Earth pressure cells: design, calibration, and performance

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EARTH PRESSURE CELLS
DESIGN, CALIBRATION AND PERFORMANCE

BY

J. J. HAMILTON

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PREFACE

The measurement of earth pressures is regarded as one of the most difficult field measurements in soil engineering, requiring a combination of careful instrumentation and skillful installation. In anticipation of a research project involving earth pressure measurements, the available literature was reviewed in order to establish the most suitable equipment and techniques for the work.

This report outlines the problems and difficulties of earth pressure cell design and operation. It describes the operating principles of several types of earth pressure cells and measuring instruments. With this background, the selection of a cell for a specific purpose is discussed.

The author of this paper, a research officer in the Soil Mechanics Section, has, for some time, been investigating various soil testing techniques.

Ottawa
November 1960

Robert F. Legget
Director

EARTH PRESSURE CELLS

Design, Calibration and Performance

by

J. J. Hamilton

The use of earth pressure cells to determine directly the stress distribution within earth structures and foundations has been promoted for two main reasons:

1) to check the theories of stress distribution employed in the design of earth structures and foundations, and to assess the assumptions which are made in these theories, and

2) to provide measurements in prototype studies in cases where the theoretical approach becomes too complicated or uncertain.

The art of measurement of earth pressures with cells has been and still is necessarily a semi-empirical approach to an extremely complex problem. The principal achievement of the work of the last fifty years has been to point out the importance of several of the variables involved and to build up confidence in the use of certain cells designed to measure pressures under sets of prescribed conditions.

Over one dozen different cell designs have been tested fairly extensively in the field and the results of these investigations have been reported in the literature. Some of these cells have proven to be satisfactory, others required modification to give desired results, while others have proven unsatisfactory and have been abandoned. This report has been prepared following a review of the better known references on this subject.

GENERAL CONSIDERATIONS

There are many considerations in the selection of an earth pressure cell to fill a particular need. Of the cells successfully used to date, none has proven to be a universal instrument capable of reliable measurements under all conditions. Greatest success has been had with cells designed specifically to operate within small ranges for the significant variables involved.

Probably the first two considerations of major importance in selecting an earth pressure cell are:

a) The type of load that the cell will be measuring, i.e. whether a dynamic load of short duration or an essentially static load, and

b) The way in which the cell is to be installed, i.e. whether installed in the face of a non-yielding structure or installed within an earth mass.

The former consideration will have great bearing on the type of gauging system used to measure and record the stresses, the latter will influence the over-all dimensions and physical characteristics of the cell.

In the design of any earth pressure cell several interdependent factors must be balanced to meet the particular needs of specific installations. Usually the pressure range to be measured, the sensitivity to small pressure changes, the desired longevity, the ruggedness and salvability of the cell are all factors which must be considered in the selection of materials and in the physical design of the cell. The elastic and metallurgical qualities, especially corrosion resistance, and the possibility of differential thermal expansion between different metals must be carefully considered. The frequency and ease of reading the pressure gauging system will be important factors in the design of this part of the cell. In cells designed to measure dynamic stresses the response time of the gauging system may be one of its most critical characteristics. The importance of the cell's reliability and maintenance of calibration will be governed to a certain extent by the accessibility of the cell and ease with which adjustments and checks can be made. The effects of temperature changes on the calibration characteristics of the gauge may be of significance in certain applications.

DIFFICULTIES IN OBTAINING DEPENDABLE PRESSURE MEASUREMENTS

Taylor (1) outlined the following reasons why earth pressure measurements by cells may not be accurate indications of in situ conditions.

1. Inherent Scattering.- Due to the local point-to-point variations in all soil properties, a pressure reading taken at a point in the soil mass probably will not be "within a few per cent of the statistical average value". An idea of

the range of scatter can be obtained by taking a number of readings at random points through the strata. The degree of precision of the average from these random readings will be a function of the number of readings taken.

2. Cell Action.- The changes in pressure distribution around an earth pressure cell due to the presence of the cell in the soil mass was called "cell action" by Taylor. This action is the result of the difference in compressibility of the relatively rigid cell and the compressible soil mass in which it is placed. The over-registration of an earth pressure cell is proportional to the ratio of the cell half-thickness to the cell diameter and can be predicted fairly closely by a formula presented by Taylor:

$$p_c = C\,p\,\frac{B}{D}$$

when

p_c = pressure registered
p = pressure that would exist at the cell location if the cell were not present
B = half-thickness of the cell
C = a soil characteristic lying between 2.0 and 1.0 for cohesionless to lightly cohesive soils and which is probably smaller in clays because of their plastic characteristics
D = diameter of the cell.

3. Unsatisfactory Mechanical Performance of Cells or Associated Apparatus.- Taylor expressed the idea that cells should be as nearly mechanically perfect as possible to help eliminate this possible source of inaccuracies.

4. Pocket Action and Cover Action.- Taylor coined these two terms to cover cases in which incorrect pressure readings result from densities or compressibilities in the soil adjacent to the cell that are different from those of the stratum as a whole. "If the soil immediately surrounding a cell is of lower density than the statistical average value for the adjacent soil, the cell reading will be the pressure that exists in a soft spot, and this pressure may be only a small fraction of the correct or statistical average pressure. This condition is termed 'pocket action'. If zones of low density occur above or below the cell, the resulting condition is called 'cover action'". Extreme care in placing and backfilling earth pressure cells is essential to minimize the inaccuracies introduced by these actions.

CELL DESIGN CONSIDERATIONS

Benkelman and Lancaster (2) and the U.S. Waterways Experiment Station (3) reported that:
"Flat cylindrical cells embedded in rigid materials would indicate true pressures provided that the diameter-projection ratio exceeded 30 and the diameter-deflection ratio exceeded 1000. For cells embedded in the soil mass, the diameter-thickness ratio should exceed 5 and the diameter-deflection ratio should exceed 2000."

Peattie and Sparrow (4) comment on these investigations as follows: "Both these experimental investigations were of limited value because of the unrepresentative nature of the soils and the fact that the soil masses were small in regard to the size of the cells." Then they conclude from the results of their studies: "No design for a cell will eliminate errors completely except in the unlikely case where the cell modulus exactly matches that of the soil and the latter remains constant. However, the errors can be reduced to small and predictable proportions by fulfilling the following criteria:

a) The error has been shown to be directly proportional to the thickness-diameter ratio of the cell, and hence this should be kept as small as possible.

b) The error is dependent on the ratio of the sensitive area of the cell face to the total facial area. For cells of diameters up to 4 inches the following proposals are made. If the cell design is such that the pressure is averaged over the responsive area, the ratio of sensitive area to total facial area should be less than about 0.25. If the cell has a pressure responsive diaphragm such as the "standard" cell this ratio should be less than 0.45.

c) Errors caused by the modular ratio E_g/E_s are not very large and it is variations in the value of the ratio which are more liable to be troublesome. The cell should be as incompressible as possible with a modulus ratio in excess of about 10. Most cell designs would appear to be incompressible when compared with the compressibility of soils. If these criteria are fulfilled, the general equation for cell action becomes

$$\frac{P_c}{p} = 1.2 \frac{B}{D} ."$$

where P_c, p, B and D have been defined by Taylor and included earlier in this report.

Types of Cells

Peattie and Sparrow (5) have outlined three basic types of earth pressure cells and four basic gauging systems used in earth pressure cells. Earth pressure cells can be grouped into one of the following types:

1. Direct acting.- In this type of cell the soil acts directly on the portion of the cell carrying the gauging system.

2. Indirect acting.- In a cell of this type the soil acts via a fluid on a second pressure-responsive element.

3. Counteracting.- A counter fluid pressure is applied to the pressure-responsive element to balance the soil pressure.

Types of Gauging Systems

The gauging systems used in earth pressure cells can be placed in one of the following four groups:

1. Mechanical gauging systems, e.g. levers, extensometers, friction-tapes, and friction plates,

2. Hydraulic gauging systems, e.g. manometers and Bourdon gauges,

3. Acoustic gauging systems, e.g. vibrating wire,

4. Electric gauging systems, e.g. electrical resistance, reluctance, inductance or capacitance systems.

Types of Cell Covers

Kallstenius and Bergau (6) discuss several types of cell covers, their advantages and disadvantages. Briefly, they are as follows:

1. Plane rigid piston type

Advantages - suitable for taking eccentric loads; produces maximum change in displaced volume for a given travel.

Disadvantages - very steep stress gradients at the edge of the piston; great thickness required to obtain "rigidity" of the piston.

2. Flexible membrane built in at its periphery

Advantages - because an eccentric load causes a smaller deflection then a centric load of the same magnitude, the membrane is less sensitive to minor disturbing factors near the periphery; since the deflection curve is continuous the stresses in the soil are more uniform.

Disadvantage - an eccentric load causes a smaller deflection than a centric load of the same magnitude and readings may be thrown off calibration seriously.

3. Hydraulically supported rubber membrane

Advantage - equalization of stresses in the soil

Disadvantages - great and uncontrollable normal travel may occur in the surface of contact if the stress conditions are very irregular (therefore not suitable for grainy materials); very steep gradients on the surrounding wall if the cover moves into the wall.

4. Modified types

A thin steel membrane resting on a fluid is a popular compromise between the piston and rubber membrane. Kallstenius and Bergau (6) suggest a rigid piston supported at the edge by a flexible ring.

CELLS DESIGNED TO MEASURE EARTH PRESSURES AT THE FACE OF RIGID STRUCTURES

Carlson Cell

Possibly the first cell used to measure earth pressures against rigid walls was the Carlson cell (3,7), an adaptation of the Carlson strain meter developed about 1930. It is an indirect-acting type of cell using an electrical resistance gauging system. Earth pressure acting on the flat circular face plate is transmitted by a confined liquid (Mercury) to a metal diaphragm. The deflection of the diaphragm actuates the strain meter. The Carlson strain meter consists of two electrical resistance wires coiled between insulators on the movable and fixed arms of the strain meter in such a manner that as strain develops, tension is increased in one coil and diminished in the other. The electrical resistance of the coils changes with the tension in the wire, and as these changes are opposite in the two coils, the effect is doubled. Since the resistance change is very small compared to the total circuit resistance, a precise bridge is required and the insulation of the cable must be particularly stable. Small resistance changes in the connector cables or splices may cause erroneous pressure indications or total failure of the meter. The successful use of these cells mounted flush in the face of rigid structures has been reported in the Vicksburg Report (3). With modifications in the dimensions of the cell, it could possibly be used for earth pressure measurements in a soil mass removed from any rigid structure.

Royal Swedish Geotechnical Institute Cell

Kallstenius and Bergau (6) report the use of an indirect-acting cell having hydraulic gauging system to measure earth pressures behind retaining walls and other rigid structures. The cell, designed and constructed in 1947 at the Institute, features a closed hydraulic system by which the soil pressure is transmitted to a Bourdon gauge at the point of observation. The cell is fitted with a rigid cover plate and has an electrical contact device which enables the track of the cell to be checked within certain limits. Its overall dimensions are: diameter 250 mm and thickness 38 mm. Following extensive calibration, the authors report successful application of this type of cell in the field.

Norwegian Geotechnical Institute Cell

Øien (8) reports the design and calibration and Kjaernsli (9) reports the results obtained with this vibrating-wire type of gauge which was specifically designed to be mounted flush with the outer surface of sheet piling driven into soft clay. Essentially, the cell consists of a diaphragm on which are mounted two arms holding a pretensioned steel wire, all enclosed in a rugged waterproof steel housing. Provision is made to force dried air through the housing and also to maintain atmospheric pressure in the housing by means of two plastic tubes which, along with the electrical cable, are brought to the surface of the ground. Deflection of the diaphragm due to earth pressure causes a change in the tension in the stretched wire which, in turn, changes the natural frequency of the wire which is set in vibration by an electromagnet.

The earth pressure cell was calibrated in a water-filled pressure chamber, as it was expected this would give essentially the same results as calibration by pressing the cell against soft clay. Øien reports an over-all accuracy of ±3 per cent of full load pressure (2.5 kg/cm^2). The sensitivity of the cell to small pressure changes is excellent but other factors such as hysteresis, zero drift, temperature variations and inaccuracy of frequency measurements, reduce the over-all accuracy.

CELLS DESIGNED TO MEASURE STATIC EARTH PRESSURES WITHIN EARTH MASSES

Goldbeck Cell

Goldbeck (3, 10) pioneered the field of earth pressure measurements with his cell, recorded in the literature in 1916. It was basically a counteracting type of cell employing a pneumatic-electrical contact gauging system. A cylindrical metal case having one open end was fitted with a metal piston which was held flush with the rim of the case by a thin metal diaphragm. The cell's dimensions were usually 5½-in. in diameter by 1½-in. thick. Electrical contact with the movable piston was made by an insulated electrical contact button fastened into the cell case. To measure the earth pressure acting on the cell, air pressure was applied to the chamber below the piston through a 1/8-in. diameter tube from the surface until electrical contact was broken (as indicated by an ammeter or light in the circuit). The air pressure required to raise the piston the small amount necessary to break contact was considered to be equal to the applied soil pressure.

The counter movement of the piston acted against the passive resistance of the soil which probably was greater than the static pressure prior to the movement. However, it was assumed that if the movement was small the pressure required was equal to the static soil pressure. Field studies of the cells indicated that cells which functioned satisfactorily in the laboratory gradually became inoperable in the field. The chief cause of failure of these cells was electrical short circuits or open circuits caused by collection of moisture in the cell due to leakage or condensation.

Waterways Experiment Station Pressure Cell

The WES cell (1, 2, 3) is an indirect-acting type employing SR-4 electrical resistance strain gauges. Pressure is transmitted from the soil through a face plate and oil-filled chamber to a machined steel diaphragm. Strain of the diaphragm is measured by the strain gauge mounted on its back. A second (dummy gauge), installed on a portion of the pressure cell not subject to strain, serves to compensate for temperature changes. The dimensions of the WES cell have changed throughout its development in order to fill different needs. The cells have ranged in diameter from 3 to 24 in. and in thickness from $\frac{1}{2}$ to $1\frac{1}{4}$ in.

Measurements of induced pressure are obtained either by a Wheatstone bridge or by a recording oscillograph depending on whether static or dynamic loads are to be applied. Calibration of the WES cell was carried out in a pneumatic chamber in which pressure is applied to the faces of the cell by rubber diaphragms. The usual problems encountered in the use of bonded resistance strain gauges such as zero drift, creep and temperature compensation must be considered in the use of the WES cell. The problem of electrical insulation is of major importance, because the resistance change to be indicated is extremely small in comparison with the circuit resistance. A resistance change occurs in pressure cell cables when the cables are subjected to various degrees of tension. Extreme care must be taken in the choice, installation, and maintenance of connector cables.

Swedish State Power Board Cell

Magnusson in 1948 (13) reported the use of an indirect-acting hydraulic earth pressure cell in the measurement of stresses in earth dams. The cell consisted of two stiff circular steel plates elastically connected by a pleated copper plate (forming a bellows). The chamber thus formed was filled with oil and connected by a brass tube to either a mercury manometer or spring manometer. The cell was 27 cm in over-all diameter and approximately 30 cm thick. The author reported satisfactory functioning of the cell for a considerable number of installations but calibration information is not given.

Kjellman Earth Pressure Cell

Magnusson (13) also reported the use of a counteracting hydraulic-type cell developed by W. Kjellman. Basically, this cell consisted of two steel plates sealed together and with provision made for these plates to be hydraulically jacked apart. The pressure required just to make these plates move against the earth pressure was measured by a manometer or pressure gauge. The cell diameter was 34 cm. The cell proved to be too delicate and ceased to function after a few measurements.

Johansson and Linde Electrical Capacity Cell

Magnusson (13) also reported the use of this cell in earth dams in Sweden. It consisted of two condenser plates separated by thin mica layers, all enclosed in a shell made up of two iron plates. The over-all diameter of the cell was 19.8 cm. Variations in pressure on the cell caused considerable variation in electrical capacity which was measured by a Wheatstone bridge. Poor performance of the electrical lead cables resulted in the malfunctioning of the cell in a relatively short period of time.

Road Research Laboratory Acoustic Stress Gauge

In 1951, Whiffen and Smith (14) reported the use of a direct-acting electrical-gauging earth pressure cell to measure sustained stresses under roadways. The over-all diameter of the cell was 5.50 in. and its over-all thickness was 1.50 in. It consisted of a cylindrical steel case, one side being a diaphragm. A minute deflection of the diaphragm would alter the tension in a taut steel wire maintained in vibration by a thermionic valve and thus change its frequency. The strain is determined by comparing the frequency of this vibrating wire with that of a similar wire stretched by an adjustable, measurable amount. The designer states that this gauge gives results independent of temperature and moisture changes and is unaffected by deterioration of connecting cables or variation of switch contacts or other connections. The cell was calibrated in an air pressure chamber. The gauge is not suitable for dynamic measurements because a vibrating wire takes a second or so to settle down to its new frequency after a new load has been applied. Satisfactory performance of a cell buried in soil for eight months is reported by the authors.

Plantema Earth Pressure Cell

In 1953 Plantema(15) reported the use of an indirect-acting electrical-measuring earth pressure cell which had been designed and constructed in 1948, laboratory calibrated in 1949, and extensively tested in the field from 1950 to 1952. It was designed for use in a soil stratum and a modification would be necessary to use it in the wall of a rigid structure. A large flexible (rubber) membrane is supported by oil which transmits the pressure to a measuring diaphragm fitted with strain gauges. The measuring range of the cell can be changed by changing the diaphragm thickness and Plantema reports two pressure ranges, 0 to 2 and 0 to 5 atmospheres. Both cells have membrane diameters of 25 cm but one cell is 3.9 cm in over-all thickness while the other is 3.5 cm. The cells were first calibrated under water pressure to examine the behaviour of the measuring diaphragm, then in a pressured container filled with sand. Calibration curves have been determined for water, loose sand, dense sand and concrete. Because of the incorporation of the strain-gauge system, Plantema states that the cell is suitable for measuring both static and dynamic stresses.

CELLS DESIGNED TO MEASURE DYNAMIC STRESSES

Dynamic stresses may be caused in soil strata by moving vehicles, compaction equipment, wind loads transmitted to the soil through structures or the effects of explosive blasts etc. The nature of the dynamic stress to be measured, especially the load frequency, will set certain requirements on the cell design. The response time of the gauging system must be rapid, hysteresis effects in the system must be negligible and the recording equipment must be capable of taking frequent instantaneous readings or continuous readings.

California State Highway Department Pressure Cell

The use of this cell to measure subgrade pressures produced by wheel loads on pavements has been reported by US Waterways Experiment Station (3). The cell might be described as an indirect type using an electrical reluctance gauging system. The operating principles of the cell have been described in the above report as follows: "Pressure applied to an outer diaphragm is transmitted by oil to a smaller measuring diaphragm. An iron disc is held against the measuring diaphragm by a flat spring and is separated from the poles of a U-shaped iron core of an electromagnet by a small air space. Deflection of the measuring diaphragm decreases the air gap between the disc and poles of the electromagnet. A rigid ring limits the travel of the disc and prevents damage by pressures greater than the design pressure. Movement of the metal disc changes the magnetic flux in the gap and thus changes the reluctance of the circuit. A balancing unit consisting of a similar coil and gap is located separately from the cell in such a way as to be unaffected by the load on the cell. The cell and balancing unit are connected in by a bridge circuit. The unbalance of the bridge circuit, due to pressure applied to the cell, causes an increase in current through the bridge. The current change is a measure of the change in applied pressure". Successful use of these cells to measure pressures of short duration is reported.

Other Cells for Dynamic Stresses

As has been mentioned earlier in this report, the Plantema cell could be used to measure dynamic stresses in road and runway subgrades if a recording apparatus having the necessary requirements mentioned earlier was used.

Although the successful use of the following principles in dynamic earth pressure cells has not been reported in the literature, they are thought worthy of mention. The change in resistance of a carbon pile stack due to the application of pressure has been used unsuccessfully in the field but with satisfactory results in the laboratory (16). The principal difficulty with the stacks appears to be that they do not retain calibration and must be recalibrated frequently.

The electrostatic charge produced in a pile of quartz crystals due to the application of pressure may provide a new principle for the measurement of stresses of short duration.

Hydrostatic Pressure Cells (Piezometers)

As the use of theories dealing with effective stresses becomes more popular, the need for the determination of inter-granular stresses becomes more important. The contribution of the neutral or pore water pressures to the total stress on a plane can be measured by piezometers.

Waterways Experiment Station Hydrostatic Pressure Cell (3)

This cell incorporates the same measuring principle as is used in the WES earth pressure cell, i.e. a diaphragm acted upon by fluid pressure; the strain of the diaphragm being measured by an electrical-resistance strain gauge.

The hydrostatic pressure cell is about 3½ in. in diameter and 2 in. thick. A perforated plate with a screen soldered to it prevents the soil from coming in contact with the diaphragm but allows free passage of the pore water so that its pressure alone acts on the diaphragm.

Owing to the electrical-resistance measuring system it is suitable for remote reading set-ups but particular care must be exercised in waterproofing and in selecting lead cables.

The very small displacement due to the deflection of the diaphragm requires negligible flow in order to register the fluid pressure.

Plantema Pore Water Pressure Cell

A modified version of the pore water pressure cell developed by Boiten and Plantema (17) is reported by Plantema (18). It is a direct-acting type of cell in which the pore water pressure acts directly on the measuring diaphragm on the back of which strain gauges are mounted. The gauge casing is in the form of a sharpened tip which can be attached to drill rods and jacked into the soil. The effects of corrosion have been minimized by using stainless steel throughout.

It has been used extensively in the Netherlands to measure pore water pressure at various depths in soil strata. After jacking the tip to the required depth, a reading is made after a period of time has elapsed ranging from 5 to 30 minutes depending upon the time required to dissipate excess pore pressure developed due to jacking. This varies with the type of clay encountered.

The response time of the cell is reported to be very short, with only 6 mm^3 of pore water required to actuate the diaphragm at one atmosphere pore water pressure.

This cell could probably be used for long-term installations at a given depth but the effects of corrosion by soil pore water on the relatively thin diaphragm should be investigated. The older design by Boiten and Plantema (17) is commercially available from Philips and possibly they now make the more recent, improved design reported by Plantema (18). The newer design has definite improvements and is to be preferred.

CONCLUSIONS

The following recommendations with regard to earth pressure measurements are indicated by the review of the literature.

1. To measure earth pressures acting on retaining walls, driven sheet piling, tunnel linings, etc. in soft clays, the vibrating wire gauge such as developed by the Norwegian Geotechnical Institute or British Building Research Station appears to offer the best opportunity for successful measurements. W. H. Ward of Building Research Station, London, in private correspondence, reported on modifications to this type of cell. At time of writing, the modified cells were being subjected to trials.

2. To measure static earth pressures in disturbed soil structures made of soft plastic soils such as earth embankments dams or roadways, the Plantema earth pressure cell is recommended. In other soils, the Vicksburg cell should be used. It may be possible to borrow this cell from the Waterways Experiment Station, U.S. Corps of Engineers, Vicksburg, Mississippi. It is not available commercially.

3. To measure dynamic stresses as encountered in highway, railway or runway subgrades, it is suggested that the pressure cell developed by the California State Highway Department offers the best features. This cell would have to be constructed. An alternative might be the Plantema earth pressure cell with the necessary recording equipment.

4. To measure water pressures in undisturbed soils in situations where a Bourdon gauge reading positive pressure cannot be employed, the Plantema (1953) pore water pressure cell is recommended.

For remoulded soils such as in earth embankments, the Waterways Experiment Station hydrostatic cell is recommended. It is not available commercially.

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APPENDIX A

SOME SUPPLIERS OF RECOMMENDED EQUIPMENT

1. Geonor A/S, Forskningsveien 1, Oslo Blindern, Norway, Norwegian Geotechnical Institute Vibrating Wire Gauge.

2. Philips Industries Limited, 116 Vanderhoof Ave., Leaside, Toronto 17. Plantema's earth pressure cell as Ground Pressure Pick-Up GM 5700 Plantema's 1948 pore pressure cell as Liquid Pressure Pick-Up GM 5701. (Plantema's more recent designs may now be available.)