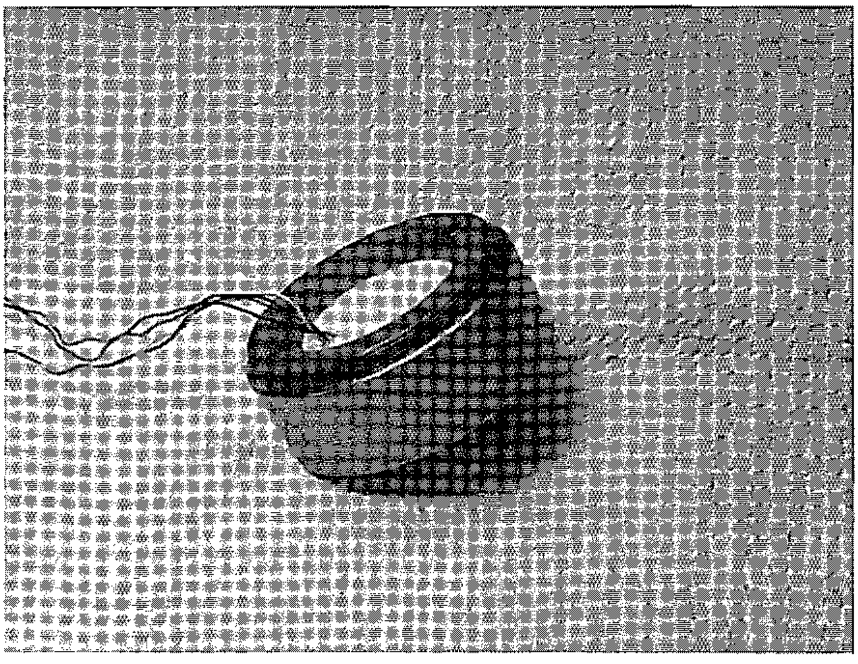


Fig 16. UT beryllium-copper cell in calibration chamber.

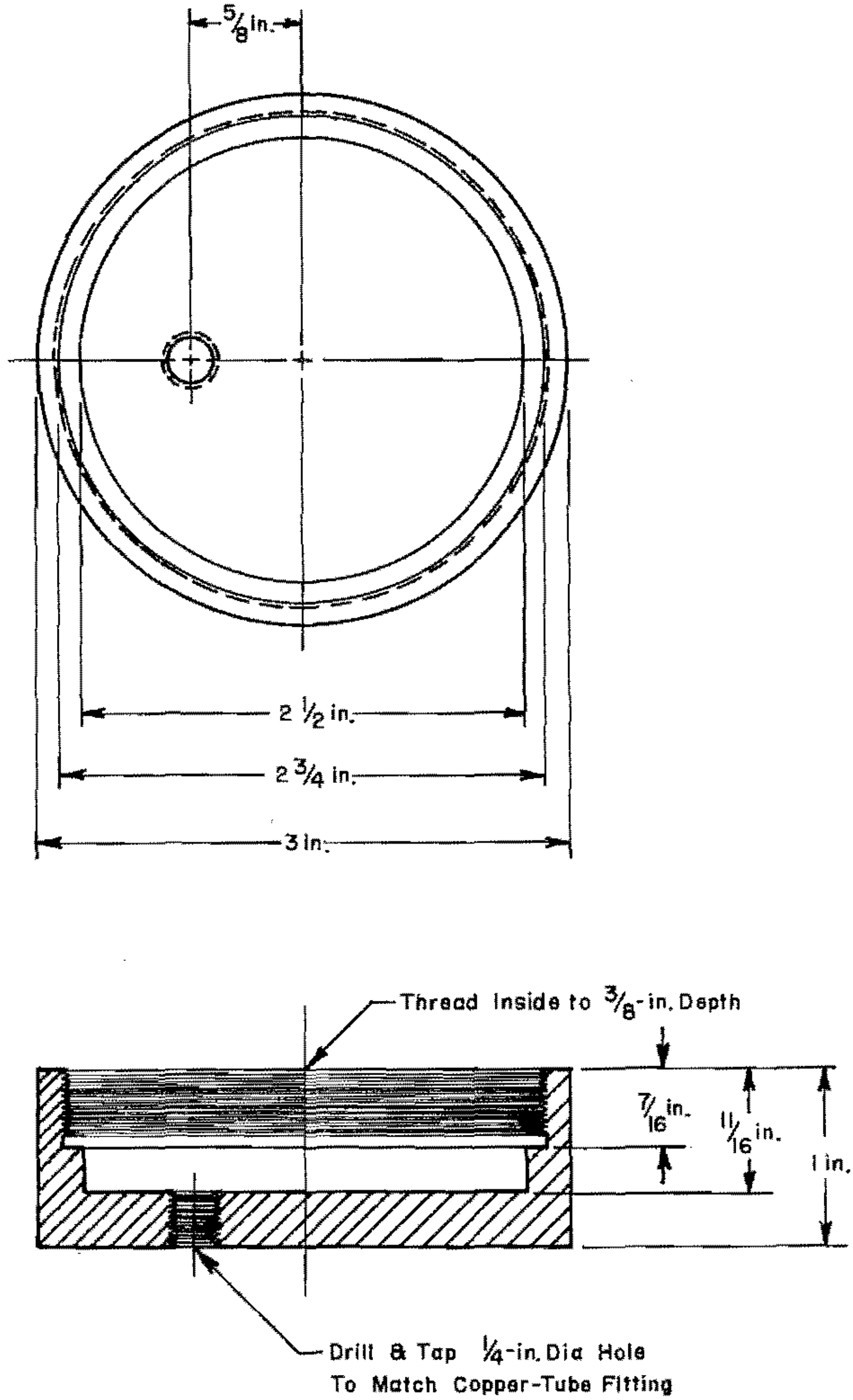


Fig 17. Hydraulic calibration chamber.

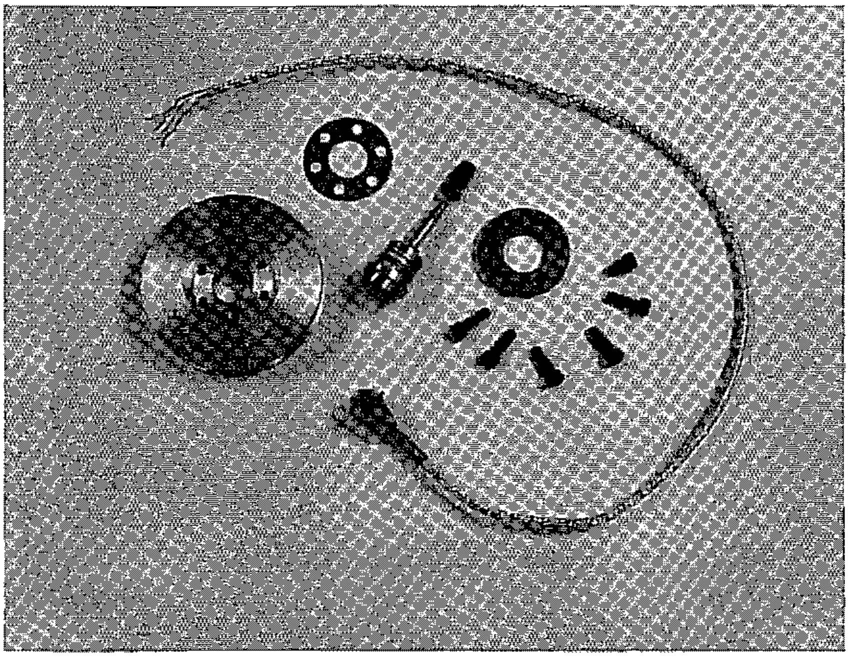


Fig 18. Consolidated Electrodynamics Corporation pressure transducer.

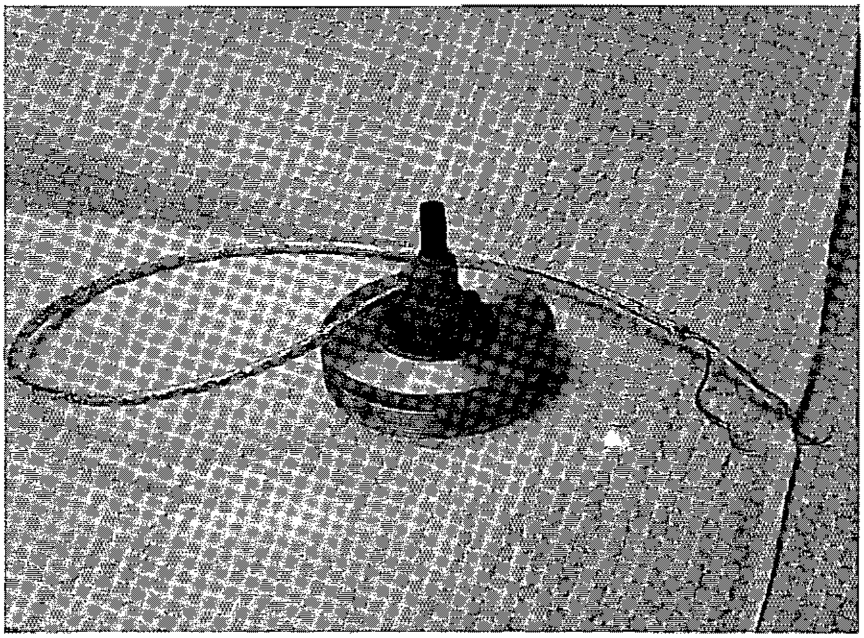


Fig 19. CEC cell in its calibration jacket.

Fig 20. Hydraulic-calibration equipment in use.

The calibration of the UT cell was conducted in the following manner. The cell was cycled to 280 to 300 psi to relieve any machine stresses. (This maximum pressure was chosen because it induces a stress in the material well below the proportional limit, and, also, 300 psi was the capacity of the dead-load tester used.) Several calibrations were run for each cell. Pressures were carried to 50 psi and to either 280 or 300 psi for each cell. The cells were designed for 50 psi at a diameter-deflection ratio of 1000; however, as mentioned earlier, much larger pressures could be applied without exceeding the proportional limit of the beryllium copper. Data for the higher pressures were taken in the event 50 psi would be exceeded in the field. Pressure was applied in increments of 5 psi up to 60 psi, in increments of 10 psi from 60 to 100 psi, and in increments of 20 psi above 100 psi. Loading and unloading increments were the same.

Very little if any hysteresis was noted in the beryllium-copper gages. The thicker cells with calibration constants around 18×10^{-6} in/in/psi exhibited better linearity, however, than those with calibration constants in the neighborhood of 23 to 25×10^{-6} in/in/psi. There is a difference in thickness of these diaphragms on the order of 0.003 inch.

A least-squares linear curve was fitted through the calibration points. The slope of this curve was taken to be the calibration constant for the gage. For each calibration the root-mean-square deviation was calculated. All of the curves were weighted toward the lower end, since more points were obtained there. Separate constants were calculated for the loading and unloading cycle. The slope of the loading curve was used for the calibration constant.

A summary of cell thicknesses and calibration constants, as well as the percent root-mean-square deviation error on the high end of the curves, is presented in Table 4. By comparing the sensitivities shown in Table 4 with those in the design map for beryllium copper, it can be seen that several of the diaphragms were cut to less than the design thickness. The specified tolerance was ± 0.001 inch, but this should be even smaller if the cells are to match in sensitivities. The variance in diaphragm thickness was confirmed by measuring the diaphragm centerline deflection at varying loads with a dial gage which measured to the nearest 0.0001 inch. There is some possibility of error here if the boundary conditions specifying a clamped edge were not entirely met. Also, the gage may have been slipping some in the threads of

TABLE 4. PRESSURE-CELL SENSITIVITIES AND PERCENT ERROR

Cell	Design Pressure (psi)	Design Diaphragm Thickness[a] (in.)	Low Pressure Sensitivity[b]	Percent Error at 50 psi on Low Pressure Curve	High Pressure Sensitivity[b]	Percent Error at 280 or 300 psi on High Pressure Curve
1[c]	50	.041	17.8	0.15	17.9	0.23
2[c]	50	.047	16.6	0.23	17.6	0.51
3[c]	44	.045	23.3	0.24	24.5	0.16
4[c]	44	.045	23.2	0.14	24.3	0.48
7	50	.047	18.3	0.10	18.9	0.31
8	50	.047	18.6	0.16	19.4	0.31
9	50	.047	17.2	0.18	17.9	0.32
10	50	.047	18.0	0.12	19.0	0.46
L1	50	.047	16.1	0.17	16.5	0.32
L2	50	.047	17.9	0.13	18.3	0.20
C1	50	.047	18.2	0.12	19.2	0.20
C2	50	.047	22.5	0.11	22.6	0.05
C3	50	.047	18.5	0.09	18.9	0.18
No. CEC 21320	100	---	----	----	94.3	0.05
No. CEC 22030	50	---	149.0	0.10	----	----

[a] Actual thickness may be less than the design thicknesses.

[b] Units: ν-in/in/psi.

[c] Calibrated through switch and balance box.

the calibration chamber, since there was some play between the threads of the chamber and those of the gage. However, this divergence cannot be attributed completely to the discrepancy in diaphragm thickness. Some error can be accounted for by the assumed gage factor of 2.0, and some error may be caused by inexact centering of the gage on the diaphragm, for without exact centering, the strains measured are not fully known.

Because the calibration constants are virtually the same for Cells No. 1 and 2, it is likely that the diaphragm thicknesses for those cells are nearly equal. Since the thickness of Cell No. 2 was better known, its thickness is probably closer to the correct value, indicating that No. 1 was thicker than stated.

Cells No. 1 through 4 and CEC 21320 were calibrated through the six-channel switch and balance unit with their field cables attached. This resulted in a lower calibration sensitivity than that obtained with the cells hooked directly to the portable strain indicator. A correction factor should be applied to Cells No. 7 through 10 to account for this lower sensitivity, since they are read through the same switch and balance unit in the field. Cells L1, L2, C1, C2, C3, and CEC 22030 are intended for laboratory use. The switch and balance unit mentioned above is discussed in detail in Appendix C.

Sensitivity of these gages to pressures applied parallel to the pressure-sensitive face was checked also. A 200-pound force could be placed on the edge of the cell without any pressure being registered.

Stability Tests

The UT pressure cells were checked for stability with respect to time and temperature. The temperature check was made by heating the cell face to approximately 280° F. No zero shift over the heating or cooling cycles was noted for gages in good operating order.

To increase temperature stability, the manufacturer uses foil conductor material which has been compensated for the temperature expansion of the metal on which the gage will be used. Since the cost of these gages is large ($30.00 each), those already on hand were used in lieu of purchasing additional gages compensated for use on copper. Table 5 gives the type of gage used on each diaphragm. As has already been stated, temperature stability was very good regardless of which type gage was used. This stability can be credited to

TABLE 5. TEMPERATURE COMPENSATION OF STRAIN GAGES ON EACH DIAPHRAGM

Gage	Compensation (Type)
1	Steel
2	Steel
3	Copper
4	Copper
7	Copper
8	Copper
9	Steel
10	Steel
L1	Steel
L2	Steel
C1	Steel
C2	Steel
C3	Steel

the fact that all four arms of the bridge were made out of the same "pour" of foil and were laid simultaneously on the same piece of material.

Time stability tests were run on the gages by applying loads of 10 or 40 psi for time periods up to four days. The load was applied by means of the dead-load tester. Several strain gages were replaced when creep in the bonding epoxy was discovered by using this test. The final gages were considered to be reasonably stable with time and completely stable with temperature as long as moisture was not allowed to enter the cell.

Cost of the UT Cell

The cell material cost $4.10 per pound, or about $3.70 per cell. The strain gage and epoxy cost $31.25 per cell and the commercial heat treating was $5.00 per cell. Machine time for one cell totaled about three hours. Assuming a machine cost of $6.00 per hour, the machining would be $18.00. This comes to a total cost of about $60.00 per cell for materials. Preparation of the cell, gaging, wiring, waterproofing, and calibration required approximately six hours of a technician's time. Additional time was required for curing and stability tests.

The cost and time required would decline if the cells were mass produced. For example, the machining time could be reduced to about one hour per cell. The above cost is very small, however, when compared to the cost of commercially available pressure transducers.

CHAPTER 4. SOIL-COLUMN CALIBRATION

One of the basic parts of the design program was the calibration of the UT pressure cell with various types of soil acting against it. This type of calibration is necessary to determine the behavior of the cell in conjunction with soil, since soil will not act the same against the diaphragm as fluid will. As explained in Chapter 2, underregistration or overregistration may occur depending on the soil conditions, the dimensions of the cell, and the cell position with respect to the soil.

Apparatus

The Royal Swedish Geotechnical Institute (Ref 6) used a large column of soil, 19.7 inches in diameter and 13.8 inches in height, supported by separate rings, 1.97 inches in height, and separated by 0.039 inch. The rings were separated to eliminate the transfer of load by means of side resistance to the sides and thence into the base. Theoretically, load transfer being impossible through the sides, all load applied uniformly to the top would be carried through the soil to the baseplate, provided the rings did not touch each other. Load was applied using a water-filled membrane and a hydraulic jack.

The apparatus used to calibrate the UT cell consisted of 12-inch-ID aluminum rings stacked to a height of approximately 4-1/2 inches, as shown in Figs 21 through 29. A piece of thin plastic was used around the inner diameter of the rings to prevent the sand from flowing out between the rings. The baseplate was a 3/4-inch-thick aluminum plate, supported at the edges by a short piece of pipe. The base was supported in the center by a 4-inch-diameter pipe which fitted another shoulder machined into the bottom of the baseplate. A receiving hole threaded to receive the UT pressure cell was at the center of the plate. At each mid-radius on a diameter, two receiving holes for the CEC commercial pressure transducers were cut. (Note in Fig 22 that one of the commercial gage receivers had been corked and taped because

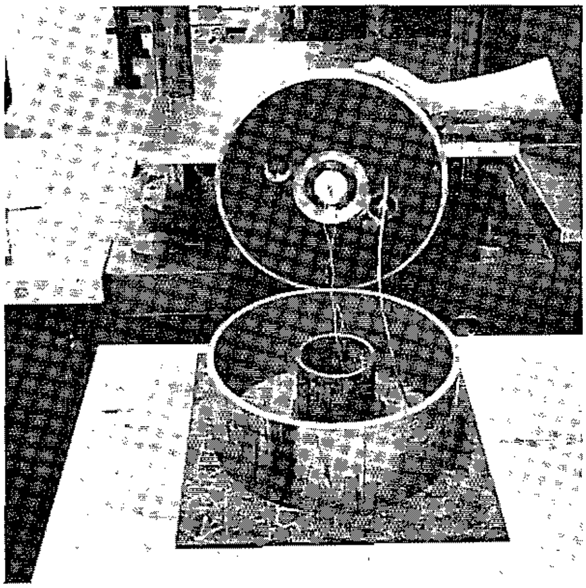


Fig 21. Base assembly for soil-column calibration, open.

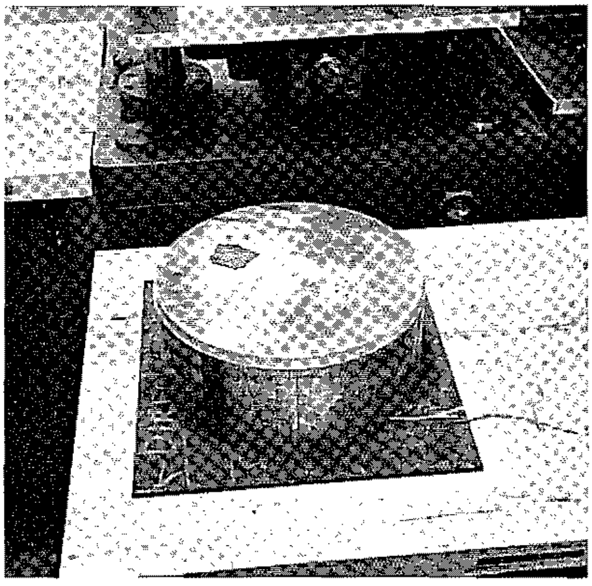


Fig 22. Base assembly for soil-column calibration in place.

Fig 23. Soil-column calibration assembly with rings and sand in place.

Fig 24. Loading plate for soil column.

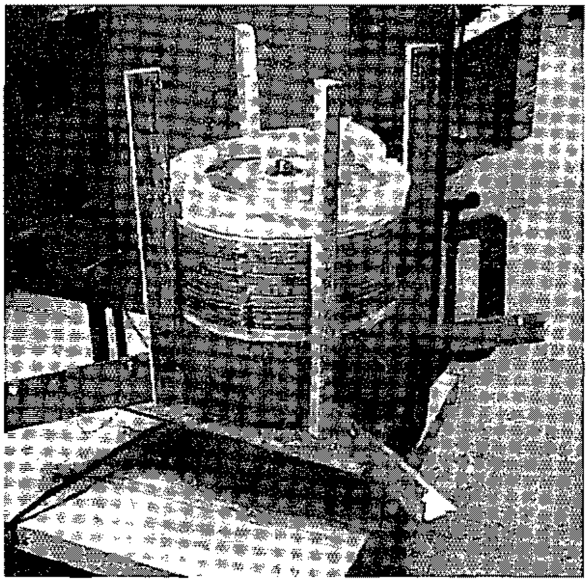


Fig 25. Preparation of soil column for calibration.

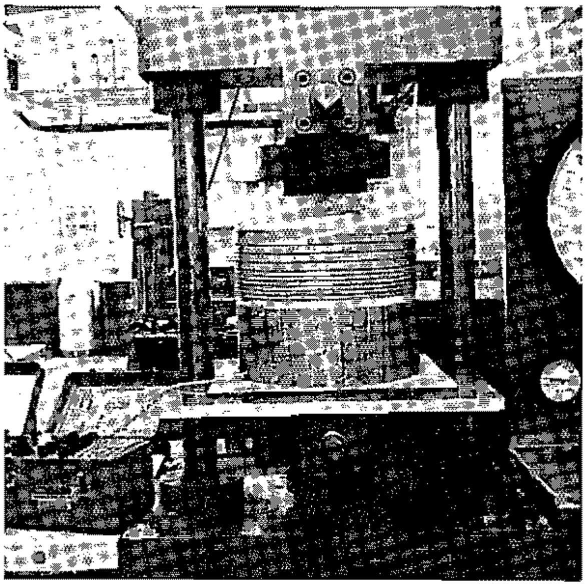


Fig 26. Soil-column assembly ready for testing.

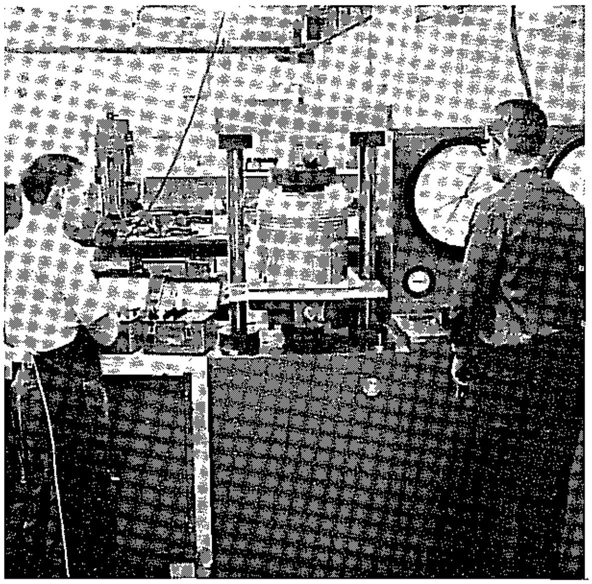


Fig 27. Testing of soil column.

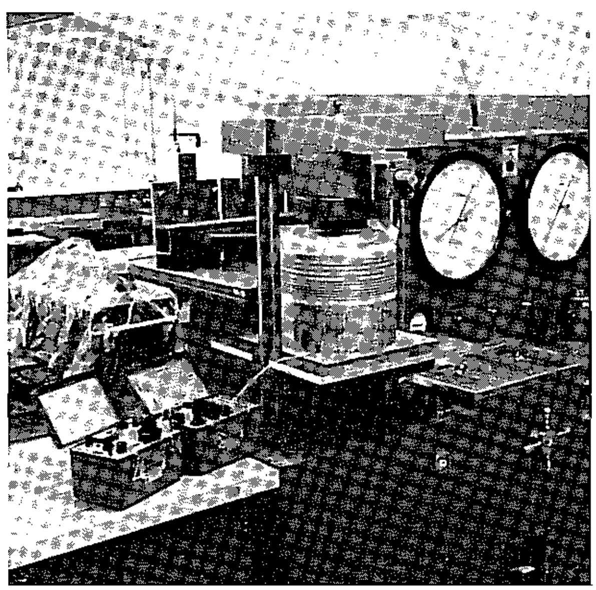


Fig 28. Equipment used in soil-column test.

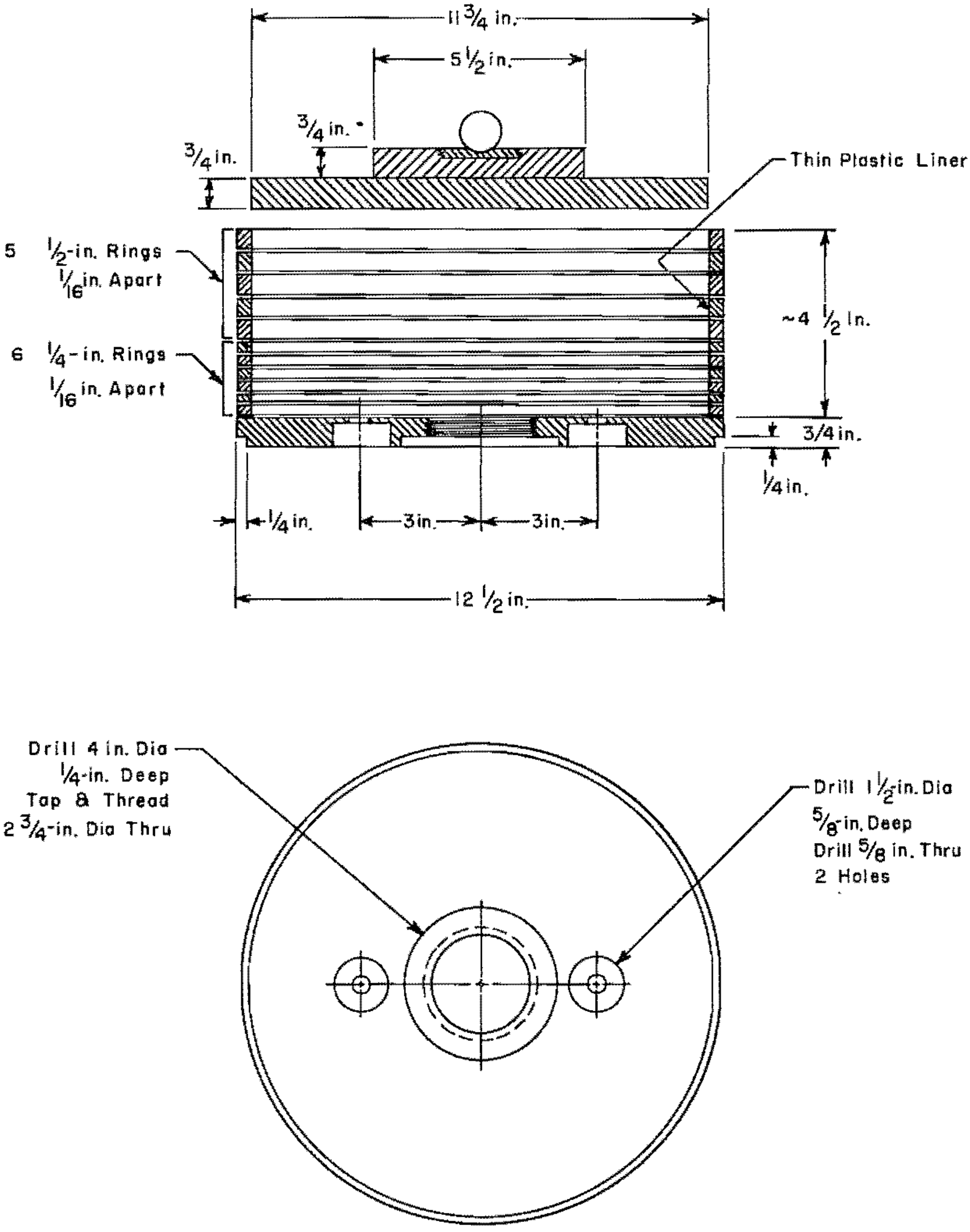


Fig 29. Rings and baseplate assembly
for soil-column test.

only one commercial cell was available at the time of testing.) Because of the threads, the UT cell could be positioned as desired with respect to the face of the baseplate to allow for checking the gage when it projects from the base into the soil.

Load was applied by means of a hydraulic loading machine acting against an aluminum loading plate, 11-3/4 inches in diameter and 3/4-inch thick. The loading plate was stiffened in the center with another 3/4-inch-aluminum plate, 5-1/2 inches in diameter. A small steel insert was threaded into the top aluminum plate and machined to receive a 1-inch-steel ball by means of which the load was transferred from the machine to the sample. Small notches were cut in the bases of the pipes supporting the baseplate to allow the gage leads to be brought out to the Budd switch and balance unit. A Budd portable strain indicator was used to monitor the gages.

The center support pipe was used to reduce bending in the plate. According to Timoshenko (Ref 21) the baseplate, if unsupported at the center and if solid, would deflect 0.041 inch at the centerline under a 100-psi uniform load. If allowed to develop, this amount of deflection could cause some irregularities in the stress distribution, just as too much deflection in the diaphragm gage itself could cause erroneous pressure indications.

Sample Preparation. The soil used in the calibration apparatus was a fine sand. The rings were stacked with 1/16-inch spacers between them and the thin plastic sheet encircling the inner diameter of the rings. The spacers stayed in place until the sample had been prepared and placed in position to be loaded. The gages had been inserted into the baseplate before the lateral support rings were stacked. The entire apparatus was placed atop a table vibrator. The vertical supports shown in Fig 25 were used to keep the rings in place during sample preparation.

The sand sample was prepared by inserting 1-1/2-inch layers of sand in three layers. The table vibrator was allowed to run continuously while filling the apparatus, some 20 minutes. When the apparatus was filled with the sample, the loading plate was put into place and leveled by using a carpenter's level.

Laboratory Tests. Readings were then taken at various loading and unloading increments. These increments ranged from about 4-1/2 to 18 psi. For newly prepared samples loaded with 100 psi, the loads reaching the UT cell at the center ranged from 64 to 71 percent of the applied load. The commercial cell varied in recording the total load from 56 to 72 percent of the load. The difference between the results obtained with the UT cell and the commercial cell may be due partly to the different positions of the cells on the baseplate and partly to the differing dimensions and compressibility of the two cells which affect arching. Table 6 compares the maximum pressures applied with the maximum pressure recorded. A computer program was written to reduce these soil calibration data.

Test 1 was run using load increments of 4.5 psi (500 pounds) on both the loading and the unloading cycles. A plot for Test 1 appears in Fig 30. The curve shown is similar for all tests using the fine sand and is very similar to curves obtained by the Royal Swedish Geotechnical Institute. Stiffening of the soil through compression probably causes a good portion of the hysteresis loop. Furthermore, if side resistance is developed between the sand and the aluminum upon release of the load, the side resistance forces can act to resist the expansion of the sand and consequently will cause a certain amount of load to remain in the sand. Tapping the sides of the sample chamber caused a decrease in residual pressure on the gages. This could mean that a slight disturbance would cause the side resistance to be reduced, thus allowing a release of load.

It was also noted that with increased rates of loading, the percent load felt by gages decreased. The possibility that arching may develop in different ways with different loading rates causing this difference should be investigated.

Direct Shear Tests. In an effort to determine if wall side resistance could indeed be a factor in the underregistration of the gages, several direct shear tests were conducted on the sand acting against the thin plastic covering over an aluminum plate. From four tests run with the plastic present and one run without it, the average angle of side resistance between the sand and plastic-aluminum system for the five tests was 28°. Assuming the side resistance angle was entirely developed at 100 psi on Test 1, the following analysis was made:

$$K_a = \tan^2 (45 - \frac{\phi}{2}) = 0.36$$

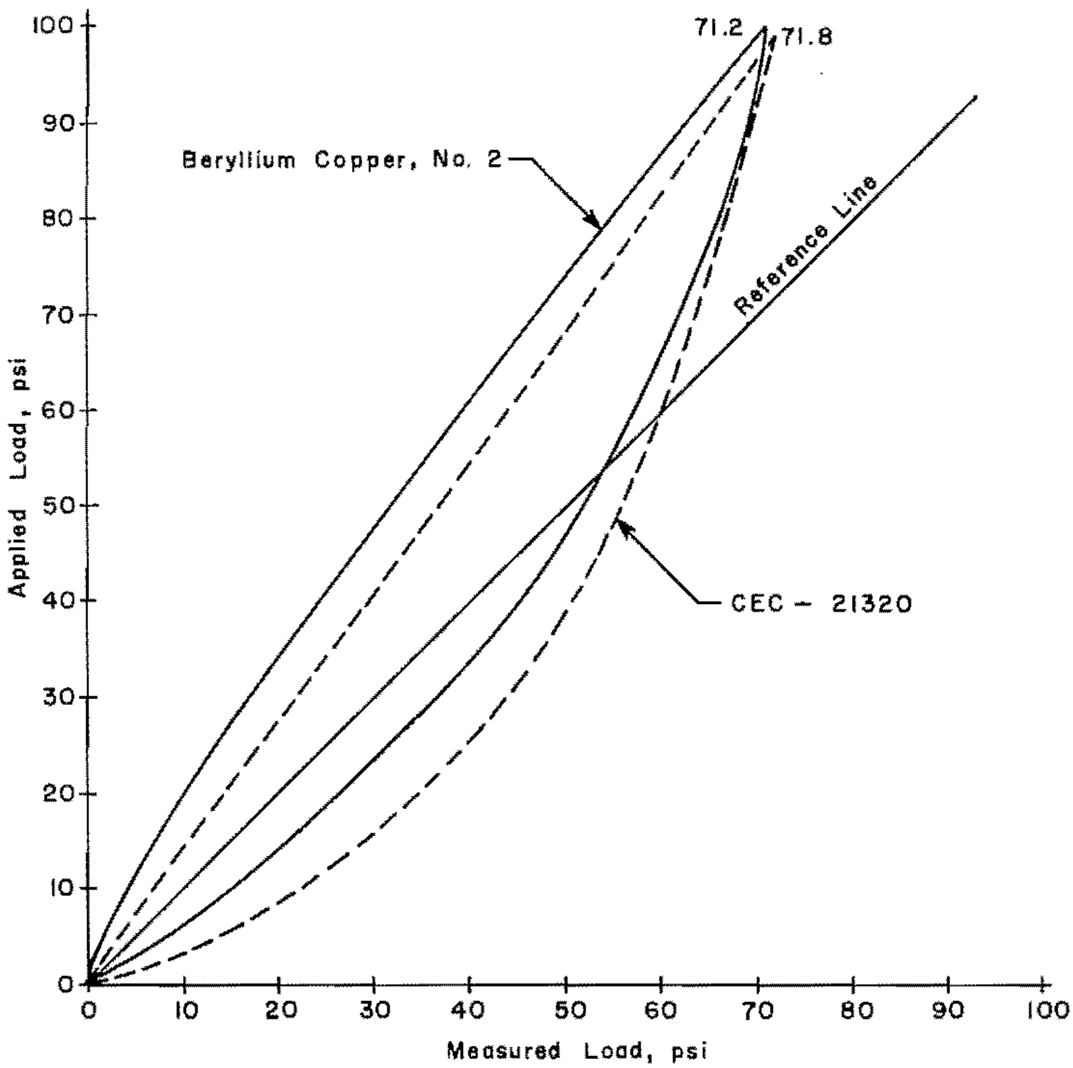


Fig 30. Plot of applied pressure versus measured pressure at base of sand column.

TABLE 6. APPLIED PRESSURES VS. MEASURED PRESSURES UNDER COLUMN OF COLORADO RIVER SAND

Test	Applied Pressure (psi)	UT Cell (psi)	CEC Cell (psi)
1	100.1	71.2	71.8
2	101.9	--	66.2
3[a]	100.1	67.5	56.8
4[a]	100.1	64.7	57.1

[a]Test run with solid pipe rather than "split rings" for lateral support.

$$\sigma_3 = \sigma_1 K_a = 36 \text{ psi}$$

$$\text{Side resistance} = \sigma_3 \tan \phi = 19.1 \text{ psi} \qquad (4)$$

where

K_a = coefficient of active earth pressure,

ϕ = angle of internal side resistance,

σ_1 = applied vertical load,

σ_3 = calculated horizontal load,

Resistance force in sides = side area (resistance) = 3240 lbs,

$$\text{Pressure on base by sample} = \frac{\text{applied load - side resistance load}}{\text{applied load}},$$

P_{base} = 71.4 psi.

The correlation between this calculated value and values measured by the gages checks too closely to be a coincidence; and, therefore, the split rings lined with the thin plastic have not produced what was hoped would be nonload-carrying sides. Sand, under load, was squeezed out between the rings. Thus, the plastic did not serve the purpose of keeping all of the sand within the rings, allowing the development of the side resistance angle.

The test in which the 2-inch-sand-filled ring was used produced erratic pressure-cell readings, probably because of the thin sand cover which does not allow the stresses to distribute themselves evenly.

Summary and Suggestions

All others (Refs 6, 7, 8, and 11) who have worked with a soil calibration chamber have found that boundary conditions were a problem. The calibration chamber used in this testing was smaller than those used by others, but it did not eliminate side resistance resulting from sand being forced between the rings. Therefore, the boundary conditions were a major reason for not using this apparatus to conduct further testings on other soils. To limit the effects of the boundary conditions, the Waterways Experiment Station recommends that the sample height be twice the diameter of the gage and the sample diameter be at least four times the height of the soil mass. For the UT cell, this would mean the test soil sample should be 6 inches high and at least 24 inches in diameter. This sample is larger than required for the CEC cell, and hence would permit its use.

A second problem may have involved the baseplate. There seemed to be a possibility that the baseplate was deflecting under load because of the support conditions. Therefore, a new baseplate was designed with the same diameter but made of 1-1/2-inch steel and supported on radii of 1-3/4, 4, and 6 inches by 30-1/2-inch bolts threaded into the baseplate. This entire apparatus was supported by another 1-1/2-inch steel plate carefully machined to have parallel sides to insure vertical loading and no tilting of the sample. Provisions were made to place three UT pressure cells in the baseplate along with the two CEC pressure transducers. The gages were situated on one diameter and were intended to give the pressure distribution across this diameter. If this distribution is known, the effect of both side resistance transfer and arching may be evaluated. Figures 31 through 33 illustrate the new baseplate. Testing using this new design has not been carried out but is recommended.

For future testing, it is also recommended that each ring be instrumented with strain gages in order to determine the lateral pressure exerted on the

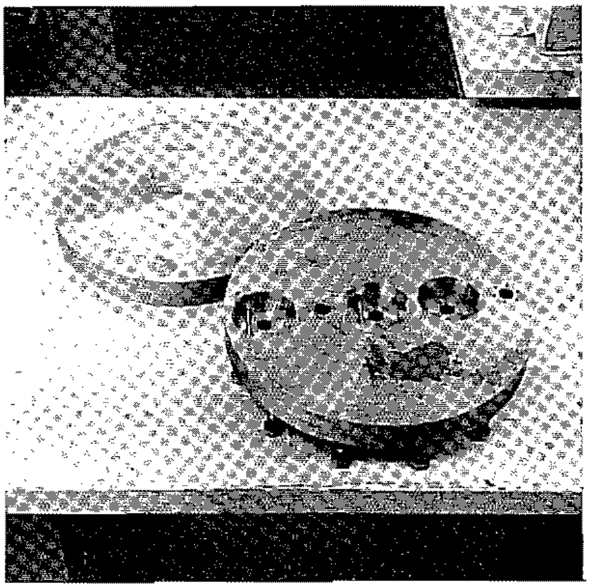


Fig 31. Top view of redesigned baseplate and its base.

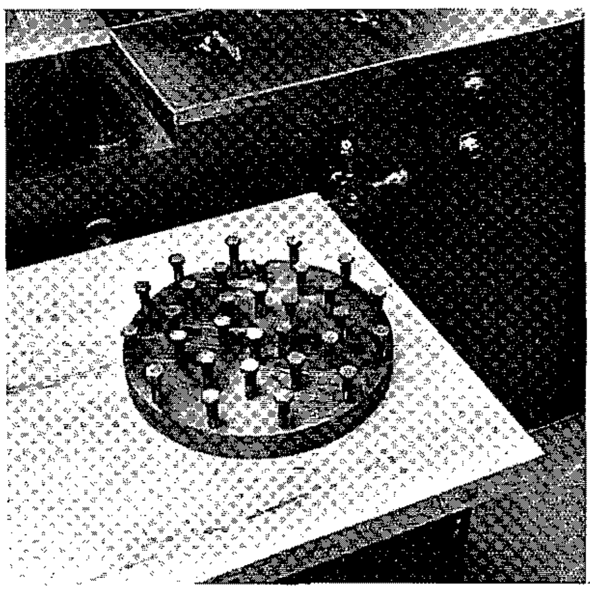


Fig 32. Bottom view of redesigned baseplate.

Fig 33. New baseplate (left) and
old baseplate (right).

sample by these rings so that there is a check on the theoretical solution of the side resistance developed along the sides. This method was used by the Royal Swedish Geotechnical Institute which found that side resistance was definitely a serious problem.

In summary, the UT pressure cell should be calibrated not only in sands, as was done here, but also in clays. A much larger pressure vessel in which to mount the gages should be constructed, and steps should be taken to assure that side resistance is carefully controlled. The boundary conditions will always prove to be a problem, but they can be controlled and evaluated to some extent.

CHAPTER 5. FIELD USE OF THE UT LATERAL EARTH-PRESSURE CELL

As stated in Chapter 1, the purpose of this project was to measure the lateral pressures exerted against a drilled shaft by the adjacent soil. The mechanics of operation of a pressure cell have been explained, as have the procedures for design and calibration of the cell. In this chapter, two field installations, at Austin and San Antonio, and use of the cell to collect field data are described.

Waterproofing

The gage must remain dry if it is to function properly because any moisture which enters the cell will reduce the resistance of the strain gage to ground. If this resistance drops below 100 meg-ohms, the gage readings will be subject to instability and drift. Ideally, this resistance to ground should be nearly infinite for maximum stability.

Waterproofing of the cells was carried out to fulfill three basic requirements. The initial requirement was to protect the gage from any water which might enter the cell. To do this, steps were taken to waterproof the strain gage itself. The second requirement was to prevent any water from entering the cell; therefore, the cell was designed with an attached coverplate. Third, provision had to be made to bring the strain-gage leads out of the cell and still maintain a waterproof system.

Waterproofing of the strain gage itself was carried out by applying sealants directly to the gage. Three types of liquid silicone rubber were used: (1) Silastic RTV 732; (2) Silastic RTV 583 silicone rubber, used in conjunction with Dow Primer 1200; and (3) "Clearseal," which is a transparent liquid rubber very much like the other materials used. These sealants were applied directly on top of the strain gage to a depth of about 1/8 inch. Each gage was waterproofed with one of the preceding materials, but the most satisfactory material proved to be the RTV 583, which could be applied by pouring.

In order to protect the gages from their environment, fitted back coverplates (Fig 34) were machined from brass. Sealing of the cell to keep out moisture was found to be a real problem. The cell can be sealed completely by several methods, including soldering or welding. Heat, however, must be limited, since high temperature can harm the strain gage and its bond.

The first method tried for sealing the back was to use three No. 2-56 machine screws to pull the back coverplate (Fig 34) down against the pressure cell (Fig 6) and hold it while the epoxy which had been placed on the contact surfaces was allowed to cure. This was unsatisfactory, however, for after remaining under 12 feet of water for four days, virtually all of the epoxy lost its bond and the cell filled with water.

The next method tried was soldering the coverplate to the cell. The cell became very hot during soldering, but the gage did not drift or lose sensitivity, and the major problems were obtaining a good solder joint without leaving pinholes in the solder and protecting lead-wire insulation from heat.

Other methods used to join the coverplate to the cell included GC Electronics Company's Pliobond cement and Okun's cold solder. The only method which proved unsatisfactory was the cold solder. Water found its way into the cell through the cold solder under field conditions. The Pliobond cement was easiest to use and proved satisfactory in this experiment and is recommended for use in the future.

The joint was tested by applying back pressure to the cell and checking for any bubbles coming from the joint while it was immersed. This back pressure was applied through the copper-tubing fitting, which was threaded into the back of the gage and protected the gage leads from the cell to the surface. Strips of teflon-thread packing tape were used to obtain a good seal of the fitting joint, and this fitting was filled with the silicone rubber to seal out any water which might enter the copper tubing carrying the leads to the surface.

After the backplates were secured to the cells with Pliobond, several layers of waterproofing were applied over the joint and over the junction of the lead outlet fitting with the coverplate. These layers consisted of two coats of Okun's Hydralloy, two coats of Pliobond cement, and two coats of GC Electronics rubber to metal cement. A few cells had a coat of silicone rubber placed over the other coats. All gages installed in the two field

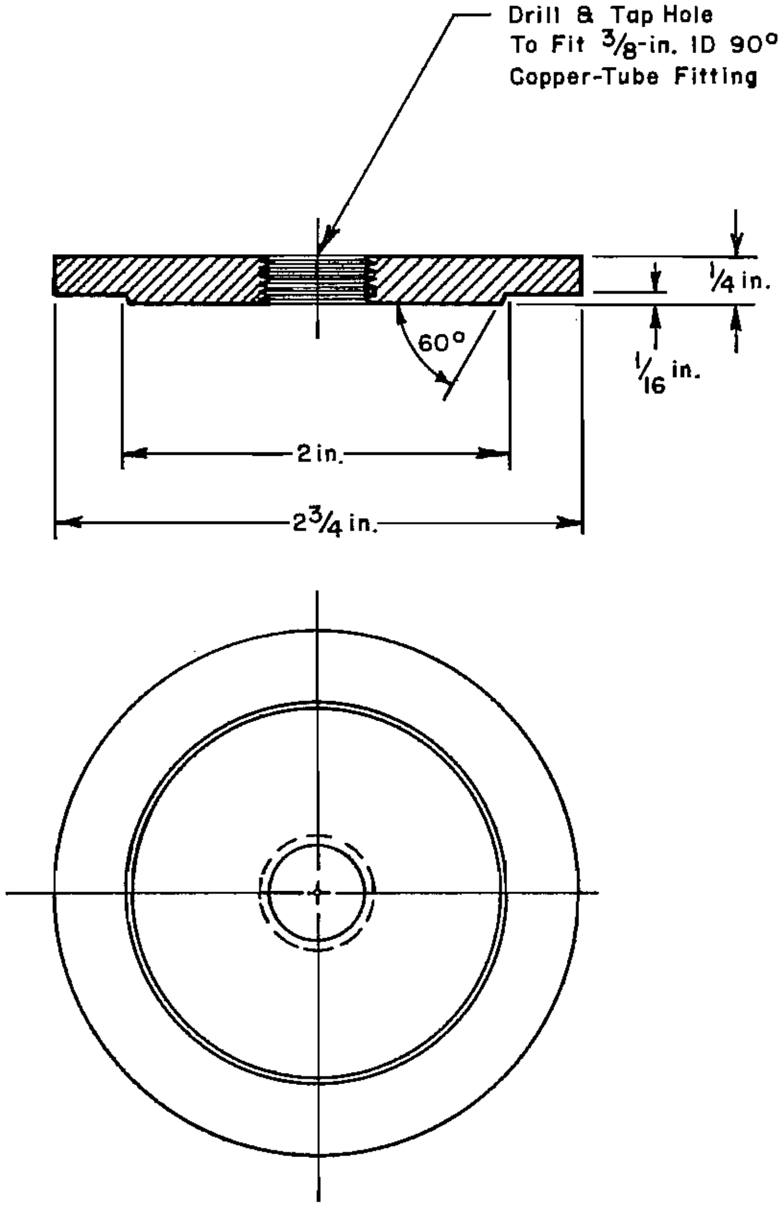


Fig 34. Back coverplate for UT cell.

installations were dipped in asphalt which covered all but the cell face. This method of waterproofing proved to be fairly effective over a period of seven months in field service. Therefore, the procedure adopted for joining the backplate to the cell used the Pliobond cement in the joint in combination with the remaining waterproofing layers just described.

Wiring

The wiring for the gages, a critical part of the gage system, was somewhat different on both of the field installations, but all gages had 30 American Wire Gauge (AWG) copper stranded wire soldered to their tabs. For the four gages for the Austin site, this wire was Teflon covered to protect the wires from the high temperature developed while soldering the backplate on these gages. These four leads were brought through the gage sealant and attached to a four-tab barrier strip embedded in the sealant. Four 20 AWG, 7 × 28, thermoplastic covered wires were soldered to this tab. A fifth wire was included in the cell, the bare end wrapped with a paper tissue. It would be a check on moisture entering the gage, as the tissue would absorb the water and provide a short circuit to ground between the bare wire and the cell. To prevent undue strain on the strain gage, a knot was tied in the cable at its point of exit from the cell. Originally, four-conductor, shielded strain-gage cable was to be used as the conductor to bring the gage output to the surface. This cable was used in the second field installation but not in the first, because the copper wire was not available.

The set of cells installed in the field at San Antonio required the cable conductors to be spliced to the 30 AWG wire after the wire had passed through the backplate. A phenolic washer was tied into the small wire to prevent undue strain on the gage. Any strain on the wire from outside the cell would be borne by this washer.

Splices between the small wire and the cable were staggered in order to avoid any bulk which might prevent the cable from fitting into the 3/8-inch diameter (run to surface) copper tube. Splices were made by first baring and soldering these wires. Then the splices had to be prevented from shorting to ground, either directly or through moisture which might collect in the tube. This was accomplished by covering each connection with William Bean Gagekote Nos. 2 and 5 and covering the entire splice zone with heat shrinkable "spaghetti." Gagekote No. 2 is a nitrite rubber which heat dries in 30 minutes. It affords mechanical protection and withstands humid atmosphere, water, and other deleterious agents. Gagekote No. 5 was used to encapsulate the splices coated with No. 2. It is a two-component rubber-like epoxy resin recommended for direct immersion in water. Adhesion to clean metal is excellent. Therefore, it is also recommended to waterproof strain gages themselves. Gagekote No. 5 may be better than the silicone rubber for future strain-gage waterproofing.

Two of the four gages in the San Antonio field installation had water-presence indicators (paper tissue) included within them. The cable shielding was used as the conductor for this device.

The wiring system seems to have been suitable for the purpose, since the cable system had desirable electrical and mechanical properties. Electrical stability requires low conductivity and high insulation resistance. Mechanical properties include sufficient strength to withstand rough field treatment, flexibility at normal and freezing temperatures, and shielding to prevent any extraneous induced voltages. The polyvinyl cover of the cable has low moisture absorption characteristics and will therefore give excellent high-insulation resistance. The four-arm full-bridge circuit used reduces the requirements placed on the cable, since cable effect is virtually cancelled out (Ref 10).

Readout System

A six-channel switch and balance unit was constructed for rapid reading. This unit is described in detail in Appendix C.

Field Use - Austin

The first test site selected was in Austin near the section of the city known as Montopolis. The criterion for selection of the site was that it be in a stiff clay which would allow a drilled hole to stand open during the installation of the UT pressure cell. Other advantages of the stiff clay were ease in sampling and testing and a homogeneous surface on which to install the pressure cell.

The main purpose of this test was not so much to gain data which could be interpreted for the soil-shaft interaction as to check out the instrumentation.

Installation procedures, construction procedures, and test procedures were to be tried in order to gain experience and eliminate future mistakes. The data obtained from this test, however, may prove to be valuable when they can be compared with that from other tests. Trends have been observed which bear checking in later tests.

Installation. Five cells were installed in this 24-inch-diameter by 12-foot-long shaft. Four of these were UT pressure cells, while one gage was the CEC, 100-psi transducer. As was stated earlier, the cells were sealed. Figure 35 shows these gages ready for installation in the shaft. The CEC transducer, Cell No. 5, and UT Cells No. 1 and 2, were placed 120^{o} apart, 10 feet below the ground surface. The other two UT Cells, No. 3 and 4, were placed 6 feet below the surface vertically above their counterparts at 10 feet.

A man entered the shaft on a ladder and installed the gages manually. The procedure was to use a spatula to smooth a surface on the wall of the hole against which to place the gage. Care was taken to maintain the ratio of diameter to projection at greater than 30 when possible. However, owing to inexperience and a small amount of calcareous material in the soil, the desired ratio was not maintained for some of the cells. Cells No. 2 and 3 were flush with the wall face, but Cells No. 1, 4, and 5 had respective ratios of 11.0, 3.67, and 1.75.

The failure plane between the shaft and the soil has been found, both on this project and by DuBose (Ref 13), to be located some distance into the soil, away from the actual contact of the soil and concrete. This is possibly due to migration of mortar into the soil from the shaft. For this reason, the diameter-to-projection ratio is not thought to be as critical as it would be were this condition not present.

The cells were secured to the wall of the shaft by driving four nails partially into the soil 4 to 6 inches away from the cell and securing soft wire to them. The wire was looped around the cell and the nails were then driven completely into the soil to obtain a snug fit of the gage face against the soil. Care was taken at this point to see that the cell face was parallel with and not oriented at some angle to the vertical, a difficult task to accomplish under field conditions. The four nails used to secure the gage to the shaft wall were oriented at 45^{o} to the vertical with respect to the gage

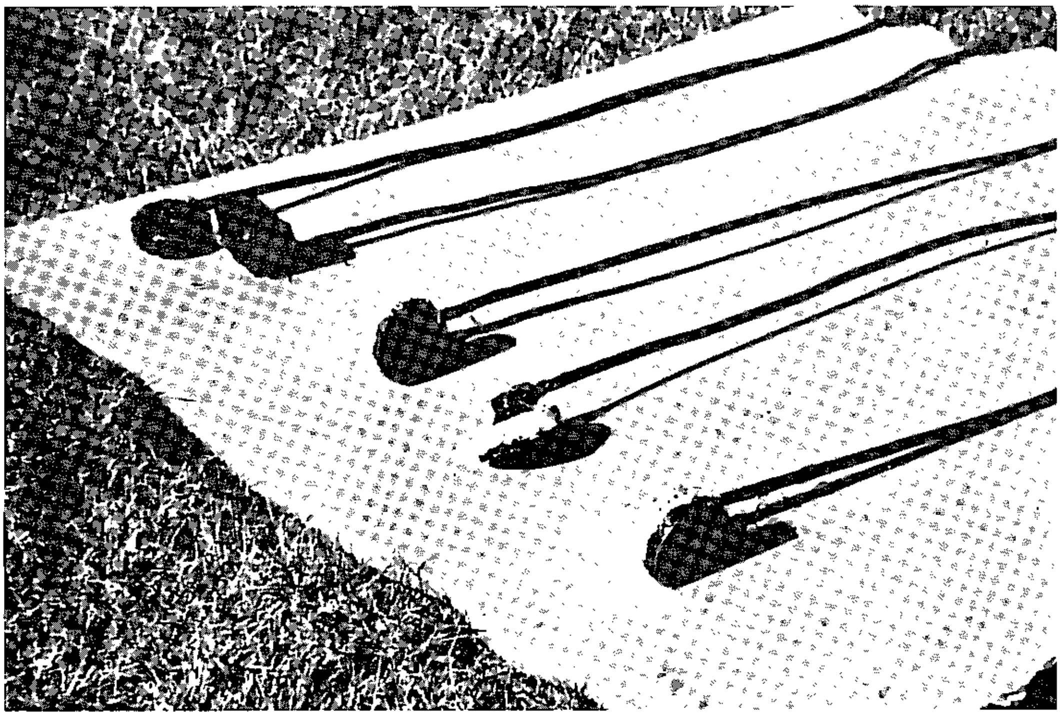


Fig 35. Cells ready for installation in Austin shaft.

center and 90° apart in order to avoid effects of the nails on stress distribution during axial loading.

The soil data for the locations of the pressure cells in this shaft are shown in Table 7. It can be seen that the soil is very stiff. Peattie and Sparrow (Ref 7) state that the most accurate pressure readings from cells will be obtained when the natural moisture content is close to or at the plastic limit. Therefore, it would be desirable if the soil in the field were more plastic, but this cannot be controlled if the true pressure conditions are to be maintained also.

With the installation of the lateral pressure cells, the stress reinforcing cage, preinstrumented with equipment to measure vertical strains in the shaft, was set in place. Temporary wooden strips were used to center the cage as it was being lowered and to prevent the cells from being scraped from the walls. The other instrumentation was affixed to the cage in such a way that it would be located at the same levels as the lateral pressure cells. This instrumentation will be discussed in detail in a future report.

Readings were taken before and immediately after the cells were installed in the shaft. The concrete was then poured, and cell readings were taken immediately.

Cure Period. Cell readings were taken daily for about ten days and less frequently thereafter. Resistance to ground was carefully checked each time readings were made (see Table 8). Cell No. 2 at 10 feet was the only cell which consistently maintained a high resistance to ground. Cell No. 3, although remaining in operating condition, developed a low resistance to ground after about three days and continually gave increases in pressure readings in the compression direction for some four or five months. This change became so great that there was no question that the gage was drifting. The other cells struck a medium between these two in operation. Observing Cell No. 2 at 10 feet, which has given every indication of being capable of the most consistent long-time and short-time readings, a maximum expansion force of concrete of some 8.5 psi was seen two days after pour. The forces then began to decrease, and some five to six days after pour the original pressure was again reached. The pressure continued to decrease slowly, reaching a minimum of some 2.5 psi less than the original some 19 days after pour. The pressure then slowly returned to the point of zero pressure prior to pour.

TABLE 7. SOIL PROPERTIES AT LOCATIONS OF UT LATERAL PRESSURE CELL IN AUSTIN SHAFT

Location	Description of Soil	Attenberg Limits % Liquid Limit	Attenberg Limits % Plastic Limit	Natural Water Content w %	Saturated Unit Weight lb/ft^3	Unconfined Shear Strength c t/ft^2	Strain at Failure %
6 ft	Gray and tan clay with small calcareous materials	45.7	24.6	19.7	132	1.90	1.5
10 ft	Tan clay with small calcareous materials	44.3	19.5	14.4	139	2.70	---

TABLE 8. RESISTANCE TO GROUND OF PRESSURE CELLS IN AUSTIN SHAFT

	Resistance in Meg-Ohms						
Date:	8/18/66	8/21/66	8/29/66	9/9/66	9/20/66	11/28/66	2/3/67
Cell							
1	10	5	7	8	50	20	100
2	100,000	5,000	5,000	5,000	5,000	10,000	5,000
3	50	5	4	5	1	0.6	7
4	10	8	8	20	50	80	700
5	300	100	60	10	100	0.5	0.2

The cure-period data as a whole could be considered quite erratic. Some gages showed pressure relief at the interface, while others showed increases. Other than on the basis of resistance to ground, conclusions as to whether or not the readings are correct would be completely out of the question at this point. Figure 36 shows the readout equipment.

Load Tests. Eight axial-load tests were carried out on this test shaft. In the first three, loads were carried to 40 tons and in the fourth, to 20 tons. In the final four tests, load was applied until there was continuous settlement with no increase in load. This failure load occurred in the range of 150 to 160 tons.

Data obtained from the pressure cells during testing can be put in the same category as those obtained during cure and under zero-load conditions. The cell which displayed the most stability prior to loading (No. 2) gave greater output during testing than any other except the commercial pressure cell. Even though the resistance to ground was low for the commercial cell (No. 5), causing the data to be something less than reliable, the load-test data obtained from it were used for comparison with Cell No. 2. This type of behavior can be expected with this cell, since it is considerably smaller and is an unbonded strain gage. The cells giving the least test response were the same cells which had low resistances to ground and apparently drifted the most.

Although conclusions would be out of the question at this point also, several generalizations can be made from the load-test data. Representative data plots for the failure-load tests can be found in Appendix D for Cells No. 2 and 5, located at 10 feet. Plots are for each individual cell, as the plot for any one cell will not necessarily be related to that for another except by the applied axial load. This is because of the many variables that can cause variations in the pressure over the surface of the shaft. Many more cells than were installed in this shaft would have to be installed to define this distribution.

There are two or three statements which can be made about the data up to this point. First, with each succeeding load test a lower maximum increase in pressure over the no-load condition immediately prior to each individual load was observed. It was also observed that the lateral pressure usually began increasing considerably in the neighborhood of 80 tons of load, which

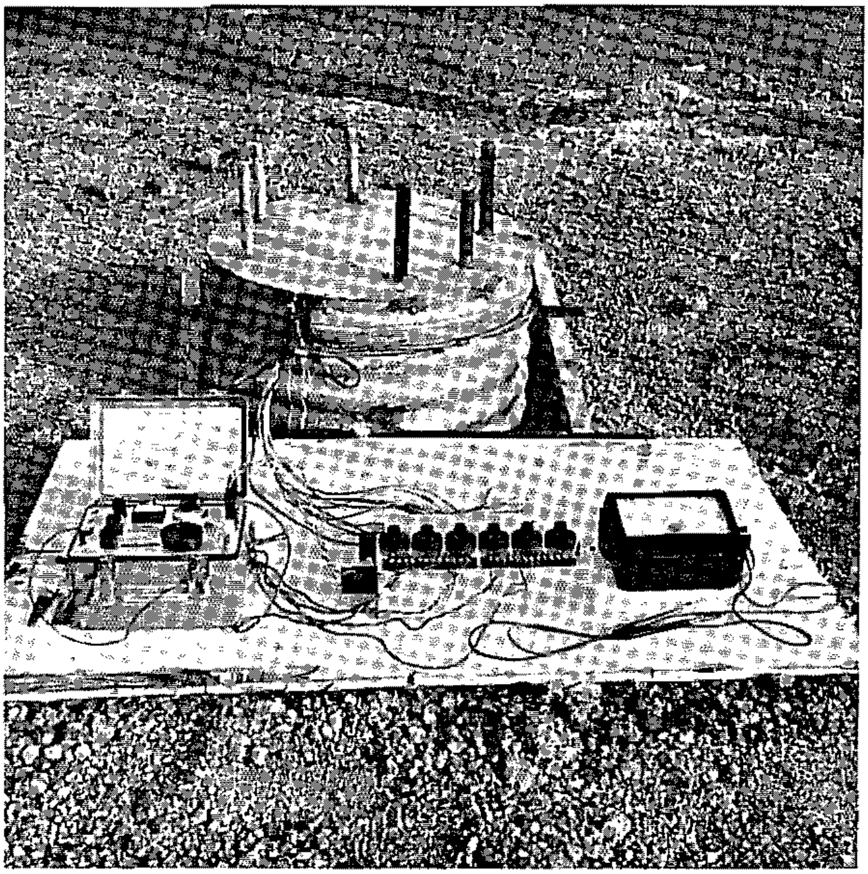


Fig 36. Readout equipment at Austin site.

was the bearing load predicted by the Texas Highway Department Dynamic Cone Penetration Test and also by Skempton's Theory for bearing capacity for foundations in clay. In general, the lateral pressures continued to increase until the maximum axial load, 150 to 160 tons, was reached or until just before it was reached. These maximum changes in pressure varied from 135 psi on Test 5, the first test going to 160 tons, to 59 psi on Test 8, the last test. Maximum pressure changes on Cell No. 5 were from 119 psi on Test 5 to 28 psi on Test 8.

Although the purpose of this shaft was not to obtain conclusive interaction data but rather to test out the instrumentation, several starting points for correlation have been defined. Also, the lateral cells are giving "reasonable data" in that lateral pressure begins building up about the time the predicted maximum bottom load is reached and continues to build up until failure. With more testing, some definite conclusions should be possible. Figure 37 shows the readout system in use during a load test, and Figure 38 shows an overall view of the test setup.

Field Use - San Antonio

The San Antonio test shaft, 30 inches in diameter by 28-1/2 feet in length (27 feet into the ground and 1-1/2 feet about the ground), had four UT lateral pressure cells installed in it. Cells No. 7 and 8 are located at a depth of 13 feet, and Cells No. 9 and 10 are located at a depth of 18 feet. The soil data at these levels show (see Table 9) that the soil is a stiff clay.

Installation. The gages at each level were placed 180° from each other, with Cell No. 7 directly above No. 9 and Cell No. 8 directly above No. 10. A man was lowered into the shaft to install the gages manually, as in the Austin shaft. The apparatus used to lower the man into the shaft is shown in Fig 39. In Fig 40 the cell leads are shown protruding from the open excavation after installation.

The cells were read at zero pressure before and after being installed in the shaft but before concrete was poured. All cells had a diameter-to-projection ratio of greater than 30, since they were all placed flush with the wall. Concrete was poured after the reinforcing cage was installed, and readings were taken immediately. As before, levels of instrumentation to measure vertical strains in the shaft coincided with the levels of the lateral pressure gages.

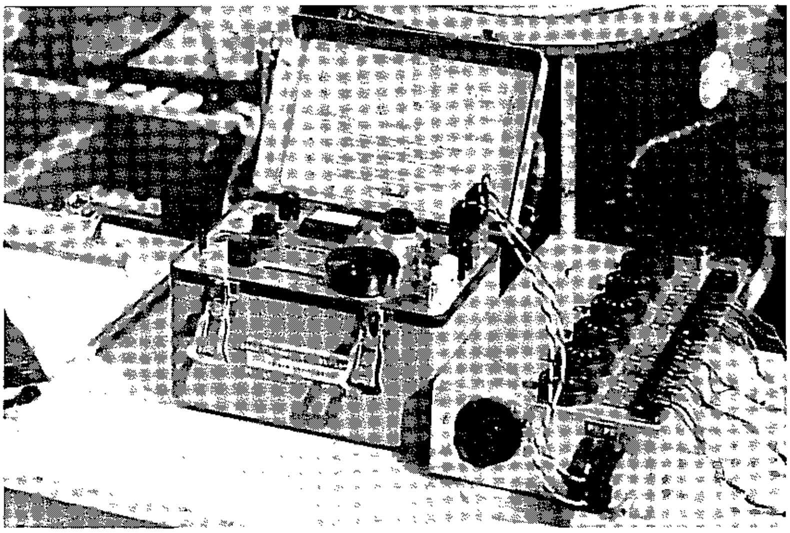


Fig 37. Readout system in use at Austin site.

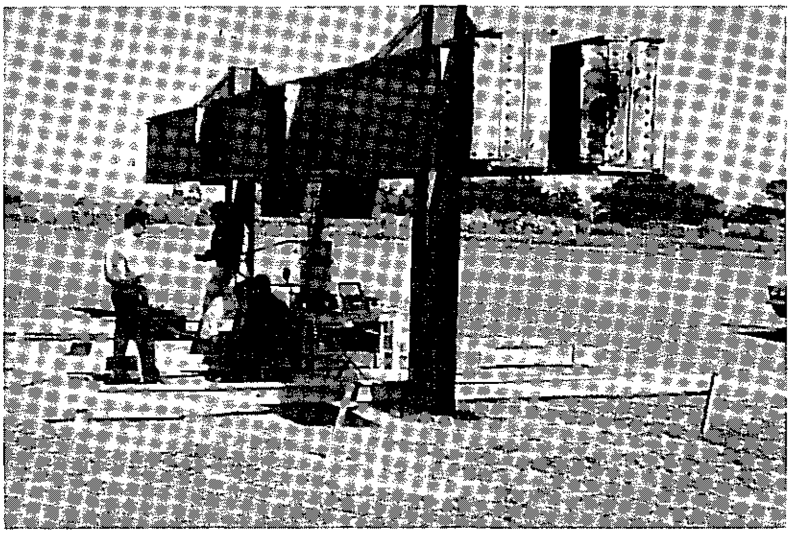


Fig 38. Overall view of Austin test site.

TABLE 9. SOIL PROPERTIES AT LOCATIONS OF UT LATERAL PRESSURE CELLS IN SAN ANTONIO TEST SHAFT

Location	Soil Description	Attenberg Liquid Limit	Limits % Plastic Limit	Natural Water Conten w %	Unconfined Shear Strength c t/ft^2	Strain at Failure %
13 ft	Yellow clay with shale	68.8	28.3	20.0	3.38	2.0
18 ft	Yellow and gray clay with shale	68.8	27.8	20.0	1.71	2.0

Fig 39. Apparatus used to lower man into San Antonio shaft to install cells.

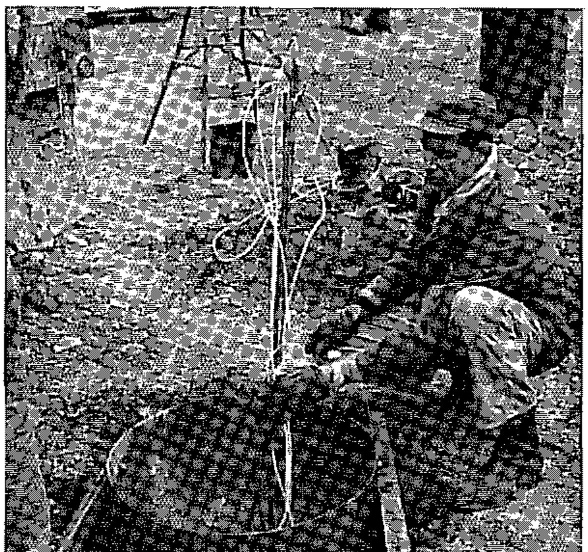


Fig 40. Cell leads protruding from San Antonio shaft after installation.

TABLE 10. PRESSURE CHANGE DURING CURE OBSERVED BY PRESSURE CELLS IN SAN ANTONIO SHAFT

	Pressure, psi								
Date:	1/18/67 (Pour)	1/19/67	1/20/67	1/21/67	1/30/67	2/10/67	2/16/67	2/23/67	4/10/67
Cell									
7	4.9	5.6	6.0	6.1	6.6	5.8	5.0	6.0	6.4
8	3.8	---	---	---	---	---	---	---	---
9	6.7	2.3	-1.8	-2.3	-2.0	-0.6	0	0	4.1
10	7.3	-0.3	-1.3	-1.1	-1.6	-0.6	+.33	-0.2	+.7

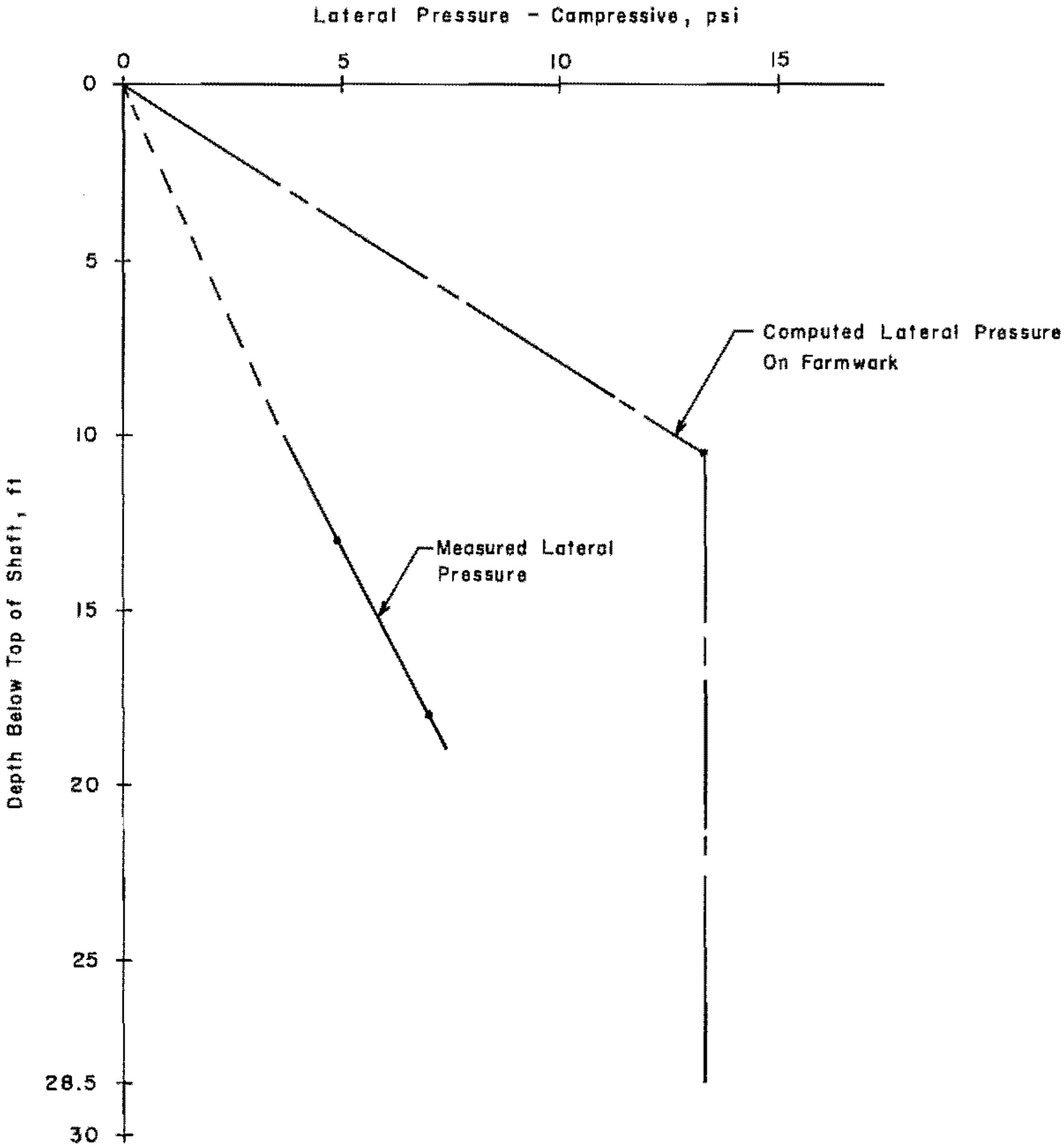


Fig 41. Lateral pressure distribution immediately after pouring, January 18, 1967.

TABLE 11. RESISTANCE TO GROUND OF PRESSURE CELLS IN SAN ANTONIO SHAFT

	Resistance in Meg-Ohms				
Date:	1/18/67	1/20/67	1/24/67	2/10/67	4/10/67
Cell					
7	100,000	1,000	5,000	1,000	800
8	5,000	1	.002	.01	.008
9	50,000	2,000	10,000	8,000	8,000
10	50,000	5,000	100,000	8,000	9,000

Cure Period. Cell pressure readings were taken daily for about the first 10 days of cure, after which the cells have been read periodically (see Table 10). The average lateral pressure against the cells immediately after pouring is plotted in Fig 41. For comparison, the standard plot using the (ACI) expression for pressure on formwork is also shown in Fig 41 (Ref 26). Again, close check was kept on the ground resistance of the gages (see Table 11). All but one cell maintained good stability and resistance to ground during the first 24 hours of cure. This cell has become inoperative. All other cells have had a consistently high resistance to ground thus far. These cells were first sealed with Pliobond cement and then waterproofed as previously discussed.

The seal may have been too efficient on Cells No. 9 and 10. The temperature above the ground was some 36^{o} F when the cells were installed. The temperature of the concrete at the level of the cells reached about 95^{o} F during the first 24 hours of cure. Within 48 hours, Cells No. 9 and 10, which had originally gone into compression, had come back through zero pressure and were showing a small pressure decrease. This was probably because the concrete had set and, thus, had removed a small amount of pressure from the cells. Cell No. 7 went into compression upon pour and has remained there ever since, though compression has decreased somewhat. The amount of compression registered by Cell No. 7 is about 5.5 psi. Cells No. 9 and 10 registered in the neighborhood of 7 psi compression immediately after pour but have returned to the original zero reading.

Present data indicate that Cells No. 7, 9, and 10 will produce reliable results. This is a tremendous improvement over the Austin shaft. Figure 42 shows the readout equipment connected to the leads while resting on top of the shaft. At the time of this writing there have been no load test performed at the San Antonio site.

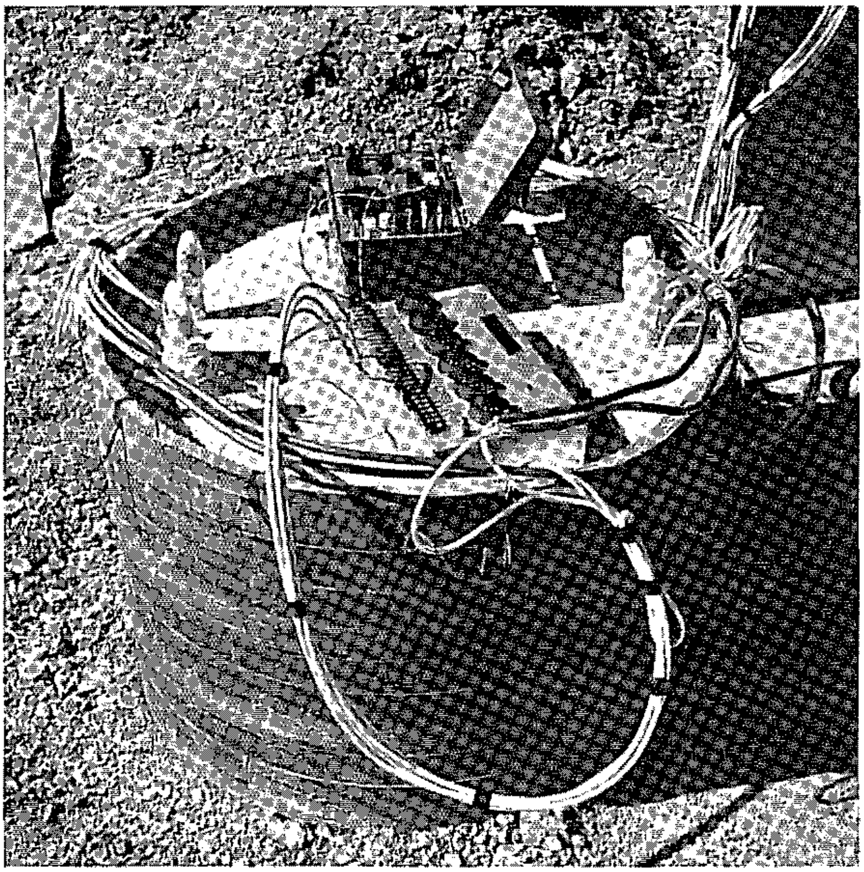


Fig 42. Lateral pressure-cell readout equipment with San Antonio test shaft.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this portion of the project was to design, construct, and test instrumentation for measuring the distribtution of lateral earth pressure along a drilled shaft. The design and construction were accomplished, and some laboratory and field testing conducted. A cell capable of making the necessary measurements with reasonable accuracy has been developed.

Several conclusions and recommendations can be made on the basis of the work conducted in the course of this project.

Conclusions

(1) The dimensions of the UT cell are satisfactory.

(2) The small commercial pressure transducer is not satisfactory for measuring pressure along a drilled shaft.

(3) On the basis of testing thus far, it is uncertain whether strain-gage pressure cells can be used to measure lateral earth pressures over long periods of time.

(4) On the basis of testing, strain-gage pressure cells can be used with confidence to measure pressure changes during a load test.

Recommendations

(1) When using the pressure cell, it must be installed flush with the wall of the drilled shaft and intimate facial contact with the soil must be assured.

(2) The diameter-to-projection ratio of the cell from the shaft is critical, since the failure surface may not be at the soil-shaft interface.

(3) Many lateral pressure cells should be installed to obtain a representative picture of the pressure distribution along a drilled shaft, since significant pressure variations exist over the shaft wall (Ref 23).

(4) A pocket of some material such as sand should not be placed in front of the cell face.

(5) If the natural water content of the soil surpasses the plastic limit, the pore-water pressure should be measured.

(6) A larger soil calibration chamber than that described in Chapter 4 should be used.

(7) Further studies of the cell with various soils acting against it should be made.

(8) If the split-ring soil calibration chamber is used, the stress in the rings should be measured, as should the vertical compression of the soil.

(9) Pressure cells to measure lateral earth pressure should be designed for a working pressure of 1 psi per foot of depth. At this working pressure the cell should be designed to take a maximum pressure at least three times the working pressure.

(10) Resistance to ground should remain above 50 meg-ohms in order to maintain confidence in the cell.

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APPENDIX A

EQUATIONS FOR RADIAL AND TANGENTIAL STRAIN AND CENTERLINE DEFLECTION FOR A CLAMPED-EDGE DIAPHRAGM

APPENDIX A. EQUATIONS FOR RADIAL AND TANGENTIAL STRAIN AND CENTERLINE DEFLECTION FOR A CLAMPED-EDGE DIAPHRAGM

The following equations describe the behavior of a clamped-edge diaphragm. These equations are functions of the dimensions and material properties of the diaphragm and the normal pressure applied to it (Ref 21).

Radial Strain

$$\epsilon_r = \frac{3q}{8h_d^2E}(1 - \nu^2)(a^2 - 3r^2) \tag{A.1}$$

Tangential Strain

$$\epsilon_t = \frac{3q}{8h_d^2E}(1 - \nu^2)(a^2 - r^2) \tag{A.2}$$

Centerline Deflection for a Plate

$$\delta = \frac{3qa^2}{16Eh_d^3}(1 + \nu)\left[4h_d^2 + a^2(1 - \nu)\right] \tag{A.3}$$

where

q = normal pressure, psi,

h_d = diaphragm thickness, inches,

E = Young's Modulus of Elasticity, psi,

ν = Poisson's ratio,

a = radius of plate, inches,

r = radius to point of interest, inches.

The assumption is that the slope of the deflected plate is zero at $r = o$ and at $r = a$.

APPENDIX B

PREPARATION OF THE CELL DESIGN MAPS

APPENDIX B. PREPARATION OF THE CELL DESIGN MAPS

Centerline Deflection/Diameter Lines

Dimensions and material properties assumed for beryllium copper, steel, and aluminum are shown on the design maps in Chapter 3.

The equation for centerline deflection for a plate, given on the previous page, was programmed for the computer. The variables are the diaphragm dimensions, the normal pressure, and the material properties. Deflection-to-diameter ratios must be used to calculate maximum allowable centerline deflections δ for any given pressure. This equation for maximum centerline deflection is

$$\frac{\delta}{D} = \overline{R} \tag{B.1}$$

where

δ = maximum centerline deflection,

D = sensitive diameter,

$\overline{R}$ = desired ratio (1,000, 10,000, etc.).

Sensitivity Lines

The radial and tangential strain equations were integrated with respect to dr/r to obtain the strain measured by the diaphragm strain gage.

Radial Strain

$$\varepsilon_r = \frac{3qa^2}{8Eh_d^2}(1 - \nu^2)(1 - \frac{3r^2}{a^2})$$

Let

$$K_1 = \frac{3qa^2}{8E} (1 - \nu^2)$$

Then

$$\epsilon_r = K_1 \frac{1}{h_d^2} \int_{r_1}^{r_2} \left(1 - \frac{3r^2}{a^2} \right) \frac{dr}{r}$$

$$\epsilon_r = \frac{K_1}{h_d^2} (\ln r_2 - \ln r_1) - \frac{3K_1}{2a^2 h_d^2} (r_2^2 - r_1^2) \qquad (B.2)$$

Tangential Strain

$$\epsilon_t = \frac{3q}{8h_d^2 E} (1 - \nu^2)(a^2 - r^2)$$

Let

$$K_2 = \frac{3q}{8E} (1 - \nu^2)$$

Then

$$\epsilon_t = K_2 \frac{1}{h_d^2} \int_{r_1}^{r_2} (a^2 - r^2) \frac{dr}{r}$$

$$\epsilon_t = \frac{K_2 a^2}{h_d^2} (\ln r_2 - \ln r_1) - \frac{K_2}{2h_d^2} (r_2^2 - r_1^2) \qquad (B.3)$$

When using the four-arm bridge, two in tension (tangential) and two in compression (radial), the apparent strain will be the absolute sum of each of the actual strains. The average measurement has been found by integrating the equations between the radial limits as determined by gage placement. The limits are measured from the physical dimensions of the gage and diaphragm. To obtain the measured strain, the radial and tangential strains are combined in the following manner:

$$\varepsilon_{total\ measured} = 2.0 \times (|\varepsilon_t| + |\varepsilon_r|)$$

or

$$\varepsilon_{tm} = 2.0\ (\varepsilon_t - \varepsilon_r) \qquad (B.4)$$

The multiplier 2.0 is necessary, since there are two tangential and two radial gages. Otherwise, sensitivity for only one radial and one tangential gage will be obtained. The gage factor of the diaphragm gage must be approximately 2.0, since the measured strain using a gage factor of 2.0 is very close to this calculated strain. A graphical solution of this equation checks very well with the integration method (Fig 9) where

r_1 = inner radius, linear radial gage,

r_2 = outer radius, linear radial gage,

r_3 = inner radius, spiral tangential gage,

r_4 = outer radius, spiral tangential gage.

APPENDIX C

READOUT SYSTEM

APPENDIX C. READOUT SYSTEM

With several cells installed in a drilled shaft, a system for rapid readout becomes a practical necessity. The change in resistance of the diaphragm strain gage, given by Eq 3, is transmitted through the cables to the Budd, Model P-350, portable digital strain indicator located adjacent to the shaft on the surface. The operator must manually balance the nullmeter on the strain indicator, and by observing the digital indicator can determine the number of micro-in/in of strain change that was experienced by the gage on the diaphragm. By applying the linear calibration constants, the change in pressure can be determined.

In order to read multiple cells without attaching and detaching the cells individually with each reading, a six-channel switch and balance unit was constructed (Fig C.1) to which the cell leads were attached. Commercial switch and balance units are available; however, several features were desired which could not be obtained on a commercial unit. An additional reason for building the special unit was to avoid the problem associated with having to share it with other projects being conducted at The University of Texas.

The features of this switch and balance unit deserve some explanation. Cell leads coming out of the shaft are connected by pairs to terminal boards two and three on the right side of Fig C.1. Consider the leads numbered one through four at one end of TB2. One pair of leads, opposite corners of the bridge, is connected to P_1 and P_2, while the other pair is connected to S_1 and S_2. Power is supplied to the strain gage from the P_1 and P_2 connections, while the gage output comes from connections S_1 and S_2. A potentiometer is put into the circuit to allow initial balancing of the strain gages to a given strain-indicator setting. This channel balance control is denoted for the circuit in question as RV-1. It is a Borg, "micro-potentiometer," model 2151B, 10 turn, 10K ohm resistance with 0.25 percent linearity. A 10 turn, concentric-scale "Microdial," series 1320, with 100 divisions per turn with lock is used on this potentiometer in order to assure

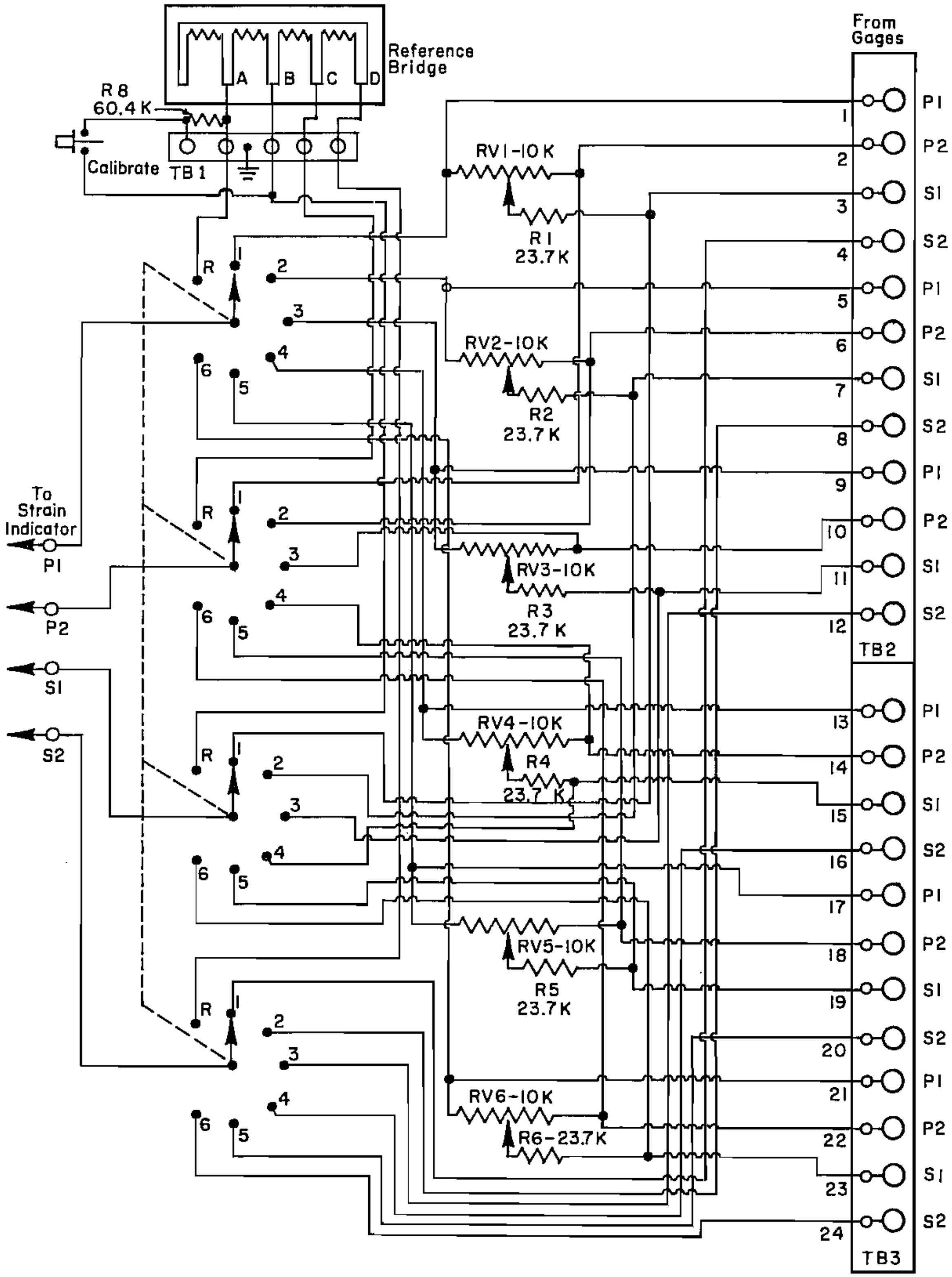

Fig C.1. Six-channel switch and balance unit.

the same setting each time the unit is used. Balance sensitivity resistors of 23.7K ohms and one percent tolerance were used to fix the sensitivity of the potentiometer in balancing all gages at the same strain reading. This resistor is denoted by R1 in channel one.

The leads from channel one are then connected to position one on the switch as shown. All six channels are connected to the switch, positions one through six, as is the reference bridge denoted by R. There are seven, four-pole positions on this switch. The switch is a Daven No. 642-DB-8 shorting-bar type switch with 1/8-inch-diameter gold-plated contacts. This is a very high quality switch and is necessary in a critical strain-gage circuit to insure repeatable contacts.

The reference bridge consists of a four-arm, Wheatstone bridge made of 1/4-inch SR-4 linear strain gages mounted with Eastman 910 cement on a 1-3/4 by 2-1/2 by 3/4-inch hot-rolled steel block. This steel block is mounted on the chassis by the use of one screw threaded part way into the block. When only one screw is used on such a heavy steel block, there should be no stress changes in the block to affect the bridge. This bridge is used to set the indicator to a given zero strain value at the beginning of each test, since there is a balance control on the strain indicator which does not have a locking, calibrated dial and could be changed without the knowledge of the operator. If this were done, absolute strain readings could not possibly be obtained. As a check on the stability of the indicator itself, a resistor, R8, of 60.4K ohms is shunted across poles A and B of the reference bridge by use of a momentary contact pushbutton switch. This resistor will produce a step of nearly 1,000 micro-in/in on the strain indicator. By use of the step, any drift of the indicator due to temperature or weak batteries can be detected. A similar check can be obtained by reversing the gage connections and obtaining a sign change from minus to plus in the strain reading (Ref 25).

External connections to the strain indicator are made with 1/4-inch "banana" jacks. Gage connections are made with Cinch-Jones series 140 barrier strips.

The advantages obtained from this unit that could not be obtained commercially were the presence of the reference bridge used as a check on the indicator and the high quality switch.

APPENDIX D

AUSTIN SHAFT LOAD-TEST RESULTS

APPENDIX D. AUSTIN SHAFT LOAD-TEST RESULTS

Figures D.1 and D.2 show the load-test results for Cells No. 2 and 5. These results are for Tests 5, 6, 7, and 8, which were the only tests carried to "failure." The point of zero pressure change represents the existing pressure at the beginning of each test. The data were discussed in Chapter 5 under Austin Load Tests.

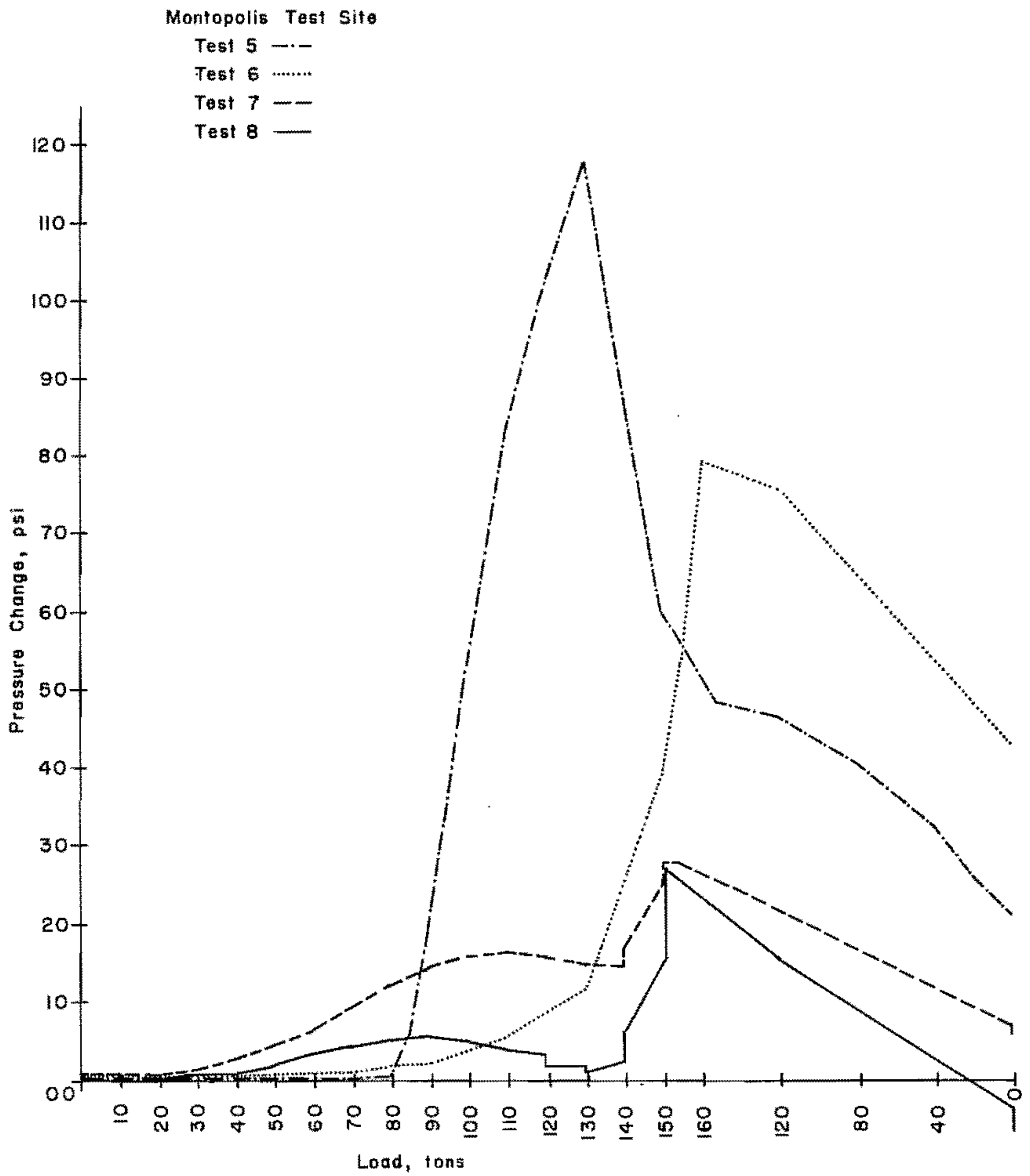

Fig D. 1. Behavior of Cell No. 5 during load tests at 10-foot depth in Austin shaft.

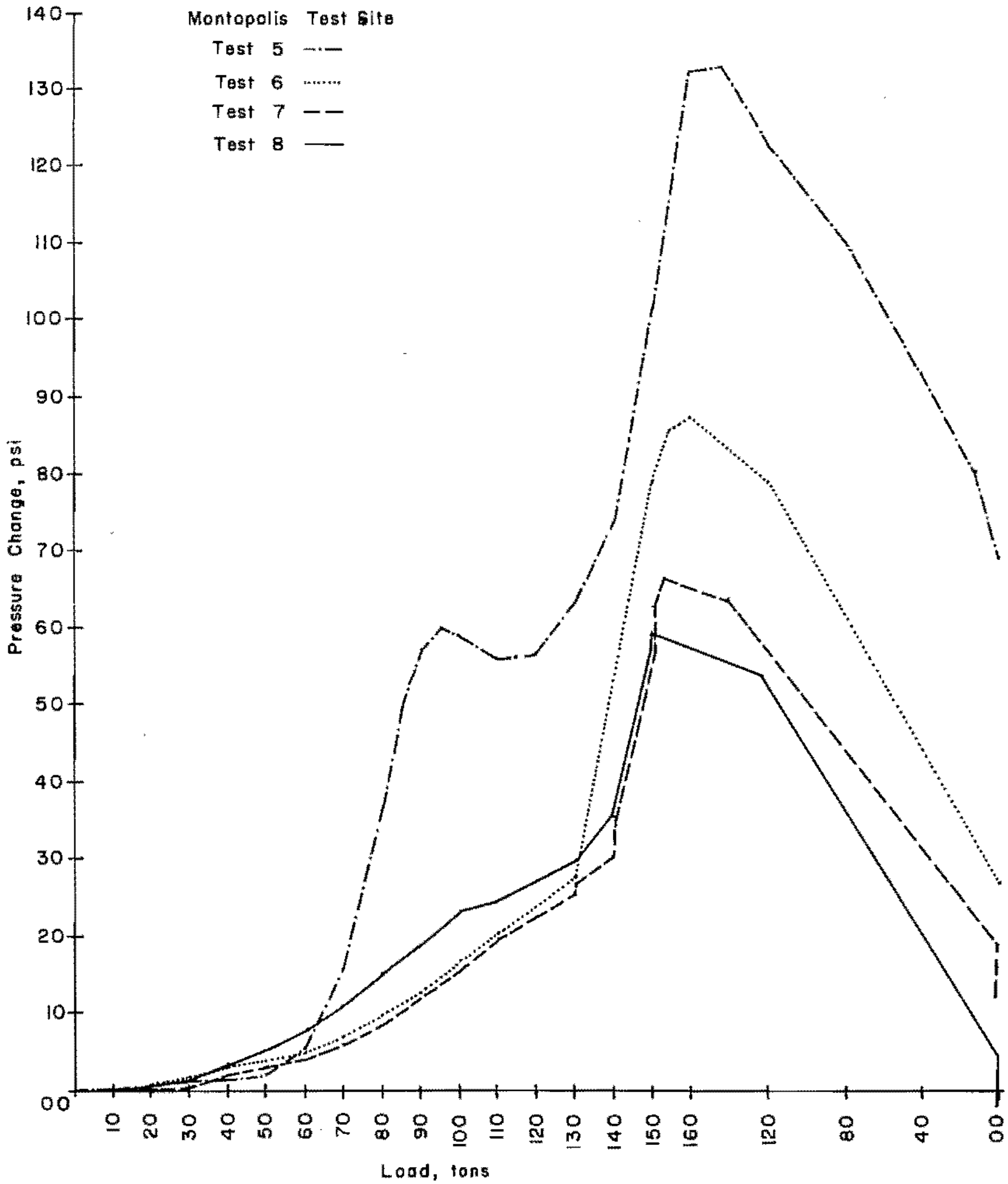

Fig D.2. Behavior of Cell No. 2 during load tests at 10-foot depth in Austin shaft.