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A Review on Pressure Measurement using Earth Pressure Cell

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ABSTRACT: Economy and reliability of any land founded structure depend on evaluation of exact stresses generated at soil-structure interface or within the soil mass under various loading conditions. Measurement of stresses provides verification of design principles and improvement of theory/model describing behaviour of soils. Pressure cells are used for measuring earth pressures acting on soil-structure or within soil mass. However, interpretation of results obtainable from an earth pressure cell (EPC) is crucial as they are affected by effect of inclusion, interaction effect with surrounding soil, effect of placement and environmental effects. Calibration of EPC performed in fluid and soil under application of same pressure leads to different results and soil calibration underestimates the measured pressure. This paper presents a review of factors affecting earth pressure measurement, devices and techniques commonly used to calibrate earth pressure cell. A comparison between the different calibration techniques with respect to their applicability and limitations is also presented.

KEY WORDS: Review, Earth Pressure Cell, Factors Affecting Output, Calibration Mechanism

INTRODUCTION

Evaluation of stresses generated at soil-structure interface or within the soil mass influences the design decisions of substructures. Although soil stresses can be estimated by many analytical techniques, the actual measurement of these stresses becomes great importance in relation to the adoption of sophisticated analysis and the development of new construction procedures. Also the information derived from pressure measurements provides valuable information for examining the validity of constitutive theories of geomaterial behaviour and computational techniques for examining soil–structure interaction problems.

Pressure measurements in soils fall into two basic categories: measurements within the soil mass and measurements at the interface between a structural element and the surrounding soil. Conventionally, embedded load cells have been used to determine the magnitude and distribution of insitu stress within embankments and backfill material. Applications of contact earth pressure cells include measurement of pressure against retaining walls, culverts, piles and shallow foundations.

As the rheology of soil is a complicated function of soil type, stress history, shear and normal stress levels, boundary and drainage conditions, and many other environmental effects, all of which are extremely difficult to build into a stress-sensing instrument, the stress registered by the EPC will not be the same as the stress which has existed at that point if the cell was not present. Due to the fact that correction factors must be consistently applied to all test results to minimize questions of accuracy and dependability studies on pressure measurement plays crucial role in geotechnical engineering.

FACTORS AFFECTING EPS OUTPUT

The conclusions of Kogler and Scheidig (1927), Taylor (1945), Monfore (1950), Loh (1954), Askegaard (1963), Tory and Sparrow (1967) with respect to the performance of an EPC were similar: when the modulus of the EPC is larger than the modulus of the medium, the stress sensed by the EPC is larger than the free-field stress termed "passive arching" and the result is an "over-registration" by the cell. When the EPC is softer than the medium, shear stress can reduce the normal stress on the face of the cell and the stress sensed by the EPC is smaller than the free field stress; this so-called "active arching" (Terzaghi, 1943) phenomenon results in an "under-registration" by the cell as shown in Fig. 1. Detailed description of factors affecting stress output and method for correction are given in Table 1.

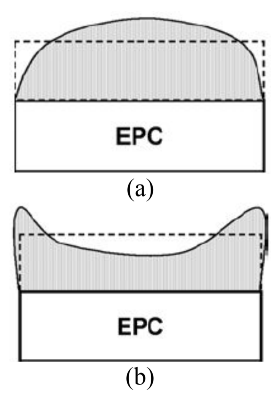

Fig. 1 Non-uniform stress distribution (a) $E_{EPC} > E_S$ – over-registration (b) $E_{EPC} < E_S$ – under-registration (After Labuz & Theroux, 2005)

Table 1 Factors affecting EPC output (Adopted from Weiler and Kulhawy, 1982)

Factors Affecting Stress Derivation	**Description of Resultant Error**	**Correction Method**
Inclusion effects		
Aspect ratio (cell thickness to diameter ratio)	Cell thickness alters the stress field around the cell	▪ Use thin cells (T/D < 1/5) (Experimentation Station, 1944) ▪ Minimizing aspect ratio increases accuracy (Askegaard,1963 and Collins et al., 1972)
Stress concentrations at cell corners	Causes cell to over-register by increasing stress over active cell face	▪ Use inactive outer rims to reduce sensitive area d^2/D^2 < 0.25–0.45 (Monfore,1950), Peattie & Sparrow, 1954) ▪ Active cell diameter to grain size ratio $d/D_{50} > 10$ (Weiler & Kulhawy, 1978)
Cress-sensitivity	Non-uniform direct lateral compression of cell causes error in measurement	▪ Consider strain gauge arrangement, add outer ring (Brown & Pell, 1967)
Proximity of structures and other stress cells	Interaction of stress fields of cell and structure causes errors	Observe minimum distance between cells ▪ Horizontally – 1.5D ▪ Vertically – 4D ▪ From face of structure to edge of cell – 0.5D
Stress-strain behavior of soil	Cell measurements are influenced by confining conditions	Calibrate cell under near usage conditions
Cell/soil interaction		
Soil-cell stiffness ratio	Incompatible stiffness between cell and soil may cause nonlinear calibration	Cell-soil stiffness ratio ≥ 0.5 (Kogler & Scheidig, 1927) i.e. use stiff cell
Diaphragm deflection(arching)	Excessive deflection changes stress distribution over cell	Design cell for low deflection ($d/\Delta > 2000$–5000)
Eccentric, non-uniform and point loads	Soil grain size too large for cell size used	Increase active diameter ($d/d_{50}>10$)
Placement effects		
Placement effects	Physical placing of soil causes disturbance of soil	Random error – Use duplicate measurements
Placement stresses	Over stressing of cell during soil compaction	Check cell design for yield strength
Environmental effects and dynamic response		
Temperature	Variation of temperature changes "zero reference" of cells: does not change slope calibration	Calibrate at operating temperature or use balance resisters
Dynamic stress measurement	Response time, natural frequency and inertia of the cell cause errors	Use dynamic calibration
Corrosion and moisture	Might cause failure or breakdown of the cell	Be particular in water proofing

CALIBRATION OF EARTH PRESSURE CELL

The calibration of pressure transducer involves the investigation of the unique relationship between the applied pressure and pressure cell output (Take, 1997). The output from pressure transducers is related to normal stress by applying calibration factor that converts cell's electrical output from voltage/strain to stress (kPa). Calibration experiments are required to determine the actual properties of the cells and to evaluate the usefulness of the design expressions. Each pressure cell comes with calibration done by manufacturer in which body of cell was placed in air bag and then pressurized. Weiler and Kulhawy (1982) noted that this method of calibration might be economical but the results are not very acceptable. They state: "When the cells are 'economically' used (meaning no in-soil calibration and no time spent investigating how stress cells behave in soil), the results are nearly always unusable if not incredible." If the calibration is not performed under conditions identical to those at the time of installation and throughout the monitoring period, the resulting readings may be of very limited value (Dunnicliff, 1988). Askegaard (1994) suggested to test the cells under as varied conditions as possible to get an estimate of the accuracy obtainable when the cells are used in practice in unknown loading histories.

Calibration methodology

The standard procedure to obtain calibration factors has been to calibrate the stress cell in a fluid (air, water or oil) and in the soil where the cell is to be used (usually by placing the soil and cell within a large diameter triaxial cell or oedometer). Calibration using fluid is done to check 1) Instrument's physical condition 2) Response to applied pressure 3) Return to zero after removal of load. Calibration using soil is performed to check 1) Hysteretic behavior upon loading and unloading 2) variation of coefficient of calibration with soil type 3) variation of coefficient of calibration with soil condition 4) variation of coefficient of calibration with stress history. The earth pressure cell calibration is not a linear relationship between output voltage and applied pressure like fluid calibration due to local arching effects around the pressure sensitive diaphragm (Trollope and Lee, 1961; Frydman and Keissar, 1987; Clayton and Bica, 1993).

The relationship between the fluid and soil calibrations was described by the concept of a cell action factor (CAF). The cell action factor, CAF is the ratio of the measured pressure to the pressure that would have existed in the absence of an earth pressure cell (Clayton and Bica, 1993). The error associated with using the earth pressure cell is then described by the nearness of the value of CAF to unity. A value of unity represents an identical response to both fluid and soil induced pressures.

In simple way,

$$\mathbf{CAF = P_{mea}/P_{app}}$$

Where P_{mea} is measured pressure by cell and P_{app} is applied pressure on cell

Techniques for calibration

Fluid calibration can be done by applying fluid pressure as dead weight in large size tank, application of pressure using pressurized fluid or using centrifuge technique. Large tanks would require applying pressure using dead weight, where as fluid calibration using centrifuge suffers from meniscus formation results in non-uniform pressure application. Calibration of EPC using soil as media by applying external oil pressure on dead weight calibrator was done by Redshaw (1954), Pang (1986) and more recently Ramirez et al. (2010). It was concluded from output that cell under-registers significantly compared to fluid calibration. Pang (1986), Take (1997) and Chen & Randolph (2006) used centrifuge technique to calibrate EPC with sand layer. It was found that reliable pressure cell output was obtained with about 10% error. Use of air pressure application to calibrate EPC is most popular and used successfully by Frydman & Keissar (1987), Clayton & Bica (1993), Labuz & Theroux (2005), Talesnick (2005), Ramirez et al. (2010) and more recently Dave & Dasaka (2010). Modification of triaxial set up for calibration of EPC was done by Clayton & Bica (1993), Chen & Randolph (2006) and Dave & Dasaka (2011a) (Fig. 2). Modified Rowe cell was successfully used by Clayton & Bica (1993) and Labuz & Theroux (2005) for calibration of EPC.

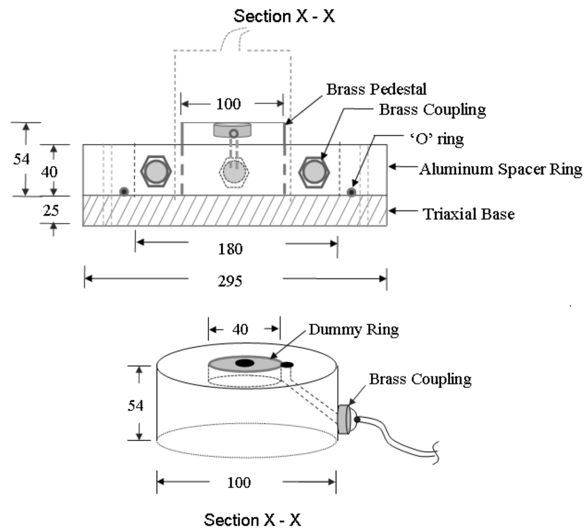

Fig. 2 Modified triaxial set up (Dave & Dasaka, 2011a)

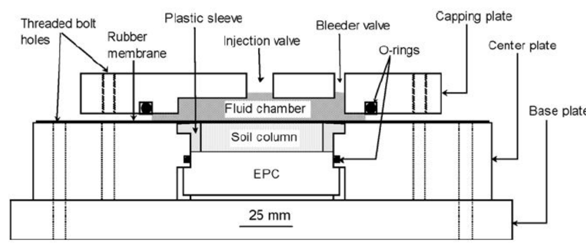

Fig. 3 Modified Rowe cell (After Labuz & Theroux, 2005)

Effect of particle size on calibration output

Significant effect of sand particle size on calibration output was observed by Clayton and Bica (1993) whereas no significant effect was observed by Labuz & Theroux (2005).

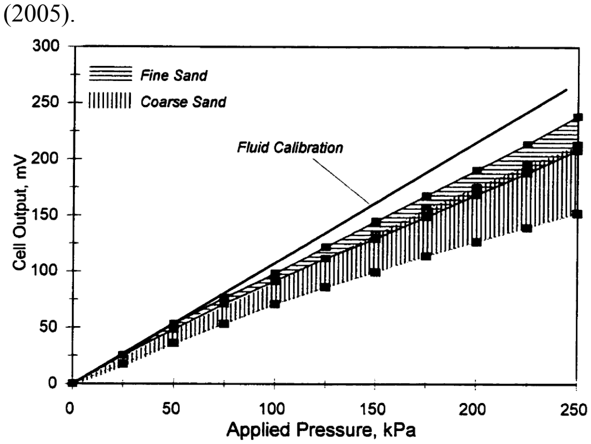

Fig. 4 Effect of grain size on calibration relationship (After Clayton and Bica, 1993)

The reason behind effect of particle size on output as stated was "even at same relative densities, the two sands used in the Rowe cell calibration tests might have markedly different stiffness".

Effect of soil density on calibration output

Significant influence of soil density on the calibration output was observed by Hadala (1967), moderate effect was observed by Clayton and Bica (1993) and very little effect was observed by Frydman & Keissar (1987) and Labuz & Theroux (2005).

Effect of thickness of sand layer on calibration output

Labuz & Theroux (2005) considered two different sand layer thicknesses and observed lower output was for thicker sand layer. Dave & Dasaka (2011b) studied effect of thickness of sand layer on calibration output by considering five different thicknesses, three different materials and two different setups. It was observed that larger sand bed thickness leads to significantly lower output of about 40%. It was concluded that it may unsafe to consider same calibration output for different thickness as routinely done in practice.

CONCLUSIONS

A review on pressure measurement using earth pressure cell (EPC), factors affecting output of EPC and correction methods for obtaining meaningful output is presented. The working of EPC involves mechanics difficult to understand and interpret also it requires skill and practice. Various techniques to calibrate EPC, factors affecting calibration output and various set up developed to obtain calibration factors matching reasonably with the working materials, pressure range and environmental conditions. From the present studies it is concluded that EPC needs to be calibrated near usage conditions else the calibration factors obtained are unreliable and of little use.

NOTATIONS

T – Thickness of EPC

d – Diameter of diaphragm of EPC

D – Diameter of EPC

Δ – Deflection of diaphragm

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