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The use of miniature earth pressure cells in a multi-gravity environment

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ABSTRACT: Although the measurement of physical phenomena such as pore water pressure, displacement and load is routinely carried out with a high degree of accuracy in small scale centrifuge models the accurate derivation of soil stresses poses a number of problems. This paper discusses the design, manufacture and use of miniature earth pressure cells in measuring changes in soil stress during the modelling of the installation and loading of compaction ground anchorages in the 500gTonne centrifuge at the University of Manchester. Data are presented illustrating the degree of accuracy and repeatability of the soil stress derivation achieved and guidance is given on the sizing and instrumentation of miniature earth pressure cells.

1 EARTH PRESSURE DERIVATION

Although the measurement of such physical phenomena as pore water pressure, displacement and load is routinely carried out with high accuracy in small scale centrifuge models, the accurate derivation of total soil stresses poses a number of problems. Clayton & Bica (1993) stated, in regard to soil stress measurement generally, "... that of the physical parameters often measured by engineers the determination of soil stress is probably the most difficult"; such difficulties tend to be exacerbated in the small scale environment of centrifuge modelling. Weiler & Kulhawy (1982) identified fourteen factors affecting soil stress derivation as summarised in Table 1. These factors are grouped into:

- Inclusion effects - which relate to the way that the presence of a cell alters the stress field in the soil.
- Cell/soil interaction - a function of the relative stiffness of the cell with respect to the soil. This is defined by the flexibility factor (Tory & Sparrow, 1967) as:

$$F = \frac{E_s d^3}{E_c t^3} \qquad (1)$$

and where F = flexibility factor; E_s= soil modulus; d = diaphragm diameter; E_c= cell stiffness; and t = diaphragm thickness.

- Placement effects.
- Environmental influences and dynamic response.

A number of small scale earth pressure cells (EPC's) incorporating features to minimise (or eliminate) the negative influences noted above were designed and manufactured for use in the multi-gravity environment of the 500g-tonne Peter W Rowe geotechnical centrifuge at the University of Manchester.

2 EARTH PRESSURE CELL DESIGN

The details of the cells are shown in Figure 1. The cells were manufactured from Type 303 austenitic stainless steel with the active face of each cell comprising a 20mm diameter strain gauged diaphragm. The strain gauges were arranged to operate with the standard centrifuge instrumentation system excitation supply of 5V in a full bridge configuration. Since the temperature change within the soil models was not expected to vary by more than 3°C it was not necessary to incorporate a temperature compensating resistor in the Wheatstone Bridge circuit.

A prototype EPC having a flexibility factor of 1.0 with a 1.74mm thick diaphragm was manufactured. However the electrical output at working stresses was very low and even after pre-amplification the signal suffered saturation by electrical noise

Table 1 Factors affecting soil stress derivation (after Weiler & Kulhawy, 1982).

Factor 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)
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<.25-.45)
Lateral stress rotation	Presence of cell in soil causes lateral stresses to act normal to cell	Use correction factors
Cross-sensitivity	Non-uniform direct lateral compression of cell causes error in measurement	Consider strain gauge arrangement, add outer ring
Proximity of structures and other stress cells	Interaction of stress fields of cell and structure causes errors	Observer minimum differences between cells Horizontally - 1.5D Vertically - 4D Cell-structure - 0.5D
Stress-strain behavior of soil	Cell measurements influenced by confining conditions	Calibrate cell under near usage conditions
Cell/soil Interaction Effects		
Soil-cell stiffness ratio	Incompatible stiffness between cell and soil may cause nonlinear calibration	Use stiff cell
Diaphragm deflection (arching)	Excessive deflection changes stress distribution over cell	Design cell for low deflection (d/Δ >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 the cell during soil compaction	Check cell design for yield strength
Environmental Effects		
Temperature	Changes "zero reference" of cells: does not change slope of calibration	Calibrate at operating temperature or us balance resistors
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 meticulous in water proofing

T = cell thickness; t = diaphragm thickness; D = out side diameter of cell; d = diameter of diaphragm; F = flexibility factor, Δ = diaphragm deflection.

generated by the centrifuge slip-rings. It was found that adequate electrical performance could be achieved in one of two ways:

i. By reducing the diaphragm thickness to 0.74mm and instrumenting with foil strain gauges with a gauge factor of 2.05. Although this gave a flexibility factor for the cell of 6.88 performance was found to be adequate. Five production EPC's, designated Type A, were manufactured in this way.

ii. Maintaining a 1.74mm thick diaphragm and instrument with 500Ω semi-conductor strain gauges having a gauge factor of 140. One production EPC, designated Type B, was manufactured in this way.

3 EARTH PRESSURE CELL PERFORMANCE

The performance of the Type A and Type B cells was compared in calibration tests carried out in a 508mm diameter Rowe cell.

The EPC's were carefully placed in a bed of pluviated air dry Mersey River sand with properties, d_{10} =1.4 to 1.8mm, U_c = 1.8, Gs =2.655, ϕ'_{peak} = 37.5° at Rd= 95%, and ϕ'_{peak} = 29.5° at Rd=50%.

Figure 2 compares the response of the two types of cell to increasing soil stress applied to the surface of the sand through a flexible boundary within the Rowe cell. Each cell was subjected to three load/un-load cycles.

The response of the Type A cells was characterised by significant hysteresis between the loading and unloading phases of each load cycle. This is evidence that the localised stress system was modified by soil arching resulting from the cyclic changes in soil stress. The response of the Type A EPC's also varied with load cycle and the trend suggested that the loading curves would tend to a constant gradient after a large number of cycles. This behaviour indicated that some rearrangement of soil grains occurred as the diaphragm deflected leading to a denser packing and stiffer zone of soil around the diaphragm. The existence of this stiffer zone in its self could be expected to lead to alteration of the localised stress regime around the cell.

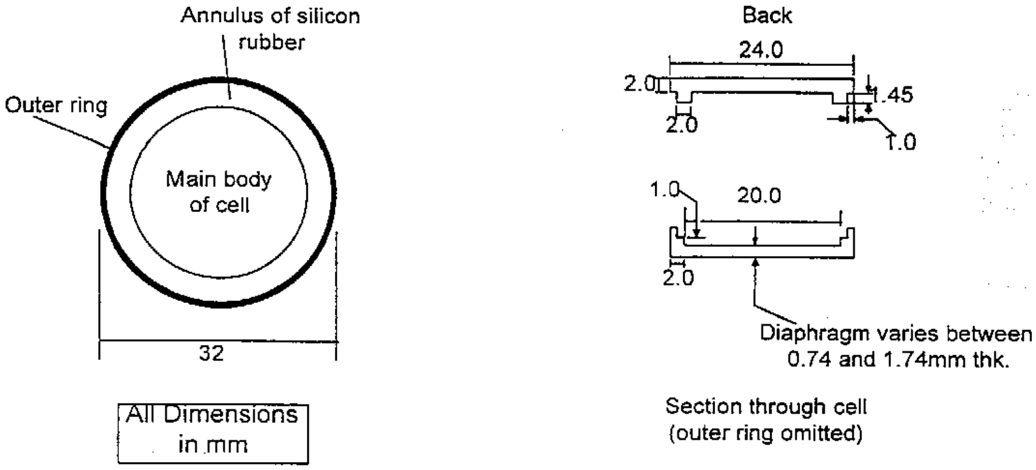
In contrast the response of the Type B cell showed little hysteresis on unloading and a much reduced tendency for the peak output to decrease with increasing load cycles. Comparison of these data from different EPC's with differing flexibility factors showed the performance of the miniature earth pressure cells to be highly dependant on the relationship between the cell and soil stiffness, supporting the findings of Tory & Sparrow (1967).

3.1 Use of the EPC's in the centrifuge

The EPC's were designed to be used in the investigation of soil behaviour around the expanding fixed length of vertical and sub-horizontally inclined model compaction ground anchors (Egan, 1997, Egan & Merrifield, 1997). In this context the soil surrounding the expanding fixed anchor length was subjected to steadily increasing stress normal to the expanding cavity. Given the performance characteristics of the EPC's a calibration procedure was developed to ensure that an acceptable level of confidence could be placed in the data derived. This was achieved as follows:

- Initial EPC calibration in a sand bed prepared by the same pluviation procedure and to the same density as the centrifuge models. This was carried out at 1g in a Rowe cell to typical centrifuge test stress levels.
- Development of in flight calibration curves by acquisition of EPC output with increasing gravitational acceleration during centrifuge spin-up. These data were then correlated to the theoretical increase in soil stress generated within the model at the EPC locations to give a second calibration factor.
- Typically four centrifuge tests were run concurrently to comprise a test series. Each test series was carried out without alteration of the instrumentation system or test parameters. The average calibration factor was then used in the data reduction for all tests in a given series.

In use in the centrifuge the Type A EPC's, while not processing ideal operational characteristics were found to be robust and give a stable and repeatable output in use and performed adequately with repeated use for the required duration. In contrast the Type B cell, while initially exhibiting superior operating characteristics began, after a time, to emit unstable output signals and eventually ceased to work altogether.



Section through cell (outer ring omitted)

Figure 1 Detail of miniature earth pressure cell design.

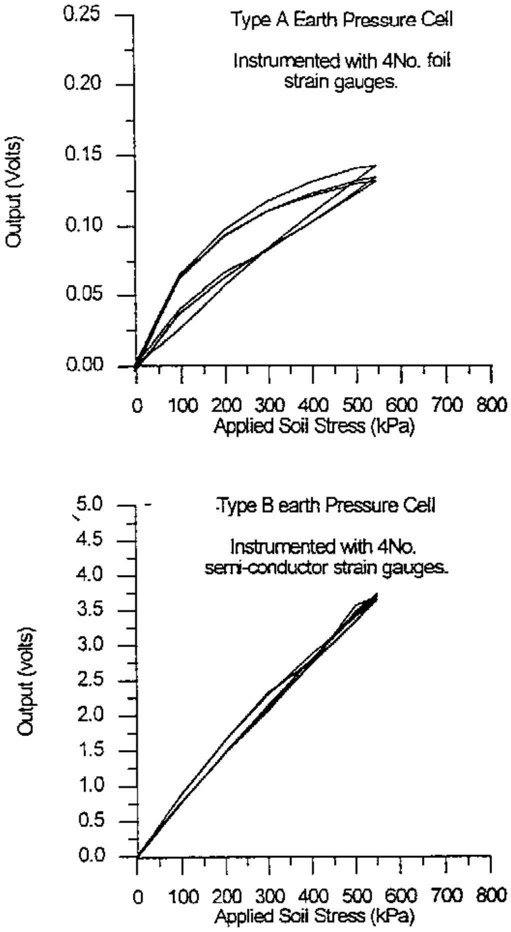


Figure 2 Performance characteristics of Type A and Type B earth pressure cells.

3.2 Data from centrifuge tests

The EPC's were placed at various depths in soil models tested at a nominal acceleration of 50g. Figure 3 shows data obtained of the at-rest horizontal total stress with depth profile for a number of tests compared to the theoretical profile calculated using Jakey's equation where:

$$\sigma_h = \sigma_v (1 - \sin\phi') \qquad (2)$$

and

$$\sigma_v = \int_0^z \gamma \omega^2 r dz \qquad (3)$$

where σ_v = total vertical stress; σ_h = total horizontal stress; ϕ' = angle of shearing resistance; γ = bulk unit weight of soil; ω = angular velocity of centrifuge arm, r = radius of point in soil.

Figure 3 illustrates the degree of accuracy and repeatability of the soil stress derivation achieved in the centrifuge tests although the spread of the data highlights the difficulties in obtaining accurate quantitative derivation of total absolute soil stresses.

The total radial stress changes measured during the expansion of the model fixed anchor length are shown in Figure 4. The normalised radial stress increase, $\underline{\sigma_r}$, is plotted against radius, r, from the centre of the cavity formed by the fixed length. The normalised radial stress increase is defined as the ratio of the change in radial stress due to cavity expansion, to the initial at-rest radial stress before the start of expansion. Where:

$$\underline{\sigma_r} = \frac{\sigma_{r1} - \sigma_{r0}}{\sigma_{r0}} \qquad (4)$$

The initial radial stress at a given depth, σ_r, before expansion of a vertically inclined fixed anchor length is everywhere equal to the horizontal stress, σ_h, at that depth.

Figures 4a and 4b compare the measured soil stress response to fixed anchor length expansion and the response calculated by finite element

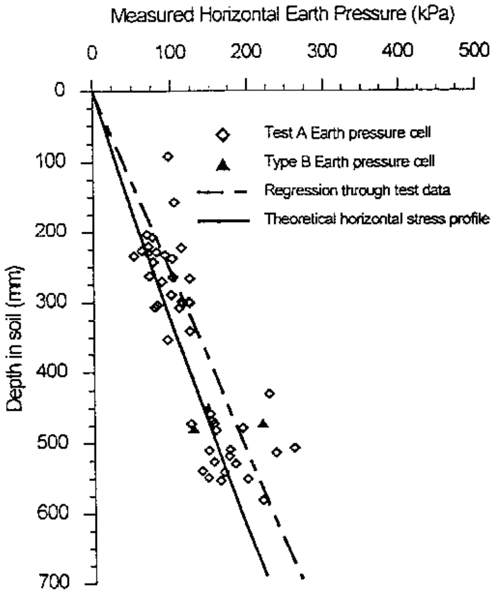


Figure 3 Distribution of horizontal soil stress with depth in centrifuge tests at 50g.

analysis (based on the algorithm presented for axisymmetric plane strain analysis of an elastic-plastic (Mohr-Coulomb) soild using 8-noded quadrilateral elements initial stress method, Smith & Griffiths, 1988) for anchor embedment in loose sand (R_d=50%) and medium dense sand (R_d=75%) respectively.

The EPC data clearly show the zone of influence of the expansion of cavity on the radial soil stresses, which decays exponentially with distance from the cavity. This is in broad agreement with traditional cavity expansion theory (Jewell et al, 1980). Good agreement is also shown between the experimental data and those from the finite element analysis at the lowest fixed anchor length expansion pressures (500kPa). At higher pressures the EPC's showed greater stress increase than suggested by the finite element analyses at a given radius, *r*.

4 CONCLUSIONS

The dereivation of total soil stress remains one of the more difficult tasks in experimental soil mechanics. The problems of inclusion effects, cell/soil interaction, placement effects and environmental influences have been addressed during the manufacture and use of effective miniature earth pressure cells within an existing centrifuge instrumentation system. The experience gained has shown that adherence to the following points will assist in obtaining optimum in-service performance:

- sizing the cells to have a low aspect ratio
- isolating the diaphragm from the outer edge of the cell body
- selecting the stiffness of the diaphragm to give a flexibility factor of at least 1.0
- in flight re-calibration and validation in similar soil conditions over a number of centrifuge tests
- careful placement of the cells to minimise soil disturbance
- spacing of the cells from other inclusions in the soil to prevent interaction effects.

In practice the need to match the stiffness of the cell to the soil in which they were placed and yet obtain a large enough output signal was found to be best achieved by the use of semi-conductor strain gauges. However the long term performance of the cell manufactured using this technology was marred by progressively increasing output signal instability and further development work to improve the durability of earth pressure cells instrumented with semi-conductor strain gauges would be of great value.

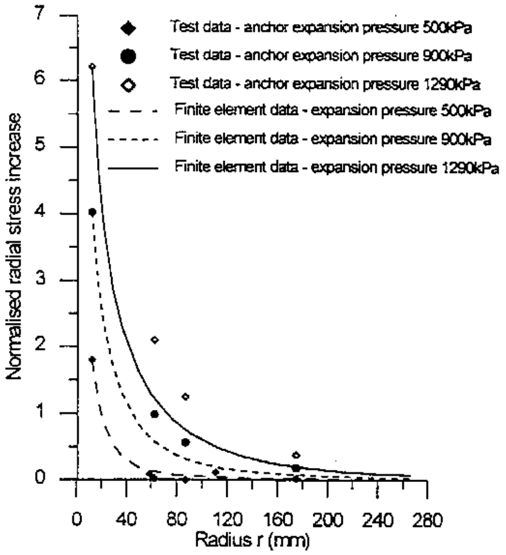


Figure 4a Comparison of the measured and computed distribution of normalised radial stress with radius from the model fixed anchor length placed in loose sand.

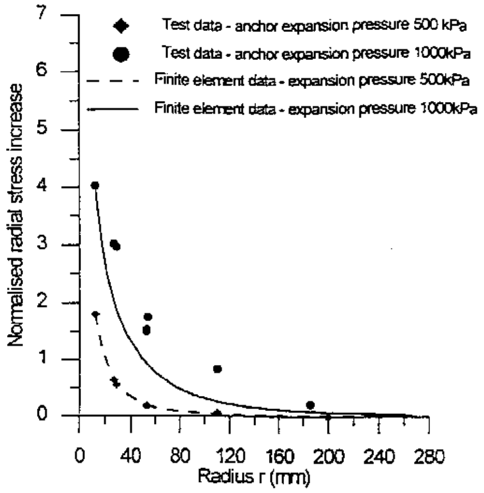


Figure 4b Comparison of the measured and computed distribution of normalised radial stress with radius from the model fixed anchor length placed in medium dense sand.

ACKNOWLEDGEMENT

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