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PERFORMANCE OF CELLS DESIGNED TO MEASURE SOIL PRESSURE ON EARTH RETAINING STRUCTURES

by

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ABSTRACT

As part of the TRRL research programme to investigate the earth pressures developed against retaining structures, a laboratory study has been made of the performance of three types of pressure cell designed to measure the pressures developed at the boundary between the structural wall and the soil. The three cells tested were a hydraulic, a strain gauge and a pneumatic type pressure cell. The influence of soil type on cell calibrations was studied using washed sand, sandy clay and heavy clay.

The relations between applied and recorded pressure for the three types of pressure cell are given for each soil type and the main factors influencing these relations are considered. The errors in cell registration were shown to depend not only on the physical properties of the soil and cell, but also on the nature of the compaction and testing procedure. The study has shown that suitable correction can be made for errors in cell registration provided laboratory calibrations of the pressure cells have been carried out in conditions which closely simulate the situations in which the instruments are to be employed.

1. INTRODUCTION

As part of the TRRL research programme to investigate the behaviour of earth retaining structures, a laboratory study has been made of the performance of three types of pressure cell designed to measure the pressures developed at the boundary between the structural wall and the soil.

The presence of a pressure cell can appreciably alter the stress distribution in the soil near to the instrument and, as a result, the cell may not register the true pressure. Although a considerable amount of information has been published giving details of the behaviour of pressure cells totally embedded in soil[1, 2, 3], much less information is available for the particular case of pressure cells mounted flush in a structural wall. A laboratory study was therefore carried out to assess the performance of the pressure cells when calibrated in three different soil types. In addition, the influence of repeated loading and frictional forces on the wall surface adjacent to the cell was considered.

2. PROPERTIES OF THE SOILS

The soils used in this study were described as a uniformly-graded washed sand, a sandy clay and a heavy clay. The particle-size distributions of the soils and the results of plasticity and specific gravity tests were determined according to BS 1377[4] and are shown in Fig. 1. In carrying out the study the soils were used at their natural moisture content and these values are also given in Fig. 1.

Additional information from undrained triaxial tests showed that the initial tangent modulus of both the sandy clay and the heavy clay remained between 18 to 25 MPa over a range of lateral pressure from 0 to 200 kPa. However tests on the washed sand showed an increase in modulus from 3 MPa at zero applied lateral pressure up to 90 MPa at 100 kPa of lateral pressure.

3. THE PRESSURE CELLS

Three types of pressure cell were used in the study to allow the influence on the results of different instruments to be investigated. The three earth pressure cells were of the following types:-

(i) Hydraulic cell

(ii) Strain gauge cell

(iii) Pneumatic cell

The overall diameter of all three cells was 140 mm, and in the case of both the hydraulic and pneumatic cells this also corresponded to the region over which the pressure cells were sensitive. However, the strain gauge cell had a slightly smaller working diameter of 114 mm. In all three cases, therefore, the ratio of cell diameter to soil particle size was larger than 50 and satisfied the design criteria proposed by other authors[5].

3.1 Hydraulic cell

The hydraulic cell has been described in detail by Irwin[6], but for completeness, the main components are shown diagrammatically in Fig. 2.

In operation, the soil pressure is applied to the upper surface of the cell. This pressure is transmitted through a 0.5 mm thick stainless steel diaphragm to a water-filled chamber beneath, where an electrical pressure transducer measures the water pressure.

3.2 Strain gauge cell

A cross-section through this cell is shown in Fig. 3. The cell consists of a Cambridge contact stress transducer[7] fitted with an enlarged top plate. The load is transmitted through this rigid top plate to thin aluminium webs which have foil strain gauges attached. The strain gauges are mounted in three separate bridge circuits enabling the normal force and its eccentricity, together with the uni-direction shear force acting on the top plate to be simultaneously recorded.

To avoid damage as a result of the large dynamic stresses developed when compacting soil during the specimen preparation, a locking system has been fitted to the cell. This comprises four micrometer screws located in the backing plate (Fig. 3). These screws can be adjusted to support the top plate of the cell to prevent movement.

3.3 Pneumatic cell

This type of cell was developed and patented by the Laboratoire des Ponts et Chaussées at Angers for measuring stresses within a soil mass.[8] However, the original dimensions of the cell were modified to conform with those of the other cells being studied.

The cell is shown diagrammatically in Fig. 4. Air pressure is applied to slightly inflate a 0.16 mm thick stainless steel diaphragm into the soil. During a measurement the flow of air through the cell is controlled to maintain a small and constant rate of flow of 0.08 litres/minute. The air pressure required to achieve this condition corresponds to the soil pressure acting on the cell.

4. PREPARATION OF THE SOIL SPECIMEN

Each cell was mounted in a recess located in the centre of a circular steel base of 540 mm diameter such that the surface of the cell was set flush with the surface of the base (Plate 1). A cylindrical metal container of height 300 mm was then fitted around the base to provide a mould in which to compact the loose soil. The container was well lubricated to minimise sidewall friction during compaction.

Compaction procedures were adopted which ensured a high and uniform density without overloading the pressure cells. Prior to compaction, both the sandy clay and heavy clay soils were broken down to lumps of less than 12 mm diameter. The loose soil was carefully spread and levelled over the base of the container and compacted in 25 mm thick layers. In the case of the sand, compaction was achieved by means of a vibratory compactor attached to a plate of the same diameter as the base. The sandy clay and heavy clay were compacted by directly loading this plate in a compression testing machine.

On completion of compaction the top surface of the soil specimen was trimmed level. When the mould was removed all three soil specimens stood unsupported (Plate 2), as even the sand was slightly cohesive when used at its natural moisture content. A rubber top cap and thin rubber sleeve were then used to completely seal the specimen as shown in Plate 3.

The bulk density of each soil specimen was determined from the volume of water displaced when the specimen, still sealed in the rubber sleeve, was totally immersed. The average bulk density and air void content for each soil is shown in Table 1.

TABLE 1

Density and air void content for each soil type

Soil type	Method of compaction	Moisture content %	Bulk density Mg/m^3	Air void content %
Washed sand	Vibration	9.3	1.85	19.8
Sandy clay	Direct loading	16.8	1.96	9.8
Heavy clay	Direct loading	28.4	1.94	2.1

5. EXPERIMENTAL PROCEDURE

When the soil specimen had been prepared, it was then immersed in a large water-filled pressure vessel. The pressure in this vessel was increased in increments of 20 kPa up to a maximum value of 160 kPa and readings from the cell were taken immediately following the application of each increment of pressure. Each pressure cell was calibrated over two cycles of loading and unloading. This procedure was repeated for all three types of cell employed in the study.

In the above series of tests the soil specimen was directly in contact with the metal base plate. The influence of interface friction on the results of the calibrations was investigated during a further series of tests in which the soil specimen was separated from the base plate by two sheets of 0.5 mm thick rubber. A thin layer of grease was spread over the base plate and between the sheets of rubber before placing and compacting the soil. With this arrangement it was considered that friction between the base plate and the soil specimen was virtually eliminated.

6. RESULTS OF CALIBRATION TESTS

6.1 Effect of repeated loading

The relation between measured and applied pressure for the hydraulic cell, obtained from the repeated loading of a sandy clay specimen, is shown in Fig. 5. The results indicate that some degree of hysteresis is present as the pressures recorded during unloading are up to 10 kPa higher than those recorded during loading. The magnitude of the hysteresis was found to decrease on repeated loading. A similar hysteresis was observed with the other soil and cell types and is attributed to the increase in density and stiffness of the soil adjacent to the cell face as a result of the repeated deflection[2].

The first loading cycle corresponds most closely with the conditions which apply when compacting soil against a retaining structure and further discussion is therefore limited to this loading cycle. However, although no further reference is given to the topic in this report, the reloading cycles are of value in assessing the accuracy of pressure cell measurements in situations where large fluctuations in soil pressure are expected.

6.2 Cell calibrations with different soil types

The calibration curves for sand, sandy clay and heavy clay are shown in Figures 6, 7 and 8 respectively. Two plots are shown for each soil type and these relate to the frictional and "frictionless" base conditions. Each figure includes the line based on the "ideal" pressure relation determined by calibrating the cell in an air-filled pressure vessel.

As shown in the figures, the initial value of applied pressure was about 6 kPa which corresponded to the deadweight of the soil specimen. The initial recorded pressures vary slightly about this value according to the cell and soil type (see Section 7). The initial results may also be slightly influenced by any residual stresses left after the placing and compaction of the soil.

6.3 Reproducibility of calibrations

The reproducibility of results was investigated by two further tests using each pressure cell. To minimise the work involved but still ensure that the range of soil types was investigated, the tests were performed using a different soil for each pressure cell. The results, shown in Fig. 9, indicate that in all cases the individual calibrations were within 7 kPa of the mean curve determined from the three tests. The largest variation in results occurred with specimens of sandy clay and this reflected the difficulty in ensuring that the soil specimen was uniformly compacted.

7. DISCUSSION OF RESULTS

The factors which were considered to have the greatest influence on the results of the calibration tests were the characteristics of the pressure cell, the type of soil and the friction across the base. Each of these factors is discussed individually in the following sub-sections.

7.1 Characteristics of the pressure cells

The error in cell registration, defined as the difference between the measured and applied pressure, is shown plotted against the applied pressure for each pressure cell in Fig. 10. The strain gauge cell under-registered with all three soils throughout most of the pressure range, whilst conversely the pneumatic cell over-registered. The hydraulic cell usually showed a slight under-registration in pressure, although in particular circumstances either a large over- or under-registration has occurred. A further discussion of these anomalies when using the hydraulic cell is given in section 7.3.

The results are generally consistent with the behaviour which might well be expected from a consideration of pressure cell theory[5]. For pressure cells, such as the strain gauge and hydraulic cells, in which the measurements are obtained by the cell plate or diaphragm moving away from the soil, the readings will be less than the applied pressure. The magnitude of this under-registration depends on the relative stiffness of the cell and soil. Conversely the pneumatic cell, whose diaphragm is inflated into the soil to record, over-registers as passive thrusts are created in the soil near to the instrument.

An alternative method of operation can be used with the pneumatic cell which produces a very different calibration. In the usual method of operation the diaphragm is inflated into the soil whenever a reading is required and then deflated. However, a calibration on sand was performed employing a technique whereby the cell diaphragm was kept continuously inflated. This result is shown in Fig. 11 and produced a significant under-registration. It is therefore important to ensure that a standard method of operation is developed and adhered to thereafter if the results of pressure cell readings are to be meaningful. For the purpose of this study all subsequent calibrations of the pneumatic cell were completed using the "interrupted" flow technique.

7.2 The type of soil

The results of the calibrations using sandy clay and heavy clay indicated that the curves became more linear with increasing applied pressure as seating effects caused by the compaction procedures were overcome. Moreover fairly good agreement was obtained between the measured and applied pressures for all three types of cell using the heavy clay as shown in Fig. 8. These results are attributed to plastic flow occurring in the heavy clay which relieved anisotropic stress conditions as the soil was used at a moisture content above the plastic limit. However, it may well be expected that at a lower moisture content the calibration with heavy clay could approximate to that obtained from the sandy clay.

The undrained triaxial tests on the sand showed that the tangent modulus varied significantly over the pressure range involved in the calibrations (section 2). This increase in stiffness with applied stress together with the granular nature of the soil increased its ability to support an "arch" of sand over the cell face. This arching effect has been described as the formation of a rigid zone of sand over the cell face[9]. Consequently the strain gauge and hydraulic cells having faces which depress under the action of pressure, showed a larger under-registration with sand than with the other soils as some of the load applied to the sand specimen was carried by the arch of sand which formed over the cell face. The under-registration was most marked with the strain gauge cell and the cell error rapidly increased with the applied pressure (Fig. 10). The hydraulic cell was less susceptible to arching as not only was the cell stiffer but, unlike the strain gauge cell, the action of the hydraulic cell diaphragm does not produce a discontinuity at the cell edge. The pneumatic cell having a diaphragm which is inflated into the soil to record is not susceptible to arching and records a similar value with both the sand and sandy clay.

7.3 Friction across the base

The magnitude of the frictional forces across the base were found to influence the performance of the diaphragm-type cells, although the performance of the strain gauge cell with its rigid top plate remained unchanged. A comparison of cases (a) and (b) in Figures 6 and 7 showed a decrease of about 20 per cent in the measured pressures for both the hydraulic and pneumatic cells when tested using the frictionless as opposed to the frictional base. The results suggested that a reduction in the lateral stress caused by friction across the base appreciably changed the nature of the stress distribution in the soil immediately over the cell face. This change adversely affects the accuracy of diaphragm-type cells[3, 5]. In addition the variation in the shear force across the face of the hydraulic cell, which has its diaphragm supported by water, may produce a change in the deflected shape of the diaphragm such that localised passive thrusts are created in the soil over the cell face. These effects were thought to account for the unexpected over-registration of the hydraulic cell tested in sandy clay.

The response of all three pressure cells in the heavy clay (Fig. 8) was found to be independent of base friction, as plastic flow occurred to maintain equal stress conditions over the cell face.

8. CONCLUSIONS

The performance of three types of pressure cell designed to measure the boundary stresses developed by the soil behind a retaining structure has been assessed by laboratory calibration.

The pneumatic type cell was found to over-register in each of the three soils tested, but had the advantages of simplicity of operation, low cost and having no requirement for any form of electrical power. The strain gauge cell always under-registered once any initial seating load had been overcome and was particularly suitable for a situation in which the stress distribution in the soil was non-uniform, or in which large shearing forces were expected across the face of the cell. The hydraulic type cell gave the closest agreement between measured and applied pressure, but its performance when large shear forces are present in the soil across the cell diaphragm needs to be further investigated.

The errors in cell registration were shown to depend not only on the physical properties of the soil and cell, but also on the nature of the compaction and testing procedure. The study has shown that suitable correction can be made for errors in cell registration provided laboratory calibrations of the pressure cells have been carried out in conditions which closely simulate the situations in which the instruments are to be employed.

9. ACKNOWLEDGEMENTS

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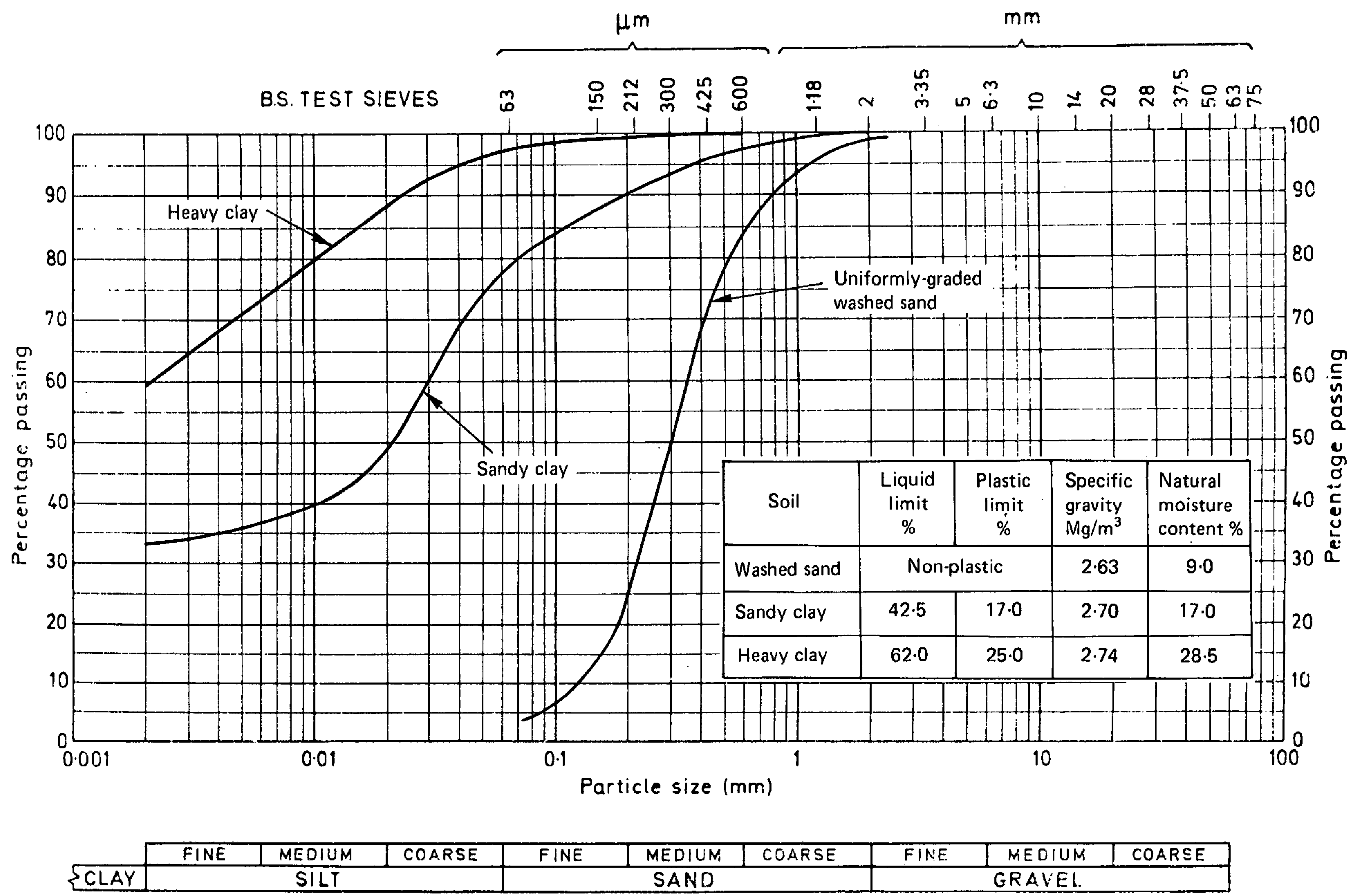

Soil	Liquid limit %	Plastic limit %	Specific gravity Mg/m^3	Natural moisture content %
Washed sand	Non-plastic		2·63	9·0
Sandy clay	42·5	17·0	2·70	17·0
Heavy clay	62·0	25·0	2·74	28·5

Fig. 1 PARTICLE-SIZE DISTRIBUTIONS AND RESULTS OF PLASTICITY AND SPECIFIC GRAVITY TESTS FOR THE SOILS

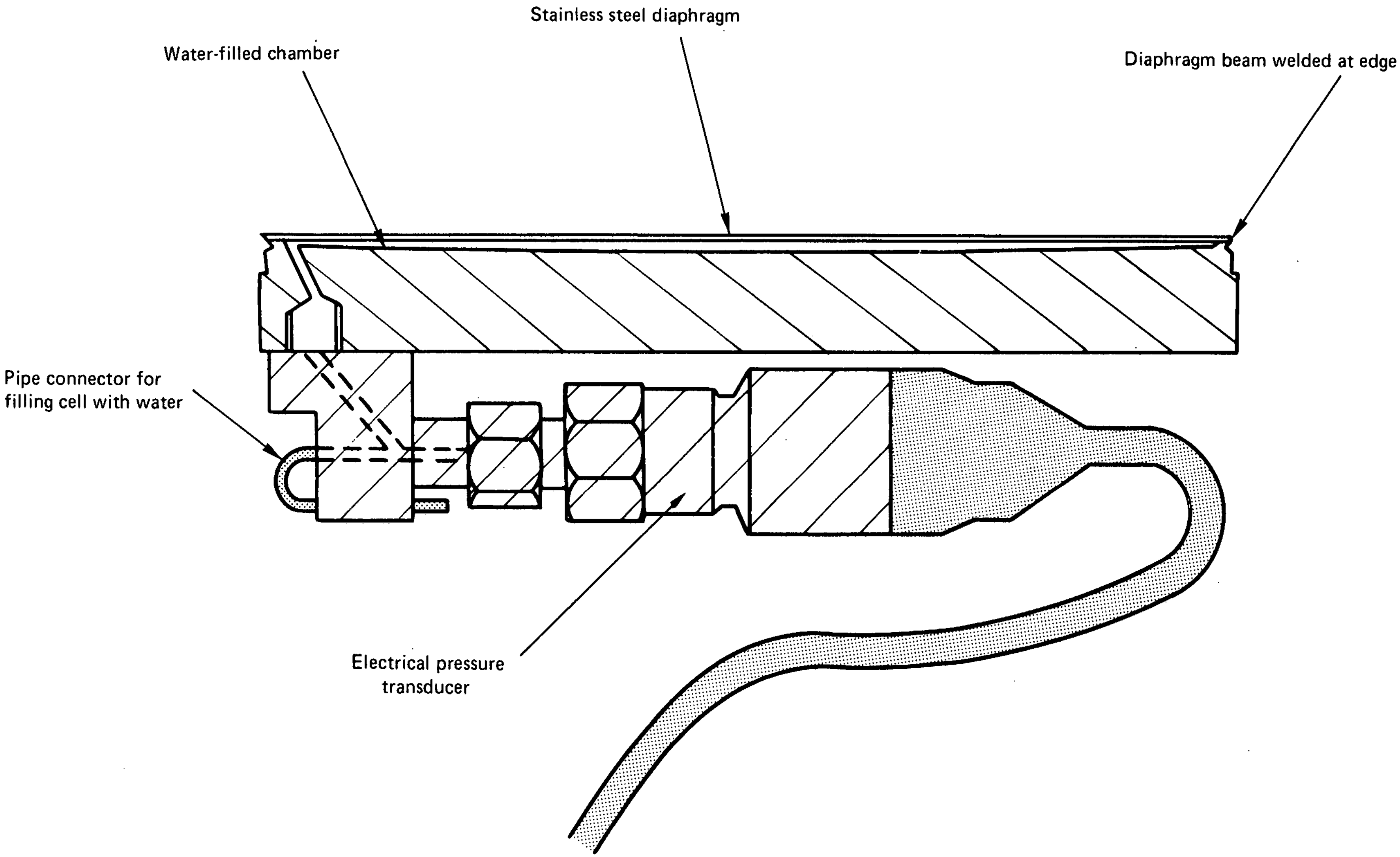

Fig. 2 SCHEMATIC VIEW OF HYDRAULIC CELL

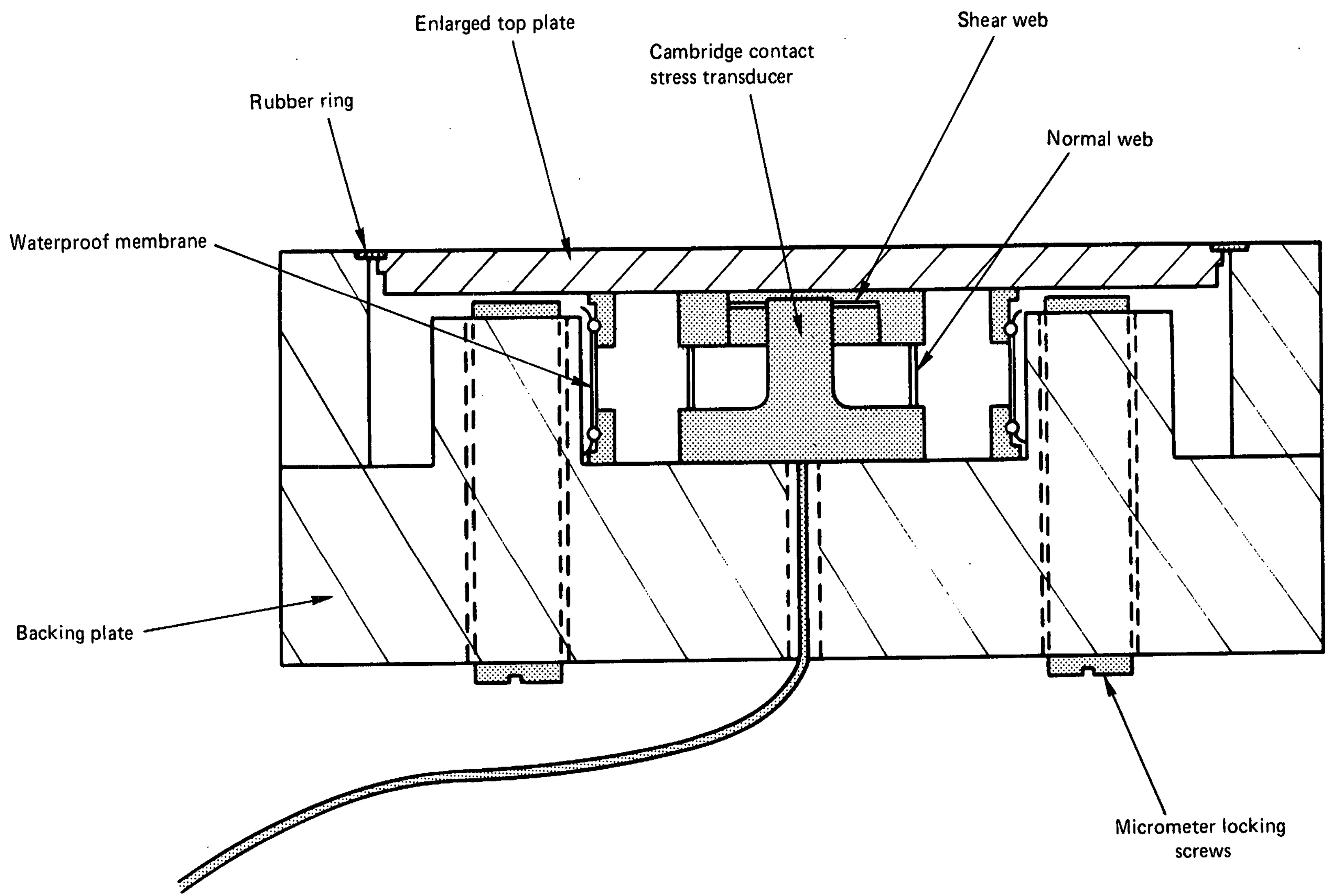

Fig. 3 SCHEMATIC VIEW OF STRAIN GAUGE CELL

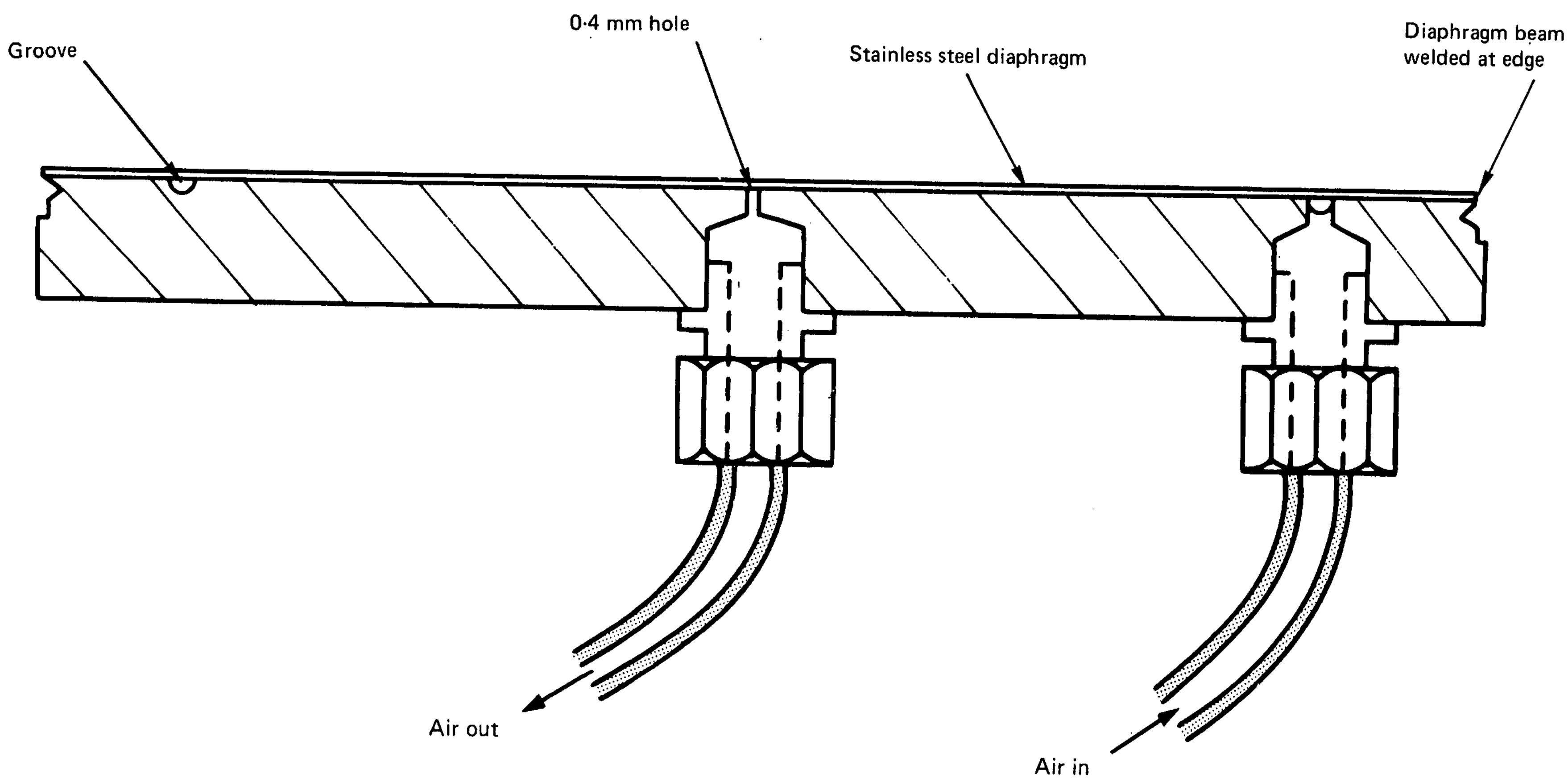

Fig. 4 SCHEMATIC VIEW OF PNEUMATIC CELL

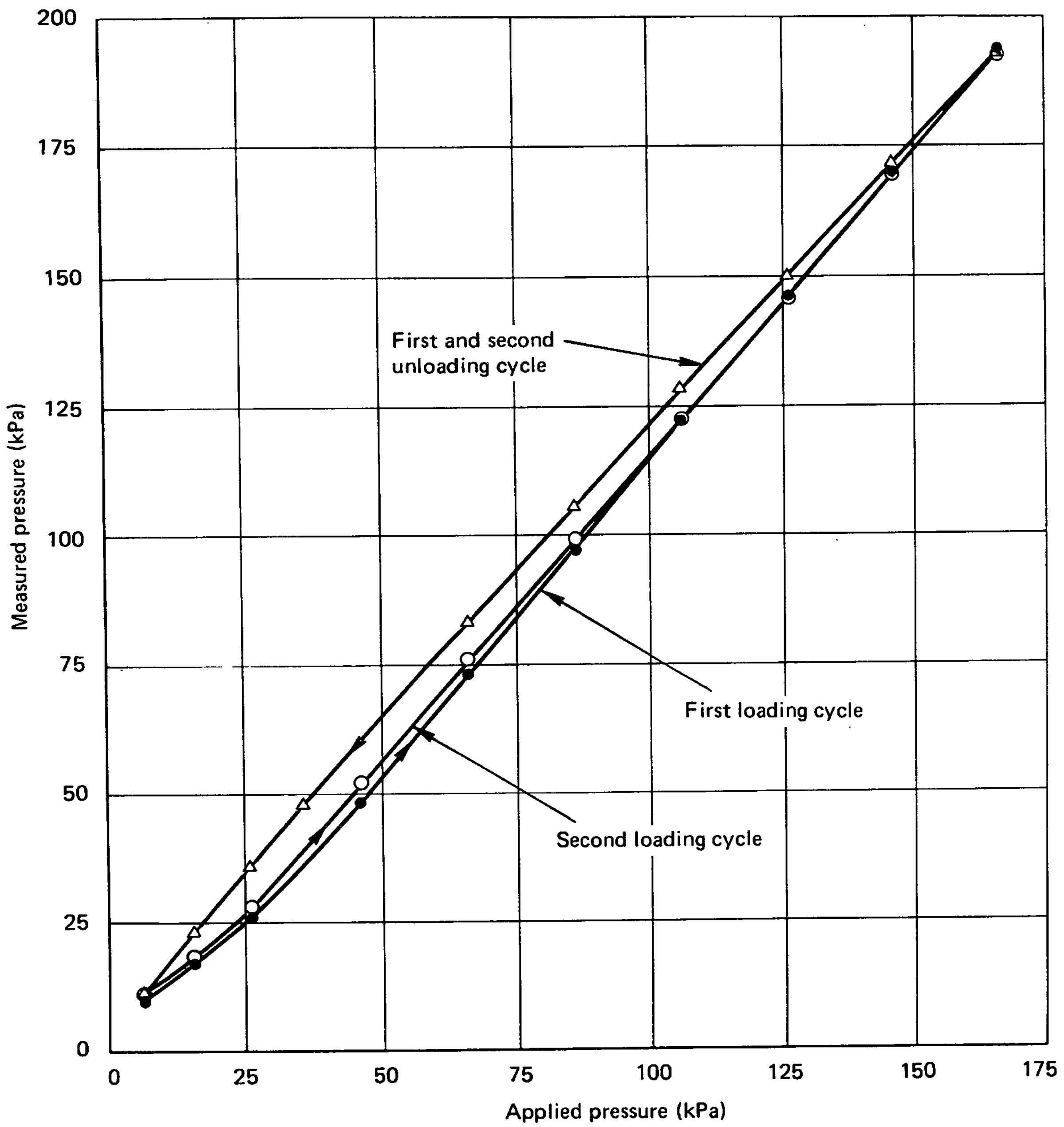

Fig. 5 HYDRAULIC CELL-EFFECT OF REPEATED LOADING AND UNLOADING OF SANDY CLAY SPECIMEN

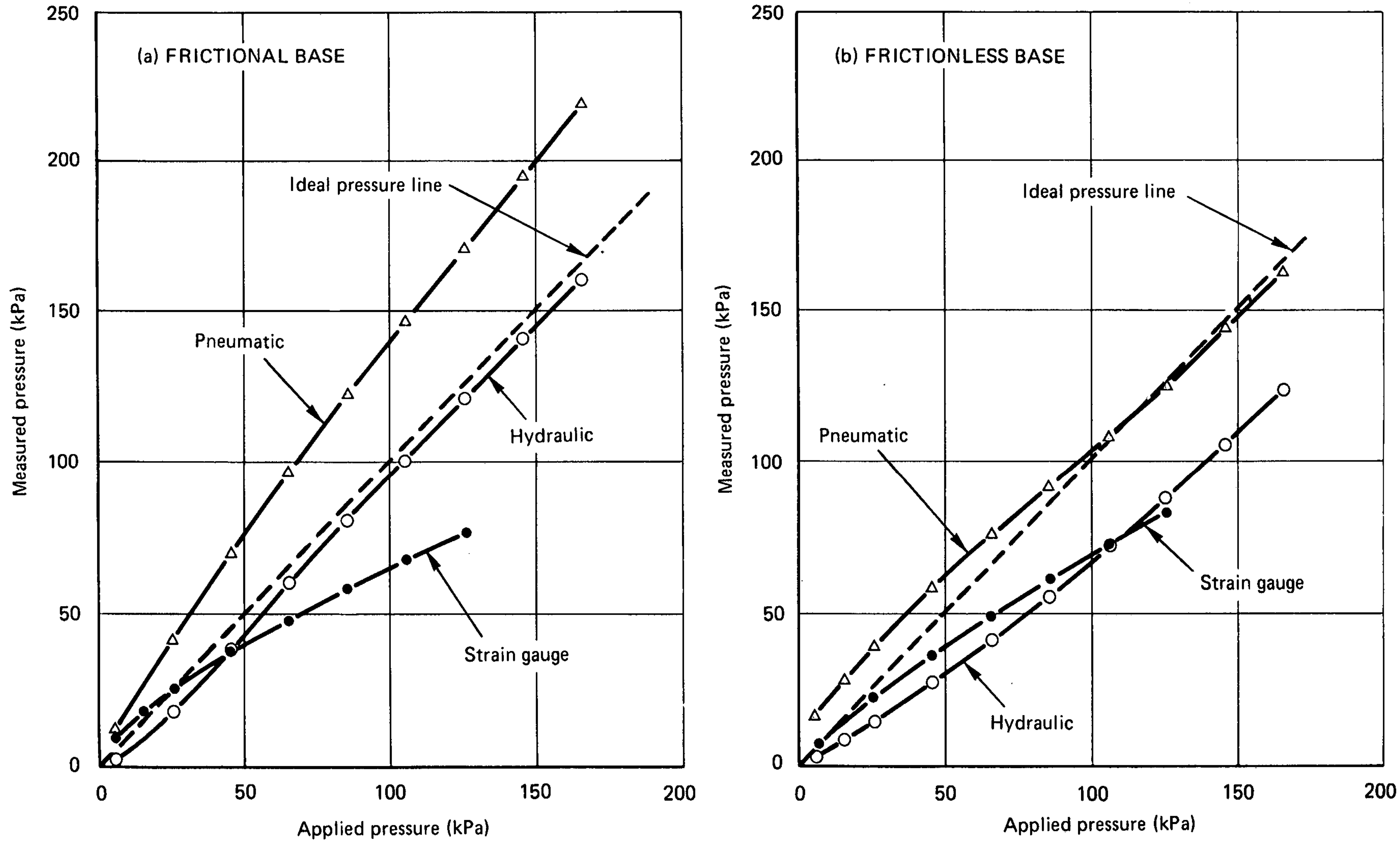

Fig. 6 CELL CALIBRATIONS USING WASHED SAND

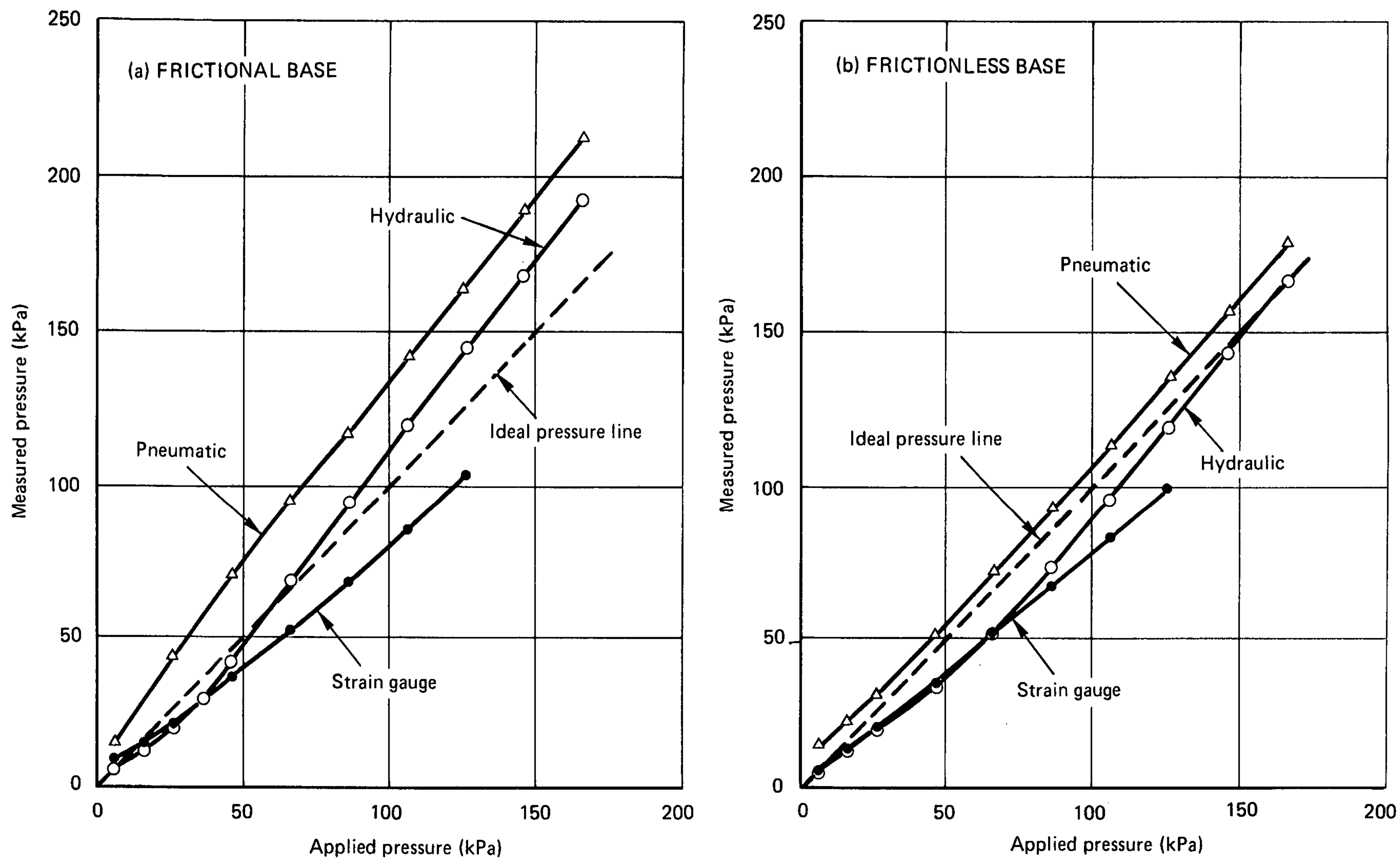

Fig. 7 CELL CALIBRATIONS USING SANDY CLAY

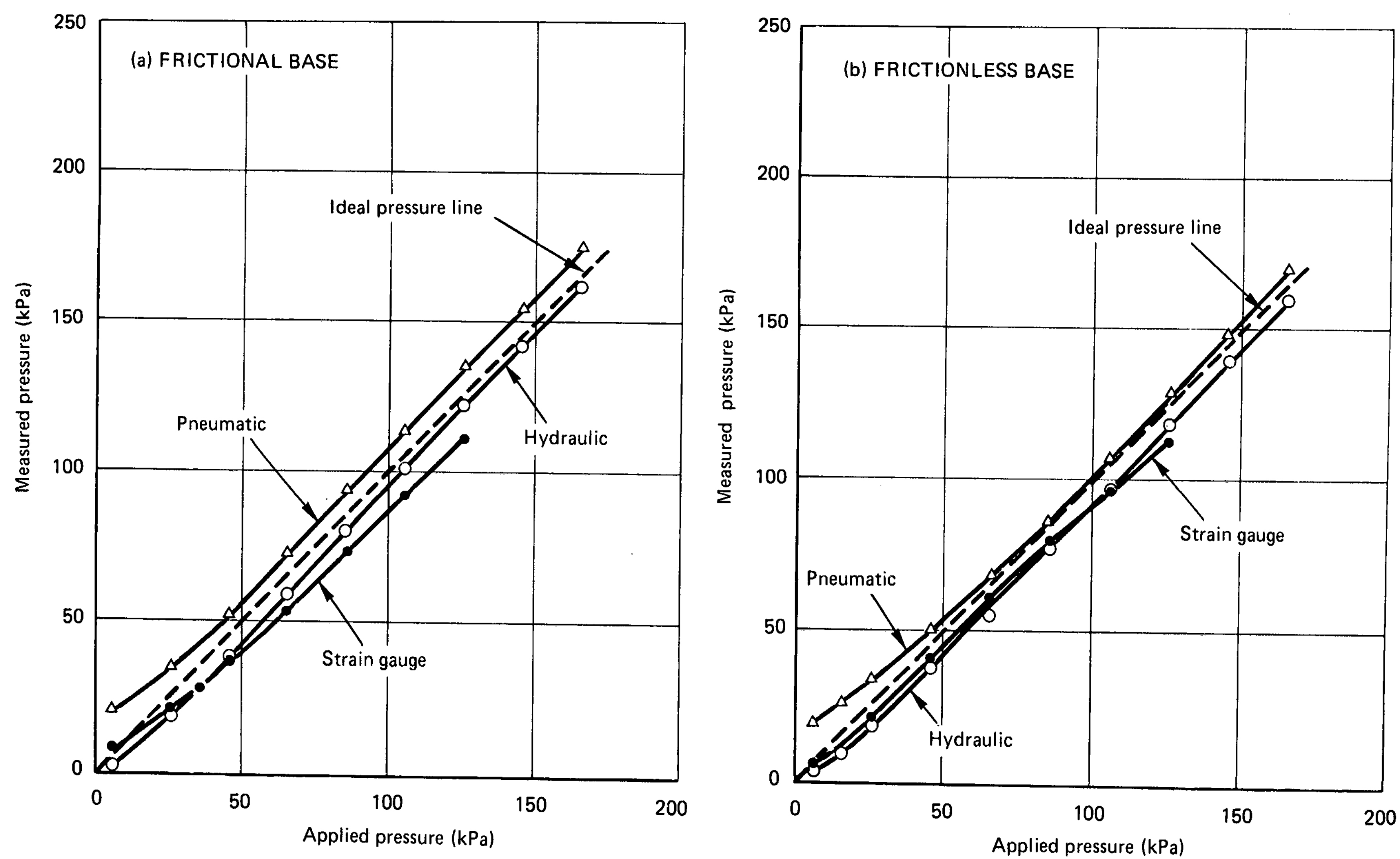

Fig. 8 CELL CALIBRATIONS USING HEAVY CLAY

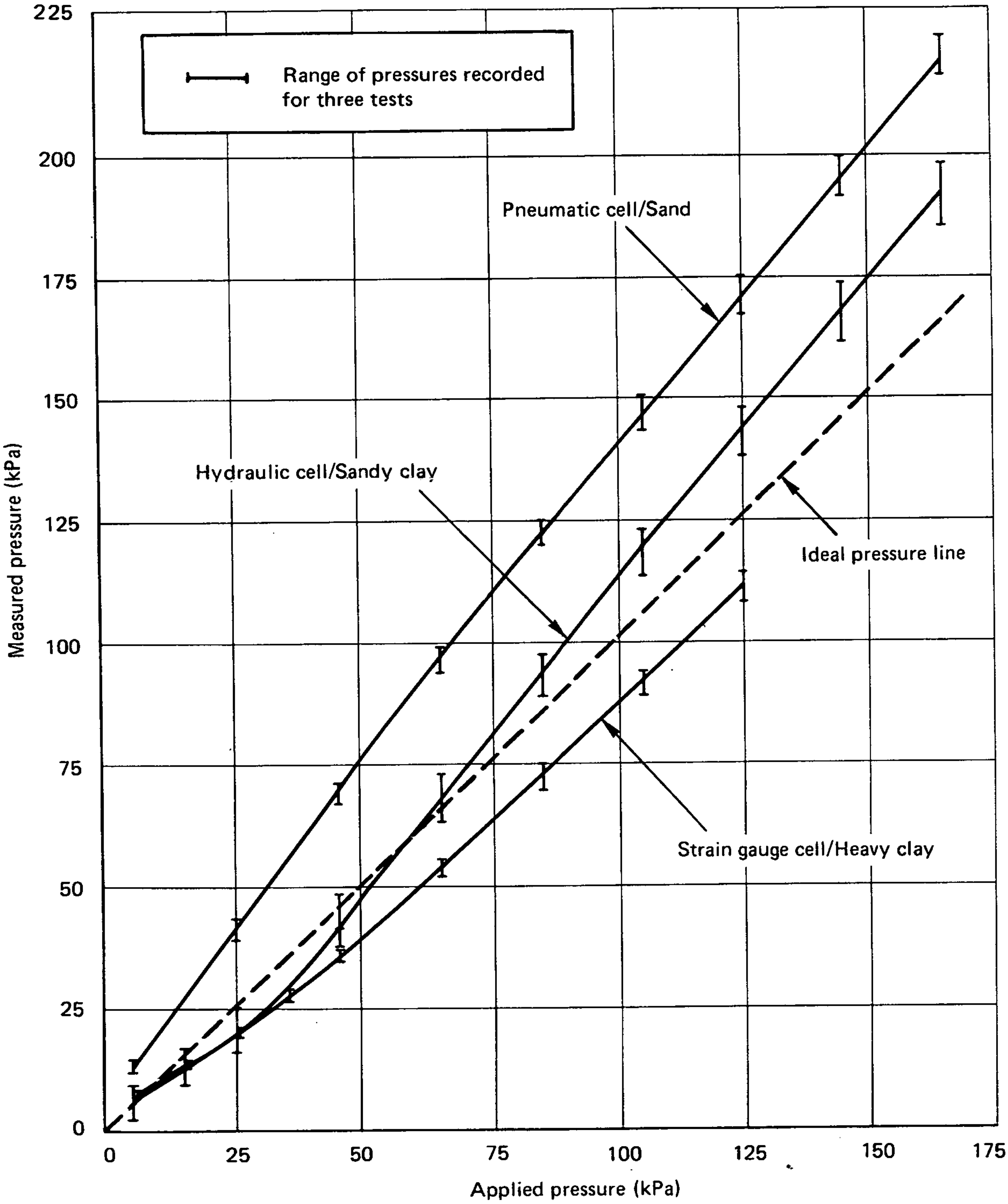

Fig. 9 REPRODUCIBILITY OF CELL CALIBRATIONS

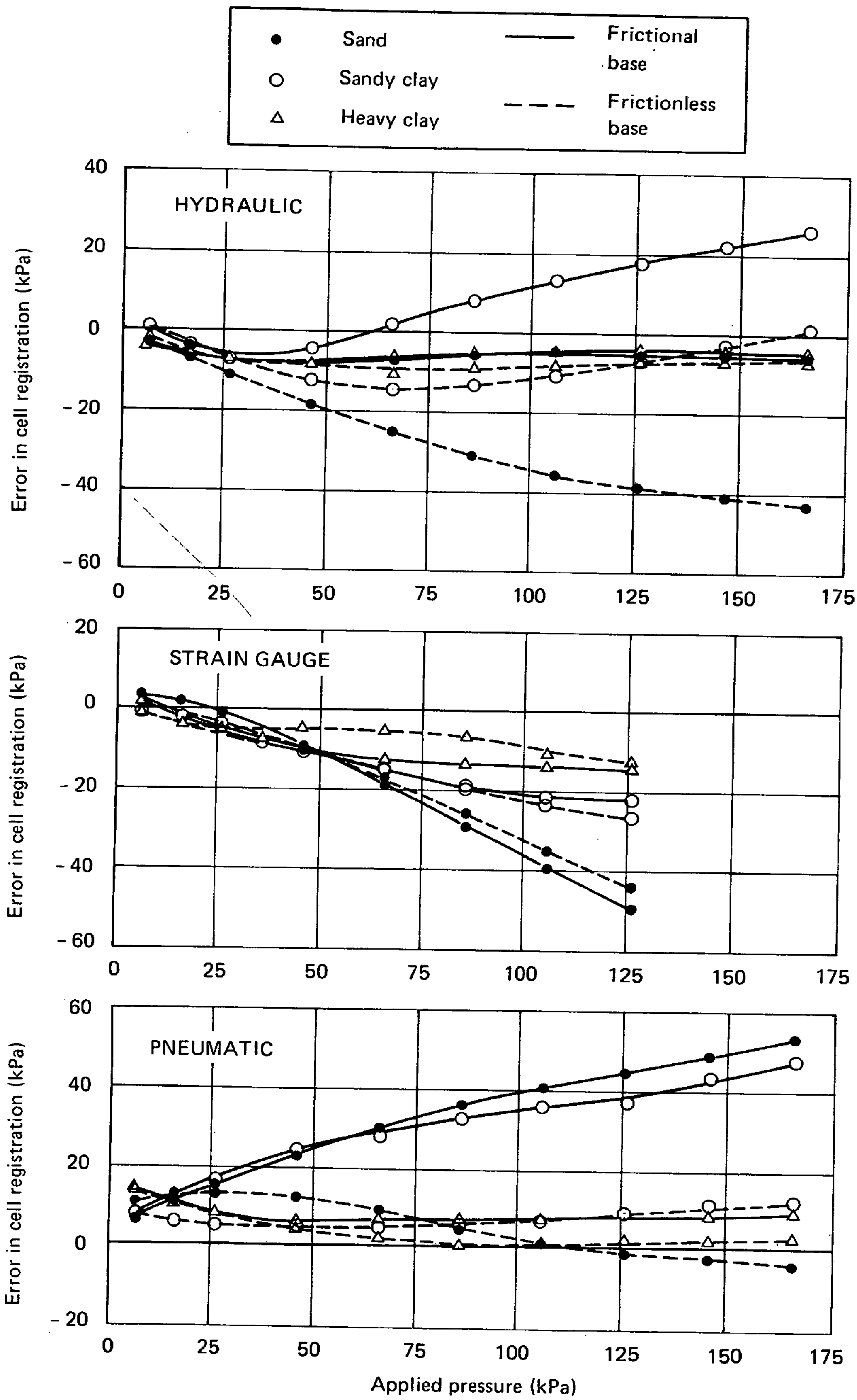

Fig. 10 COMPARISON OF CELL PERFORMANCE

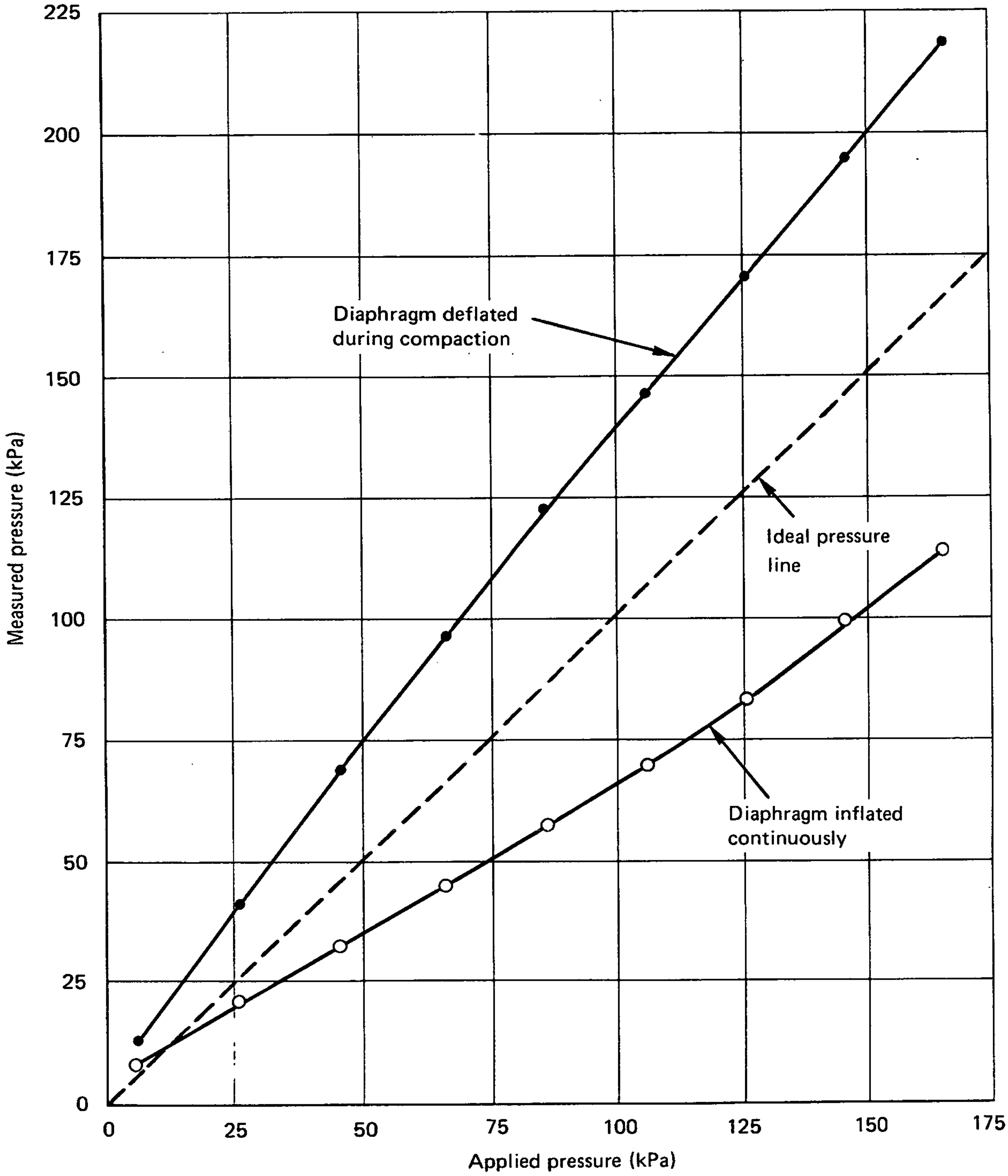

Fig. 11 PNEUMATIC CELL-EFFECT OF DIAPHRAGM INFLATION DURING COMPACTION AND TESTING OF SAND

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PLATE 1

Pressure cell mounted in base

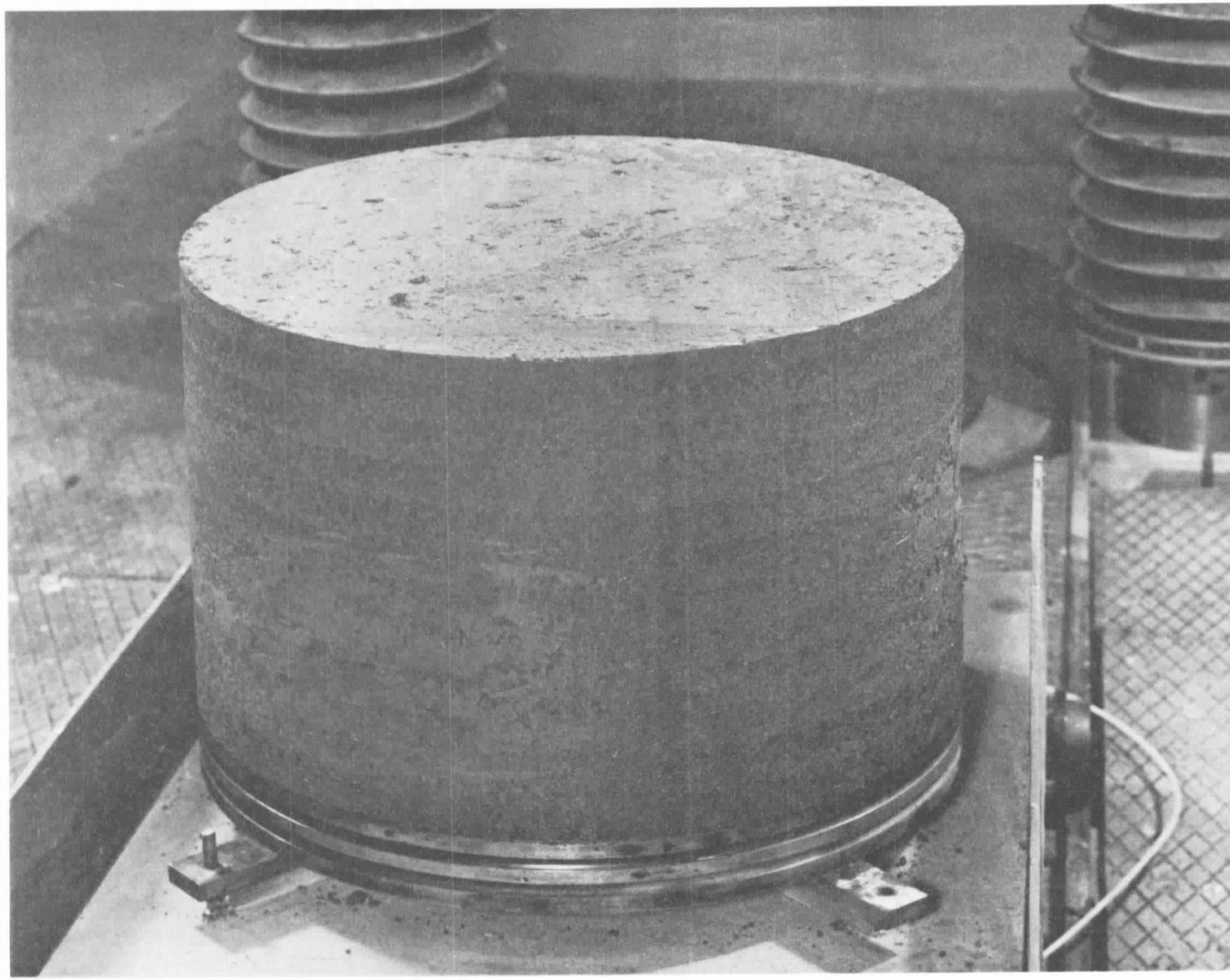

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PLATE 2

Sandy clay specimen after compaction

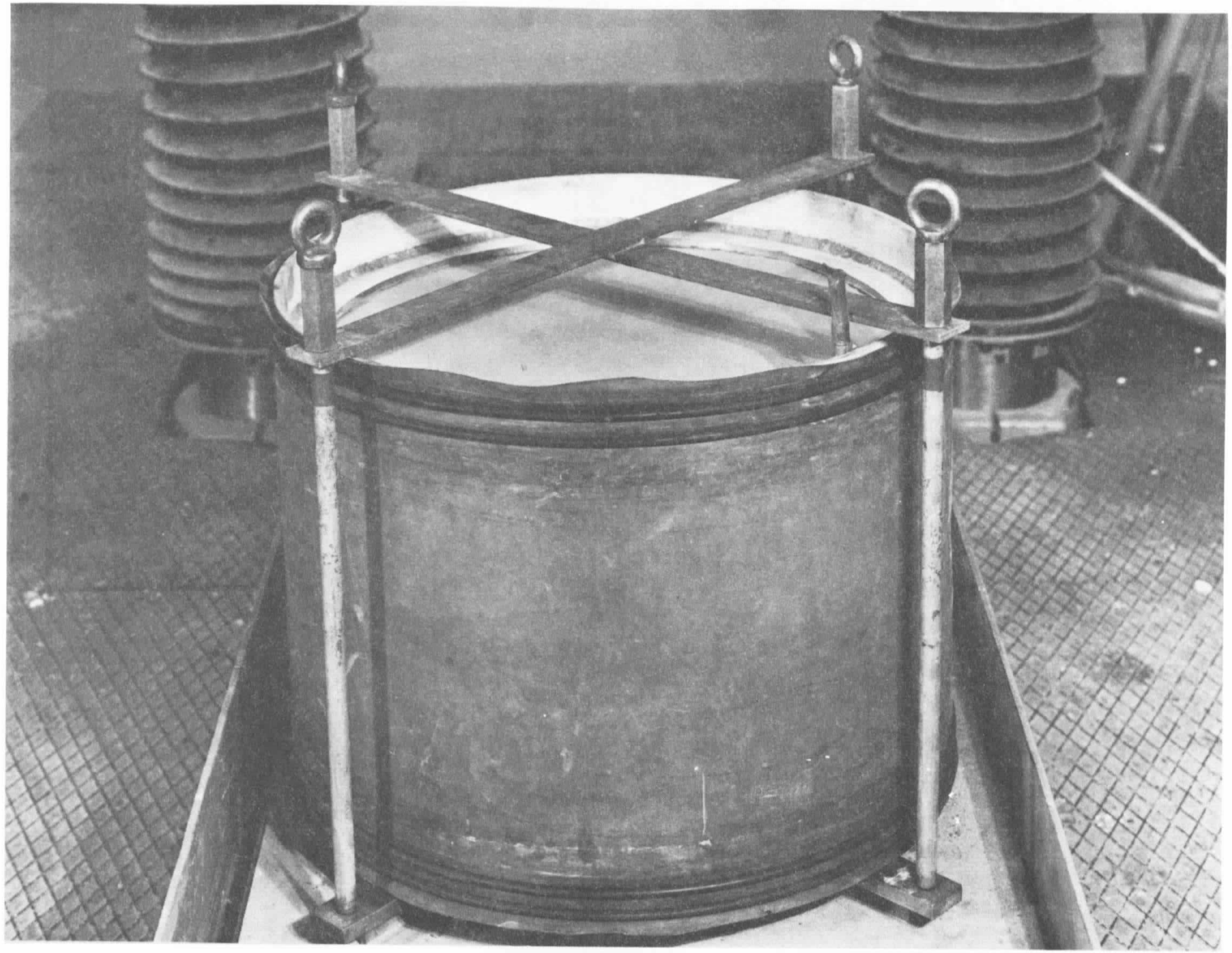

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PLATE 3

Specimen assembled for testing

(1661) Dd209410 2,050 11/75 HPLtd So'ton G1915
PRINTED IN ENGLAND

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