The Measurement of Soil Pressures

Mesure des pressions dans le sol

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Summary

The paper describes an investigation into the measurement of soil pressures under single loading, unloading and repeated loading The effects of diaphragm stiffness and the nature of the soil material are discussed. The experimental work has shown that the measurement of pressures in clay fills is likely to present far less difficulty than measurements in sand. It is also considered that the instrumental accuracy and reliability available with cells using the vibrating-wire measuring principle is more than adequate for most engineering purposes and there is no apparent obstacle to their widespread use.

Sommaire

Cette communication décrit les recherches des auteurs sur la mesure des pressions dans le sol pour des conditions de chargement unique, de déchargement et de chargement répétés. Les effets de la rigidité du diaphrame et de la nature des sols sont discutés. Les essais réalisés ont montré que la mesure des pressions dans des remblais en argile est susceptible de s'effectuer avec moins de difficulté que dans les sables.

Il semble que la précision et la fidélité des mesures, que l'on obtient avec des capteurs de pression utilisant des cordes vibrantes, doivent permettre de résoudre la plupart des problèmes posés à l'ingénieur et il n'y a pas d'obstacle apparent à en étendre l'utilisation.

Introduction

The inherent variability of the physical properties of soil masses gives dual significance to the problem of soil pressure measurement. Because of this variability, in the first place, it is most important to obtain actual field measurements for the purpose of comparison with theory and design practice, and secondly, the mechanics of measurement are made more difficult and complex.

For the past six years the authors have studied this problem and this paper is an attempt to survey the results and experiences obtained up to the present time.

In general there are two approaches that may be employed to estimate soil pressures. The indirect method, in which strains are measured on the structure that supports the soil mass, and the direct method wherein the pressures are recorded by a measuring device.

The indirect method has been extensively used with considerable success (e.g. Tschebotarioff (1948, 1957) Ward (1955)) but it is obviously limited to those cases where the soil mass is supported by a structure of sufficient flexibility to permit accurate strain measurement. Where the structure is relatively rigid and/or pressures within the mass are required, the direct method must be used. In a series of laboratory experiments in which wedges of sand were supported on a thin steel plate (Trollope 1956) a comparison was made between the indirect method using electrical resistance strain gauges attached to the plate, and the direct method, using an inductance type pressure cell (referred to below). The conclusion drawn from this work by the authors was that the direct method offered the greater accuracy and hence their work has been directed to a detailed study of pressure cell performance.

The design and construction of a suitable pressure cell can be based on one of two measuring principles. Either the pressure is transmitted to the cell body which moves as a whole unit — the piston type cell, or the pressure is transmitted to a deforming diaphragm — the diaphragm type cell. The latter type was chosen for two main reasons, ease of construction and avoidance of edge effects inherent with the piston type cell.

Subsequently it was learned that the authors' thinking on this question was closely parallel with that of Kallstenius and Bergau (1956) and indeed there is considerable accord between the philosophy of soil pressure measurement as expressed by these writers and the authors' experience.

The remainder of this paper is therefore concerned with the direct measurement of soil pressures using diaphragm type cells.

Pressure Cells

Fig. 1 shows the four measuring devices that have been developed in the authors' laboratory. The operating and construction details of these cells have been published elsewhere, hence they will not be included here.

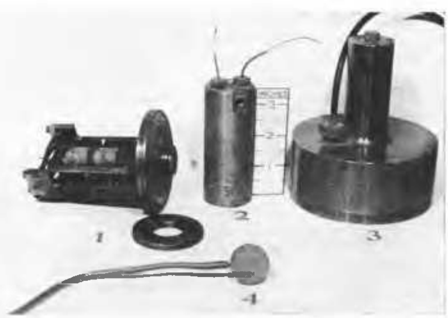


Fig. 1 Photograph of Pressure Cells.
Photographie des capteurs de pression.

Cell No. 1 (LEE & BROWN 1957) employs an electro-magnetic device wherein the diaphragm movement causes a change of inductance. These cells were designed for laboratory use on small models with an operating range of 0-1 lb./in^2. Cells of this type are not suitable for field work however, as they are insufficiently robust.

Cells Nos. 2 & 3 (LEE 1960) are vibrating — wire type units in which the wire is attached directly to the moving diaphragm. No. 2 was designed for laboratory use and for use on small structures in the field with an operating range of 0-100 lb./in^2. This range may be varied at will, however, merely by changing the diaphragm thickness. No. 3 was specially designed for installation in the periphery of a reinforced concrete culvert under an earth dam with a pressure range of 0-150 lb./in^2. The sensitivity of these cells is greater than that of the inductance type, they are more robust and the electrical system is very stable. Both cells have given reliable service under field and laboratory conditions for 18 months — 2 years. In the authors' opinion this type of cell is the most satisfactory for boundary pressure measurements and is sufficiently sensitive to meet all practical requirements.

Cell No. 4 (TROLLOPE & CURRIE, 1960) is an embedded cell for measuring pressures within soil masses. The design is based on the principle of an electrical resistance strain gauge cemented to the deforming diaphragm. The gauge is a special spiral-pattern foil unit developed by REDSHAW (1954).

Experience with this type of cell suggests that it is not sufficiently sensitive and this coupled with the difficulties of electrical resistance circuits leads to the conclusion that an alternative measuring system should be sought.

Although no attempt has yet been made by the authors to develop an alternative system; their present view is that a modification of Kallstenius and Bergau's device offers the most promise. It is suggested that a diaphragm type capsule filled with incompressible fluid and with the pressure in the fluid measured *outside* the soil mass by a vibrating wire cell would give the required sensitivity and accuracy.

Calibration Procedure

In order to calibrate the various cells a large pressure chamber is required. When such a chamber is occupied by soil the most serious problem is that of side-friction on the walls of the chamber. Previous investigators have either attempted to eliminate this side friction (PLANTEMA 1953, KALLSTENIUS and BERGAU, 1956) or to assess its effect indirectly (U.S. WATERWAYS EXPERIMENT STATION 1944).

The principle adopted in the present investigation was to measure independently the pressures on the base of the chamber.

To do this the base was formed of a series of concentric rings (Fig. 2). Each ring was supported at three points and the load in each support measured by means of linear vibrating-wire strain gauges. A sheet of polythene plastic was placed over the rings and the system calibrated under water pressure. Various depths of soil from 2 ins. — 18 ins. were then placed in the chamber, water pressure was applied to the upper surface of the soil and the resulting base pressures determined. Fig. 3 shows the results of these tests.

It has been suggested (TROLLOPE & LEE 1957) that the zone in which stress redistribution within the soil may occur following diaphragm movement is restricted to that of a cone, having as its base the cell diaphragm and side slopes of approximately 60 degrees. Thus for a cell of diameter 1 in. the minimum depth of soil required is approximately 0·9 ins. For depths of soil greater than this value the cell performance should be independent of depth. The calibration tests confirmed this, and hence for convenience the majority of the calibration work described in this paper was carried out with a depth of soil of 6 ins. With this system it is considered that the average field pressure over the cell diaphragm could be predicted within an accuracy of $\pm$ 2 per cent.

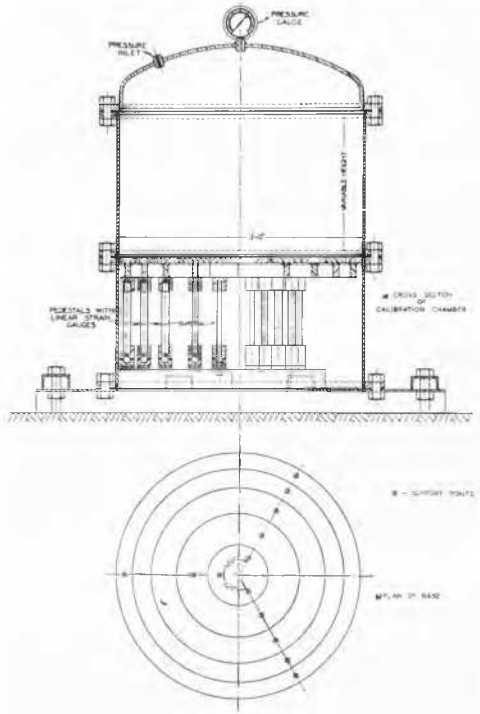


Fig. 2 Calibration Chamber.
Chambre d'étalonnage.

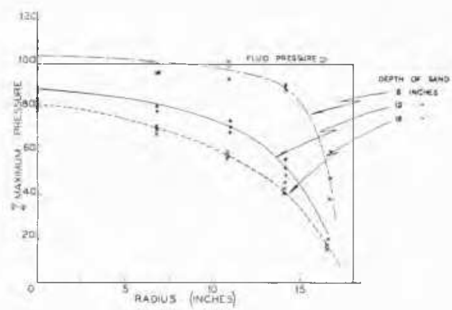


Fig. 3 Measured Pressures on Base of Calibration Chamber.
Pressions mesurées à la base de la chambre d'étalonnage.

Experimental Results

If a pressure cell is to be effective its performance must be predictable throughout its range of operation. For convenience it is possible to consider cell behaviour in three categories.

i) first loading;
ii) unloading;
iii) repeated loading.

First Loading

Before proceeding to a discussion of first loading calibration it is necessary to define replicate loading as distinct from repeated loading. For the purposes of this paper, replicate loading is defined as that in which the experimental conditions are similar but the soil is removed and replaced between loadings. In contrast, repeated loading is that in which the external load is applied and removed without disturbing the soil.

The primary aim in developing a cell to measure pressures in granular materials is to produce a system that gives a linear calibration characteristic. Any departure from linearity is associated with stress-distribution within the material. It has been shown (TROLLOPE & CURRIE, 1960) that for embedded cells that incorporate a deforming diaphragm, movement of the diaphragm is the major cause of this stress redistribution. The compressibility effect, due to deformation of the body of the cell, is negligible. It follows, therefore, that the results of a study of diaphragm effects on boundary cells may be extrapolated to embedded cells without serious consequences. The authors have previously demonstrated (1957) that, provided the central deflection : diameter ratio of these cells is restricted to less than 1:2000, a sensibly linear calibration curve may be obtained. For deflection ratios in excess of this amount, the calibration curve takes the form of a convex curve owing to the effects of arching in the material over the diaphragm. It was observed, however, that although the calibration under sand loading was linear, there was no unique slope to the calibration curve, but the sloped varied about a mean that was 93 per cent of the fluid calibration.

This feature was attributed to local variations in density (and hence stiffness) of the sand over the pressure cells, as even small variations in density can produce significant variations in the effective modulus of deformation of granular materials. It is virtually impossible to place granular materials so that the density is completely uniform throughout the mass. It was concluded, therefore, that the cells were measuring the "correct" pressure but that this pressure was not necessarily the mean field pressure for the sand mass. The present series of tests have confirmed this observation, and it appears that because of local density variations the pressure at a measuring point may vary within $\pm$ 15 per cent of the externally applied (fluid) pressure even in carefully placed soil masses. A single observation cannot be expected, therefore, to give absolute accuracy except within these limits.

On the other hand, an adequate number of replicate tests should give a mean calibration factor, identical with that of the fluid calibration. In the case of the work previously reported using cells of the No. 1 type (Fig. 1) the mean calibration factor was, however, 93 per cent, within the range 85-105 per cent, even though all calibrations were linear. Thus it is necessary to seek an alternative explanation for this discrepancy of 7 per cent between the mean sand calibration factor and the fluid calibration factor.

In more recent tests with the vibrating wire cells, a mean calibration factor much closer to 100 per cent has been obtained. These cells differ from the previous ones only in that the diaphragms are much stiffer. This experience suggests, therefore, that the flexibility of the diaphragm (defined as $\frac{d\Delta}{dp}$, where $d\Delta$ is the increment in the central deflection of the diaphragm and dp is the pressure increment applied to the diaphragm) is a contributing factor in cell performance. A satisfactory diaphragm must therefore satisfy two requirements : the central deflection must not exceed the value below which the calibration curve is linear and the diaphragm stiffness must be such that the mean calibration factor (slope of the calibration curve) is close to that under fluid loading.

In 1957 the authors derived an approximate theory to describe the influence of arching on the linearity of the calibration curve under sand loading. In the light of the more recent work this theory has been extended in an attempt to include the flexibility effect.

For the conditions obtaining in the calibration chamber in a single loading cycle, let p_0 be the externally applied (fluid) pressure (the weight of the sand layer is neglected) and p be the corresponding pressure that is applied to the cell diaphragm.

For increasing loads the increment dp may be greater or less than dp_0 depending on whether the density (or stiffness) of the soil over the diaphragm is greater or less than the mean soil density (or stiffness). Let this effect be described in terms of a factor η so that :

$$dp = dp_0(1 + \eta) \qquad (1)$$

The factor η may be positive or negative and its value defines the actual pressure transmitted from the soil to the cell diaphragm.

Now, as given in the previous theory the pressure (p) recorded from the movement of the diaphragm may be less than p if the latter pressure is not uniformly distributed owing to the arching effect and

$$dp = dp(1 - \rho) \quad \ldots. \quad (2)$$

Previously it was assumed that ρ is a linear function (δ) of the total deflection (Δ) only. The experimental evidence suggests however that the flexibility of the diaphragm $\left(\frac{d\Delta}{dp}\right)$ can also contribute to the under registration of these cells. For a given cell $\frac{d\Delta}{dp}$ is a constant, at least within the elastic range.

Hence we may express the under registration factor ρ, to a first approximation as

$$\rho = \xi_1\Delta + \xi_2 \qquad (3)$$

where $\xi_2 = f\left(\frac{d\Delta}{dp}\right)$

Then substituting in (2)

$$\text{we get} \left(\frac{dp}{1 - \xi_1\Delta - \xi_2}\right) = dp_0(1 + \eta) \qquad (4)$$

whence

$$p = \frac{1 - \xi_2}{\xi_1}(1 - \exp(-p_0\xi_1(1 + \eta)) \qquad (5)$$

It follows from equation (5) that the recorded pressure will tend to a constant value $\frac{1 - \xi_2}{\xi_1}$ as p_0 increases. The shape of the p vs. p_0 curve is therefore similar to that obtained by the previous theory but both the initial slope of the curve and the ultimate value now depend on ξ_2 as well as ξ_1. Equation (5) therefore expresses the general shape of the calibration curve but under conditions of replicate loading we cannot expect the recorded pressure (p) to be the same in each loading cycle as both ξ_1 and η may vary from test to test.

It has already been noted, however, that provided the total deflection Δ is restricted then a linear calibration curve is obtained. Hence, within this range it may justifiably be assumed that the arching effect is negligible and ξ_1, is zero. Each single observation therefore should give a linear calibration curve the slope of which depends on the values of ξ_2 and η. The value of η is a property of the soil as placed, thus if a sufficient number of replicate tests are carried out and the mean value of p is recorded then η should tend to zero.

If therefore we integrate equation (2) and in place of the single observation value p write the mean value p mean, we get

$$p_{\text{mean}} = p_0(1 - \xi_2) \qquad \dots\dots \quad (6)$$

where, again $\xi_2 = f\left(\dfrac{d\Delta}{dp}\right)$

Thus according to this theory the mean calibration factor depends only on the flexibility of the diaphragm and it appears that an equivalent fluid calibration factor $\left(\dfrac{p_{\text{mean}}}{p_0} = 1\right)$ can only be obtained if the diaphragm is infinitely stiff. The calibration problem must therefore be solved empirically by specifying the permissible under registration of the mean calibration factor. Fig. 4 shows the values of the mean calibra-

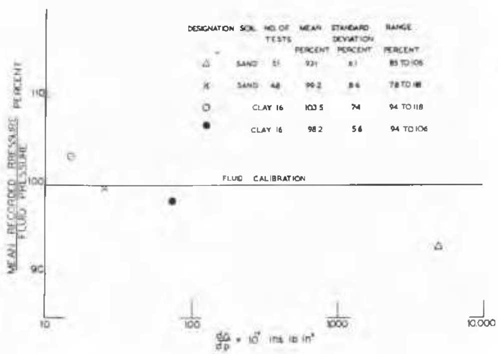


Fig. 4 Results of First Loading Calibration Tests.
Résultats des essais d'étalonnage pour le premier chargement.

tion factor obtained by the authors with cells of widely differing diaphragm flexibility. The tests using the vibrating wire cells were carried out with both sand and clay. The properties of the sand have been described previously (Trollope and Currie, 1960). The clay used was a remoulded tertiary clay the properties of which are given in Fig. 5. The clay was compacted in layers 1 inch thick and the triaxial compression tests carried out on samples 1 ½ inch in diameter.

It will be noted that for the tests using clay on the cells with the stiffest diaphragms, the mean calibration factor exceeds 100 per cent. As far as the authors are at present aware, there is no physical reason for this to occur with a boundary cell under increasing pressure. Fewer tests have been carried out with clay than with sand and as the over registration could be accounted for within the limits of experimental error associated with the calibration equipment it is not clear at present whether this over-registration is significant. The available test information is obviously insufficient to permit even an approximate description of the nature of the function

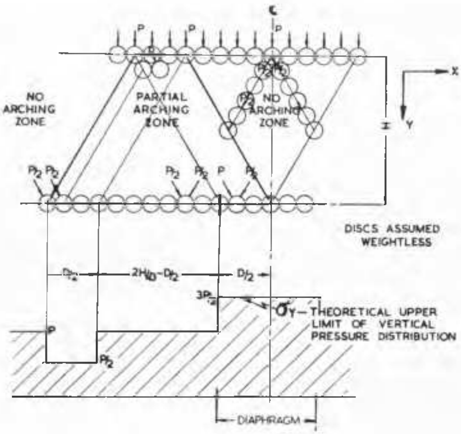


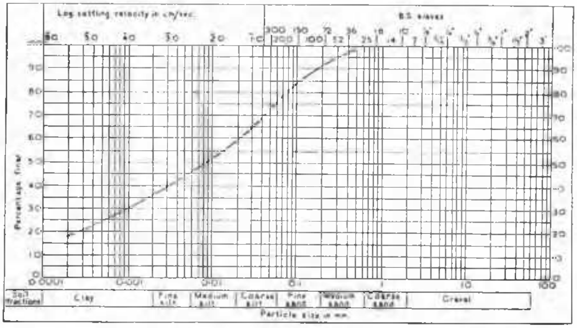
Fig. 5 Theoretical Two Dimensional Solution for Pressure Distribution on Unloading Diaphragm.
Solution théorique à deux dimensions pour la distribution des pressions pendant le déchargement du diaphragme.

$f\left(\dfrac{d\Delta}{dp}\right)$, but it does appear that the effect of the diaphragm flexibility is significant. Further tests with diaphragms of intermediate flexibility are required to enable this function to be defined empirically. Nevertheless it may be concluded from these tests that for the mean calibration factor to be within 2 per cent of the fluid calibration factor the diaphragm should be designed so that $\dfrac{d\Delta}{dp}$ is less than 10^{-5} ins/lb./in^2 and preferably of the order of $0{\cdot}3-0{\cdot}5\times10^{-5}$ ins/lb./in^2.

It is also significant that the measurement of pressures on the boundaries of clay masses is likely to be easier than corresponding measurements on sand or gravel masses — at least up to the strength and stiffness values used, and they cover a wide range of practical clay conditions.

Unloading

The behaviour of soil pressure cells in the unloading cycle is more complex than that under first loading. In addition to the inherent variations of density and stiffness within the soil, the movement of the diaphragm into the soil mass tends to generate higher pressures than at the corresponding stage on the loading cycle. This tendency may be illustrated qualitatively by considering the analysis of the stresses developed in a mass of systematically packed mono-sized discs. A similar model was used by the authors (1957) to describe the effects of arching during the loading cycle when the diaphragm moves away from the superimposed soil mass. The solution for the case where the diaphragm moves into the soil mass is given in outline in Fig. 5; owing to space limitations the details of this solution will be published elsewhere. It will be noted that, according to this theory, the upper limit of the increased pressure due to this effect is 150 per cent of the applied (fluid) pressure. The actual increase occurring on any cell diaphragm will, however, depend on the relative stiffnesses of the diaphragm and the superimposed soil mass. The stiffer the soil, the less the diaphragm movement required to develop the higher pressure, and conversely to the loading case, zero



UNDRAINED TRIAXIAL COMPRESSION TESTS

COMPRESSIVE STRENGTH lb/in²	E_{50} SECANT MODULUS lb/in²
78.3	5200
68.8	3600
75.6	3200
74.6	3800

Liquid Limit	39.0%
Plastic Limit	19.0%
Plasticity Index	20.0%

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Fig. 6 Properties of Syndal Clay.
Propriétés de l'argile de Syndal.

increase in pressure can only be expected with an infinitely stiff diaphragm.

It has been observed in all tests to date that the greater the over registration in any single loading cycle the greater the observed hysteresis on unloading, where for present purposes, hysteresis is defined as the difference, in ordinate of recorded pressure, between the unloading curve and the loading curve (Fig. 7). For the cell to over-register in the first instance it implies that the soil at that particular location is of above average density and stiffness and hence will be more sensitive to the tendency of the diaphragm to move into the mass. It is clear therefore, that the stiffness of the diaphragm is again of major importance in determining the unloading behaviour of these cells. Examination of the test results indicates that the shape of the unloading curve is consistent and the maximum hysteresis is virtually independent of the thickness of the sand layer between 18 ins. and 2 ins. Fig. 7 shows a plot of maximum hysteresis vs diaphragm flexibility for both sand and clay using No. 2 type cells.

The two conclusions that may be made from these graphs are; that the maximum hysteresis increases linearly with increasing diaphragm flexibility and that the hysteresis effect is very much less with the clay than with the sand.

Repeated Loading

It has been observed from tests using No. 4 type cells with sand (Trollope and Currie, 1960) that with excessive diaphragm deflection there is a serious change in the shape of the cell calibration curve when the load is repeated even though on first loading the curve may be reasonably linear. The characteristic of this behaviour is that it takes few repetitions (less than 10) to establish the altered shape of the calibration curve. As a result of the previous work it was suggested that this change reflected an increase in density and stiffness of the sand over the diaphragm following repeated flexing of the diaphragm and it was postulated that this effect was most marked with the type of sand used — one of relatively uniform particle size. To test this observation, experiments were carried out using No. 4 type cells and a mixture of sand with varying

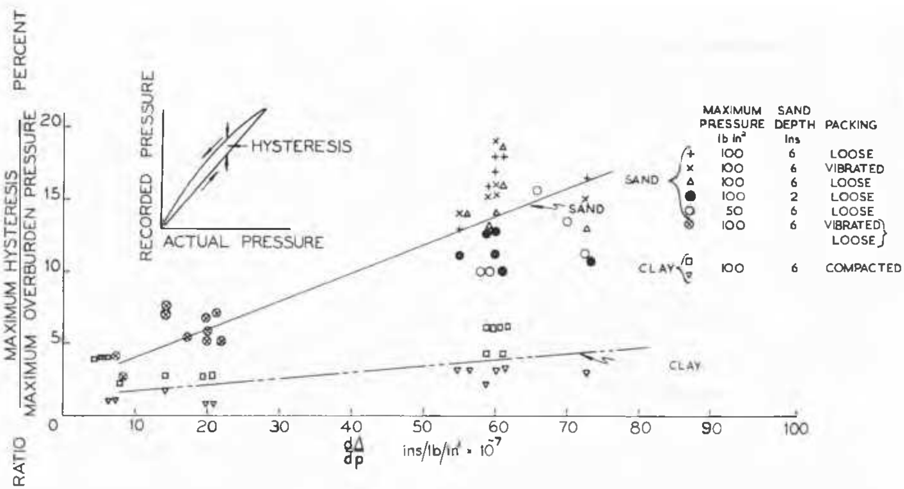
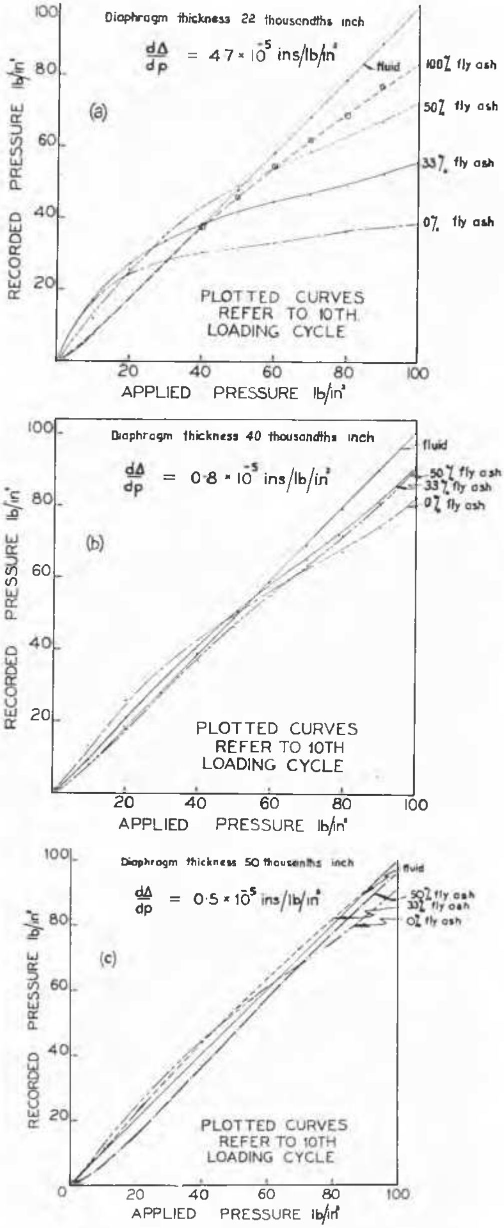


Fig. 7. The Relation Between Hysteresis and Diaphragm Flexibility.
Relation entre hystérésis et flexibilité du diaphragme.



8 *a*, *b*, *c*

Fig. 8 Calibration of Embedded Cells on Sand Fly-Ash mixes under Repeated Loading.

Étalonnage des capteurs enfouis dans des mélanges sable-cendres volantes pour des chargements répétés.

amounts of fly-ash. It had previously been establiched in the authors' laboratory that the fly ash behaved as a very fine lightweight granular material. The results of these tests are shown in Fig. 8 and it will be noted that there is a marked improvement with the more flexible diaphragms whereas with the stiffer diaphragms the effect is noticeable but negligible. Repeated loading tests were also carried out using No. 2 type cells with sand and clay. Fig. 9 shows the extreme variations obtained with the sand and Fig. 10 a typical result obtained with the clay. This topic has not been studied as exhaustively as the other aspects of cell behaviour, but it is clear from these results that the cells that are satisfactory from the point of view of the loading and unloading cycles are also satisfactory under repeated loading. It is also significant that the behaviour with clay in this respect is very much better than that with sand.

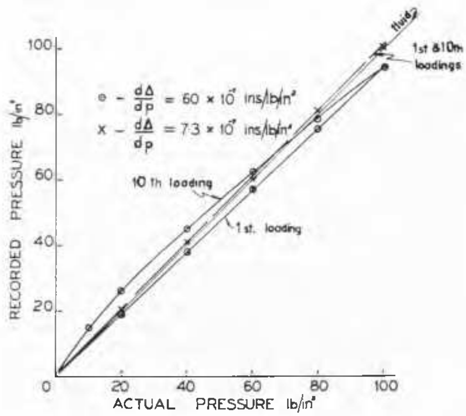


Fig. 9 Repeated Loading Calibration with sand.

Étalonnage pour des chargements répétés avec du sable.

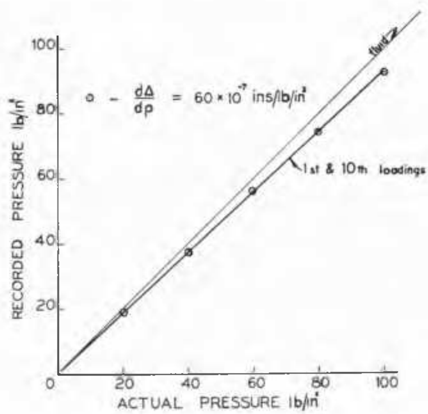


Fig. 10 Repeated loading Calibration with Clay.

Étalonnage pour des chargements répétés avec de l'argile.

Conclusions

1. The design of a deforming diaphragm type pressure cell is governed by the flexibility of the diaphragm. To limit the effects of soil density variation on loading, unloading, and repeated loading cycles within practical requirements the diaphragm should be designed so that $\frac{d\Delta}{dp}$ is less than 1×10^{-5} ins/lb./in^2 and preferably should be of the order of $0{\cdot}3-0{\cdot}5 \times 10^{-5}$ ins/lb./in^2. If this condition is satisfied then that of linearity of the calibration curve will be met provided the maximum deflection : diameter ratio is 1:2000.

2. The measurement of pressures in clay fills is likely to present far less difficulty than similar measurements in sands and gravels.

3. Satisfactory boundary cells, using the vibrating-wire measuring principle, have been developed and it is considered that this system is the best at present available for these purposes.

4. In the case of boundary pressure type cells the available instrumental accuracy is greater than that required, because of the inherent variation of soil properties. There is thus no obstacle to their widespread use. The situation is similar for large embedded cells required for field use, but more work is required on small embedded cells for laboratory purposes.

Acknowledgements

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