ROYAL SWEDISH

GEOTECHNICAL INSTITUTE

PROCEEDINGS

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INVESTIGATIONS OF SOIL PRESSURE MEASURING BY MEANS OF CELLS

By

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Preface

In 1942, the Swedish State Power Board appointed a committee to study soil pressure determination. In 1943, a report was made by Mr Walter Kjellman, member of this committee. This report contained a general theory of the influence of the cells on the pressure in soil. It also gave calibration results for different Swedish soil-pressure cells. One of them was of Mr Kjellman's own design. None of the cells showed an acceptable life in the field. Therefore, research into this problem was begun in 1946 at the Royal Swedish Geotechnical Institute, whose head Mr Kjellman was at that time. This research was sponsored by the Swedish State Committee for Building Research. Mr Kjellman and Mr Torsten Kallstenius—Head of the Mechanical Department of the Institute—started more far-going investigations. Since 1948, Mr Werner Bergau, of the same department, has been a full-time participant in this work.

Stockholm, May, 1956

Royal Swedish Geotechnical Institute

§ 1. General Considerations and Object of Investigations

§ 1 a. Introduction

Soil pressure measurements have been treated in a great number of publications. Only some of them—which are of special interest in this connection—are given in the Bibliography (see the end of this report).

The soil pressure on a structure can be determined indirectly, by measuring the stresses in the structure or the reactions between the structure and supporting elements outside the structure. In many cases, however, this type of measurement is not possible. The soil pressure can then be measured directly by means of pressure cells. The indirect method is preferable in a great number of cases because the evaluation of cell records may be intricate.

A study of what has been done to develop such cells produces the impression that special emphasis has generally been laid on the instruments. Only few authors have fully considered the very great importance of the influence of the cell on soil pressure distribution.

As early as in 1913, A. T. Goldbeck (8)[1], the pioneer of soil pressure cell design, discussed this problem. He tried to solve it by fitting a rim around the piston and by using a—as he deemed—very small piston travel.

Theoretical studies of the influence of pressure cells on pressure distribution have been made by Carlson, Hast (9), Kjellman (12), Taylor (26), Walén (31), and others. Laboratory tests have been performed by Benkelman and Lancaster (1), Goldbeck (8), Hast (9), Kögler and Scheidig (14), and W.E.S. [Osterberg (19) and Taylor (26)].

It is obvious that soil pressure measuring is still in a preliminary phase of development, and much research remains to be done. When some authors claim that they have obtained very high accuracies in measurements, this may be a specially favourable case of measurement or this may be due to underestimation of the difficulties connected with disturbances of stress distribution in the soil.

This report can give no definite solution of the problem, but may contribute to its elucidation.

§ 1 b. Object of Investigations

As the Institute wanted to measure soil pressures, in the first place those acting on retaining walls and other structures, and as previous experience had shown that soil pressure measurement is a difficult problem, the investigations were confined to cells embedded flush in walls. The influence of the cell cover

[1] The numbers in parentheses refer to the bibliography at the end of this report.

movement on the pressure distribution in the soil was not sufficiently well known, and should be specially investigated.

It was intended to design a cell that could measure soil pressures with an accuracy of about $\pm 5\,\%$ over a period of about ten years.

§ 2. Considerations on Cover Movement

§ 2 a. Circular Surface Moving into Elastic Medium

If a circular surface moves into a semi-infinite elastic medium which is isotropic and follows Hooke's law, the pressure distribution can be calculated by using the theory of potentials. By means of this theory we can obtain the average increase in stress on the surface for a certain definitive travel of, for instance, the centre of the surface. We can deduce the expression

$$\Delta \sigma = \frac{\delta}{2\,a} \cdot E \frac{m^2}{m^2 - 1} \cdot C \qquad (1)$$

where $\Delta \sigma =$ average change in stress on the surface,
$\delta =$ travel of centre of surface into the medium (deflection),
$a =$ radius of circular surface,
$E =$ modulus of elasticity of medium,
$\frac{1}{m} =$ Poisson's ratio of medium,
$C =$ constant depending on the deformation of the surface.

The constant C has been deduced from Boussinesq, as interpreted by different authors, (10), (16), for different kinds of surface curvature and is shown in the table below.

Table 1.

Surface	Stress distribution	C
Part of a sphere	Ellipsoidal; maximum at centre	$\frac{8}{3\,\pi} = 0.85$
Liquid surface	Uniform	1.0
Rigid plane surface	Infinite stresses at periphery; minimum at centre	$\frac{4}{\pi} = 1.274$

We observe that the average increase in stress is in theory influenced only within about $\pm 20\,\%$ by the kind of stress distribution on the contact surface.

The normal stresses in the medium outside the circular surface were here assumed to be zero.

§ 2 b. Circular Surface Moving away from Elastic Medium

Here we assume the circular surface to be surrounded by an infinite rigid surface. Between the elastic medium and the boundary surface acts an initial normal stress $= \sigma_o$, which tends to give the medium a displacement in the same direction as that of the movement of the circular surface. For an infinitely small travel, Eq. (1) may be assumed to be applicable, but as the travel increases, an increasing part of the normal stresses will be taken up by the rigid surrounding plane until at last the circular surface is entirely relieved from stresses (*cf.* Fig. 1 b).

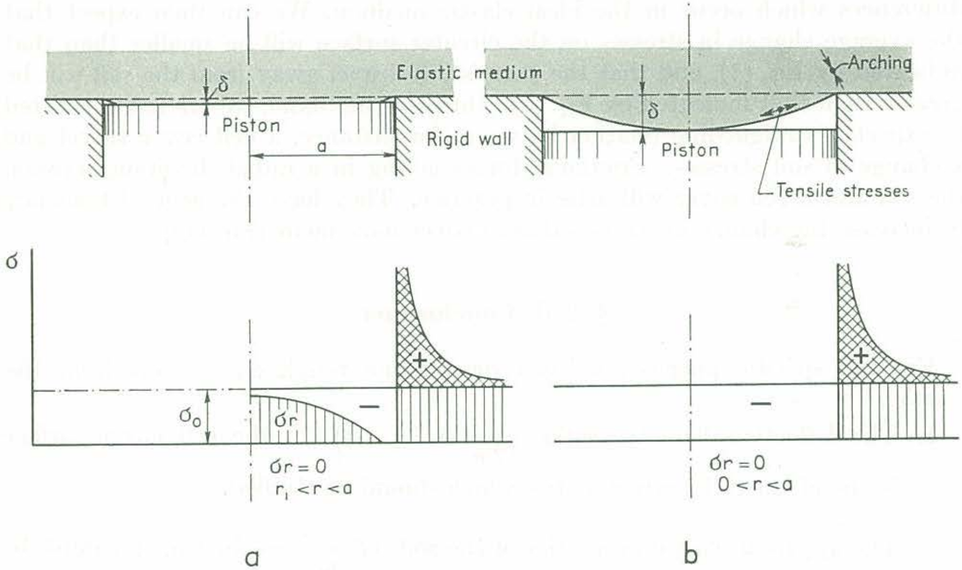

Fig. 1. Cell moving into a wall.

It seems thus that the rate of decrease in the average stress when the circular surface moves away from the medium is greater than the rate of the corresponding increase in stress when the movement is opposite.

As has been shown by Walén (31), if the circular surface is part of a sphere, contact will be discontinued when

$$\delta = \frac{m^2 - 1}{m^2} \cdot \frac{\sigma_0}{E} \cdot a \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

It is obvious that this expression is also valid for those surfaces which lie outside the spherical surface of the medium.

§ 2 c. Replacement of Elastic Medium by Soil

A soil differs from the ideal elastic medium in several important respects, for instance,

1. A soil has a limited shear strength and often a negligible tensile strength,
2. A soil is semi-plastic,
3. A soil is anisotropic and does not follow Hooke's law, and
4. A soil cannot always be regarded as unlimited.

The effects of these soil properties on Eqs. (1) and (2) are stated in what follows.

Limited shear strength and semi-plasticity will tend to reduce the stress differences which occur in the ideal elastic medium. We can then expect that the average change in stresses on the circular surface will be smaller than that indicated by Eq. (1), and that the permissible travel away from the soil will be greater than that indicated by Eq. (2). On the other hand, we are not permitted to expect a straight-line relation between, for instance, a cell cover travel and a change in soil stresses. Frictional forces acting in a radial direction between the soil and a cell cover will arise in practice. They have the general tendency to increase the change in stresses due to cover movement [Eq. (1)][1].

§ 2 d. Conclusions

For our specific purpose, we can draw some rough conclusions from the above.

1. The deflection-diameter ratio $\left(\frac{\delta}{2\,a} \text{ in Eq. (1)}\right)$ of the cell cover surface is one of the cell characteristics which should be studied.
2. The apparent elastic properties of the soil $\left(E\,\frac{m^2}{m^2-1} \text{ in Eq. (1)}\right)$ must be studied when calibrating cells also with regard to the boundary conditions.
3. The stress conditions, which are dependent on the shape of the deformed cover, especially the conditions near the edge, are of interest.
4. When the cover moves into the soil, the obtained change in average stress should be smaller than that indicated by Eq. (1) owing to the semi-plastic properties of the soil.
5. When the cover moves away from the soil into the wall, the change in stresses should be smaller than that indicated by Eq. (1) so long as the travel is very small, and should be greater if the travel is greater.

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[1] In this publication we have confined ourselves to explain the behaviour of soils in terms of the classical theory of elasticity in the way hitherto generally accepted. At the Institute, however, new theories have been conceived directly based on the specific nature of soils. These theories, worked out after preparing this manuscript, will certainly give a better approach to the understanding of soils and will be published separately.

§ 3. Considerations on Cell Cover Types

The cell cover acts as a transmitting organ between the soil and the measuring system. The type of deflection and the type of the cell cover are of great importance. Some of the principal cover types are therefore discussed below.

§ 3 a. Plane Rigid Piston

A plane rigid piston is very suitable for taking eccentric loads, which are common in soil pressure measurements. The piston may be either long and axially guided or short and resting on a flexible circumference. In both cases the piston transmits the whole load applied to it directly to the support.

For a given travel, the piston produces a maximum change in displaced volume, and is therefore suitable for using a fluid as a pressure-transmitting agent.

The very steep stress gradients (Fig. 1 a) obtained in the soil at the edge of the piston may cause plastic flow or even rupture, and must be specially considered. In frictional soils this gives a kind of "edge effect".

Sometimes the great thickness, required to obtain "rigidity" of the piston, is a drawback.

§ 3 b. Flexible Membrane Built In at its Periphery

The deflection of a flexible built-in plate under a load is dependent on the bending moment of the load. Thus, an eccentric load causes a smaller deflection than a centric load of the same magnitude. This is a disadvantage of the flexible membrane, but at the same time it makes the membrane less sensitive to disturbing factors near the periphery. As the deflection curve is continuous, the stresses in the soil are more uniform, and stress equalization by plastic flow is less probable than in the case in § 3 a. The maximum deflection is much greater than the average, and it is the central deflection rather than volume change that should be utilized in measurements.

§ 3 c. Hydraulically Supported Rubber Membrane

This type of cover will bring about an equalization of stresses in the soil when this is possible. If the stress conditions are very irregular, great and uncontrollable normal travel may occur in the surface of contact. This type is not suitable for grainy materials because the grains will deflect the membrane very much in the contact points. On the surrounding wall, the stresses will be very high if the cover moves into the wall, and this will result in the same disadvantages as in the case of the pistonlike cover.

§ 3 d. Modified Types

A modification, very common at present, is a compromise between the types discussed in § 3 a and § 3 c. Here a comparatively thin steel membrane rests on a fluid. The disadvantages of the rubber membrane are therefore slightly reduced but the real travel of the membrane is still very uncertain.

Another modification, which seems to the Authors to be of great interest, and which has finally been recommended, is a rigid piston supported at the edge by a flexible ring. Here the advantages of the rigid piston and the flexible membrane can be combined without involving too many disadvantages.

§ 4. Considerations on Cover in Contact with Grains

In a granular material, the soil pressure is transmitted to the cell cover in a number of points. If the grains are relatively large in comparison with the cell cover area, the number and the position of the contact points will affect the readings of the cell.

Another important influence is the movement of the grains in relation to the cell cover on account of the local deformations caused by the contact forces.

Some estimates of the possible influences are given below.

§ 4 a. Grain Size in Relation to Cell Diameter

§ 4 a 1. Diameter of Rigid Piston

First we consider a circular surface with the radius a, free to move axially at the periphery. A number ($= n$) of spherical grains acts on this surface. Each grain will then represent a partial surface with the hypothetical diameter d, so that

$$d \approx 2\,a \sqrt{\frac{1}{n}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Now we are interested in the random distribution of the contact points at the periphery, where the probable number of grains ($= n_p$) is

$$n_p \approx \frac{2\,\pi\,a}{2\,a\sqrt{\frac{1}{n}}} = \pi\sqrt{n} \quad \ldots\ldots\ldots\ldots \quad (4)$$

Half of the partial surfaces of these peripherical grains will lie outside the radius a. To get a correct result of measurements, we must assume that half of these peripherical contact points lie outside, and the other half inside, the circular surface. On the other hand, the probability of another distribution must be taken into consideration as these points need to move only very little to pass the periphery. The safest way is to reckon with the possibility that the contact points of all peripherical grains are either entirely outside or entirely inside the cell radius. We further assume that all contact forces are equal.

The resulting error $\frac{\Delta P}{P}$, *i.e.*, $\frac{\Delta \sigma}{\sigma}$, will then be

$$\underline{\frac{\Delta \sigma}{\sigma} \approx \pm \frac{n_p}{2\,n} = \pm \frac{\pi}{2\sqrt{n}}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

For instance, if the maximum error due to this cause shall be less than 3 % (this would be a permissible partial effect if the total error were about 5 %), then we put

$$0.03 > \frac{\pi}{2\sqrt{n}}$$

and we obtain the condition $n > 2\,750$.

This would mean that the average hypothetical grain diameter should not exceed about 2 % of the cell diameter. If the grain diameter is larger, the number of tests must be increased in order to obtain the same accuracy. Probability calculations have been made[1], but will not be published here.

§ 4 a 2. Diameter of Flexible Cover Built In at the Periphery

If a flexible cover is built in at the periphery, then it is evident that the grain distribution at the periphery has no great influence on the bending of the cover. On the other hand, the grain distribution near the centre has the greatest influence.

Rough calculations made by the Authors indicate that the maximum grain size can be a little greater than in the case of the rigid piston.

§ 4 b. Influence of Surface Hardness

As the grains are in contact with the cell cover and the surrounding wall on very small surfaces only, local stresses and deformations will be appreciable. Now, if the cell cover is made of steel and the wall material is softer, the grains will pass into the cover less than into the wall surface. The influence of this is similar to that which would be produced by the movement of the cell into the soil. This action must be considered when the cover travel is small.

The distribution of the grains close to a smooth plane surface or close to a projecting edge will be different from that in the interior of the soil mass.

§ 5. Test Cell Used in Investigations

§ 5 a. Principles

A soil pressure cell should disturb the soil as little as possible. No sudden movements should occur, especially at the moment of reading. Therefore, we chose a cell type in which the cover yields continuously as the soil pressure increases.

[1] Made at the Institute in 1947 by Mr Henry Ericsson—former head assistant in the Mechanical Department of the Institute.

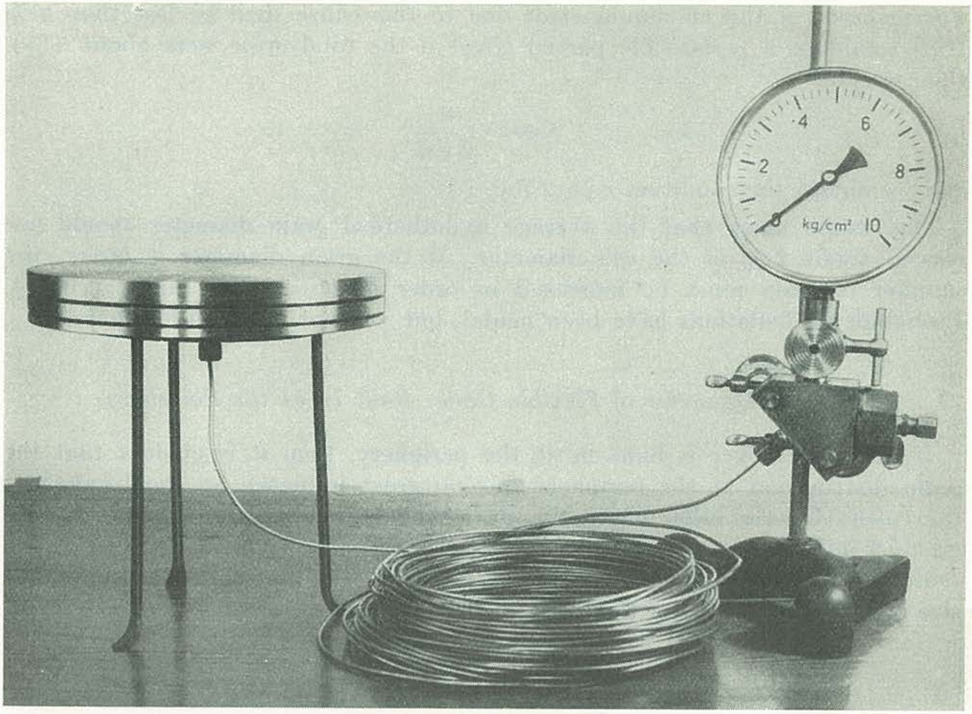


Fig. 2. The test cell.

We adopted a closed hydraulic measuring system (Figs. 2 and 3) in which the soil pressure is transmitted to the point of observation by means of a fluid under pressure. This system is simple, and is partially independent of the properties of the parts which are inaccessible after the cell has been installed.

The main drawbacks of this system are: possible leakage of fluid, hysteresis in the cell proper, errors in the Bourdon gauge, and thermal expansion of the fluid.

The first two drawbacks were reduced by the installation of an electrical contact device in the cell. This device enables the travel of the cell cover to be checked within certain intervals. It is easy to observe the moment when so much fluid has been lost that some more must be filled (Fig. 4). Owing to the contacts, the Bourdon gauge can be replaced for calibration without changing the position of the cell cover. For this purpose the Bourdon gauge is first shut off by means of a needle valve. After replacing the gauge, the position of the cover can be checked by means of the contacts. In this way it is also possible to replace the Bourdon gauge by a more precise pressure gauge.

The contacts work in oil and are used very seldom. Besides, the current is on only when the contacts are checked. Since the current is low, and is normally

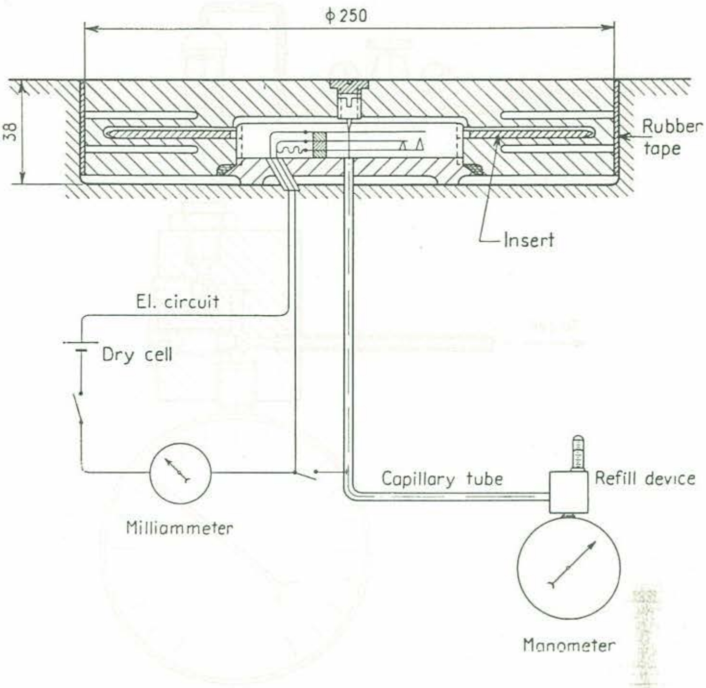


Fig. 3. Measuring system of test cell.

not broken during a check, the contacts may be expected to have a very long life and to maintain a high accuracy (± 0.001 mm).

In this way the system may be kept in operation over the ten-year period which was required, and it is not necessary that the elastic or electrical properties of the construction materials shall really remain exactly constant.

To eliminate the disadvantage of thermal expansion of the fluid, the fluid volume is kept small, and the volume displaced by the cell cover is made as large as possible by using a reasonably great cell diameter.

§ 5 b. Design

A rigid cover was chosen not only for the reasons stated in § 3 a, but also because it was easiest to calibrate its travel in advance. The main part of the soil load, 94 %, is taken by the supporting fluid. The remaining part of the load is carried by a peripherical membrane, which makes it possible to measure even if the loads are eccentric.

Although a cell in a wall may have any thickness, it was kept small in order to make installation simpler. The cell diameter—250 mm—ought to enable sufficient displacement of fluid even when the cell cover travel is very small.

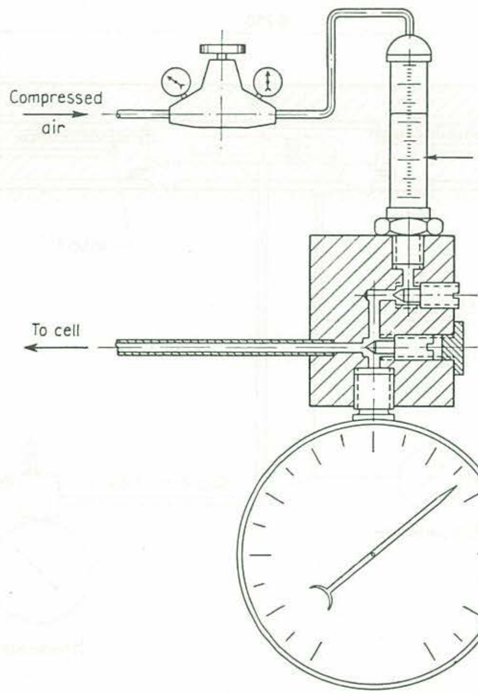


Fig. 4. Refill device (filling position).

The permissible cell cover travel was calculated from Eq. (1) by using the same values of the soil characteristics as those adopted by other researchers:

$$E = 1\,000 \text{ kg/cm}^2{}^*,\ m = 3.3$$

The permissible influence of the cell cover travel was to be equal to 5 % of the soil pressure.

Consequently, we obtained a cell cover travel of 0.045 mm at a soil pressure of 5 kg/cm² [according to the WES tests (19), it could have been 0.125 mm at 7 kg/cm²]. The test cell was designed to give deflections adjustable between 0.020 and 0.150 mm (§ 5 c).

In the cell, only small stresses were permitted in order to prevent hysteresis. Welding or soldering were not used. All iron parts were heat-treated.

The cell bottom has a ring-shaped contact area to ensure close contact with the supporting structure. A ring-shaped insert reduces the total fluid volume and protects the cell against excess loads. The cell is connected by a capillary tube, 1 mm in inside diameter, to a Bourdon gauge, which requires 66 mm³

* The tests described below gave other values.

of fluid for a soil pressure change of 1 kg/cm². The fluid finally chosen was Dow DC 200 silicone oil.

The contact device for checking the cover travel is built up of ordinary telephone-relay silver contacts (Fig. 3). A screw in the cover enables adjustment of the first contact to mark the point of zero movement. An intermediate contact closes at a point when refill of oil is advisable. The third contact fixes the extreme limit of travel, beyond which the cell cannot be used.

§ 5 c. Mechanical Calibrations

The test cell was checked very thoroughly.

First, the deformations under different kinds of loads—centric and eccentric, concentrated and uniformly distributed—were checked during repeated loadings without oil in the cell. During a fortnight, a stress four times the calculated highest working stress was applied in order to check hysteresis and creep. Neither was detected. Then the cell was filled with oil and tested. Although the oil was boiled and the whole system was evacuated, it proved impossible to avoid gases in the oil-filled cell. This was probably partly due to the interior

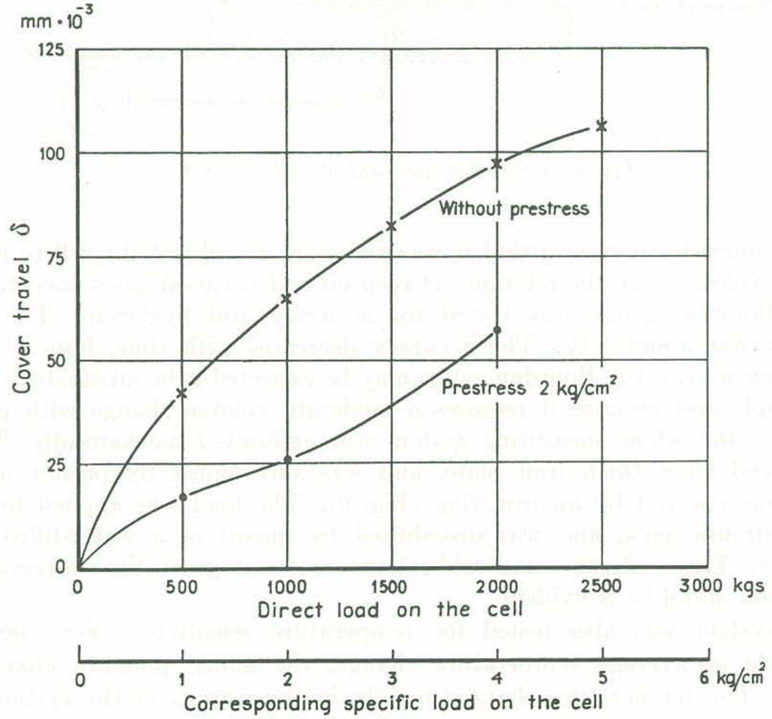


Fig. 5. Average cover travel of test cell.

of the cell that was a little complicated. The gas content increased the cell cover travel above its calculated value. Loading tests showed that the travel could be decreased by filling extra oil into the cell so as to give it an initial inner overpressure (Fig. 5). In practice, this overpressure ("prestress") will be obtained as soon as the cell is situated at a lower level than the manometer. Calibrations have shown that the pressure readings change 1 % for every 10 metres of difference in level between the manometer and the cell.

On the other hand, a greater cell cover travel was obtained by permitting more gases to remain in the cell. It was thus possible to vary the rigidity of the cell. Unfortunately, the adjustment was difficult. The cover travel did not bear a straight-line relation to the applied pressure, and the curvature became greater as the gas content increased.

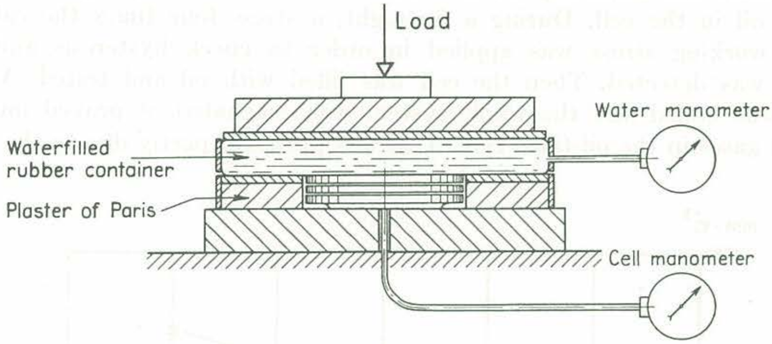


Fig. 6. Set-up for mechanical cell calibration.

Preliminary tests showed that it was necessary to subject the cell to repeated loading cycles, before the relation between oil and enclosed gases was stabilized.

The Bourdon gauge was tested for accuracy and hysteresis. The overall accuracy was about 2 %. The accuracy decreases with time, but, if checked about once a year, the Bourdon gauge may be expected to be satisfactory because it is simple and because it requires a moderate volume change with pressure.

Finally, the whole measuring system was calibrated mechanically. The cell was placed on a thick iron plate, and was surrounded by plaster of Paris, which was covered by an iron ring (Fig. 6). The load was applied by means of a hydraulic jack, and was distributed by means of a water-filled rubber container. Fig. 7 shows some calibrations made at great time intervals. The calibration stability is evident.

The system was also tested for temperature sensitivity. For one degree centigrade of average temperature change, the gauge pressure changes 0.02 kg/cm^2. The temperature changes mainly in those parts of the system which are situated above the ground, and its effect on the measurements is equal to half the above value. This effect can be corrected for.

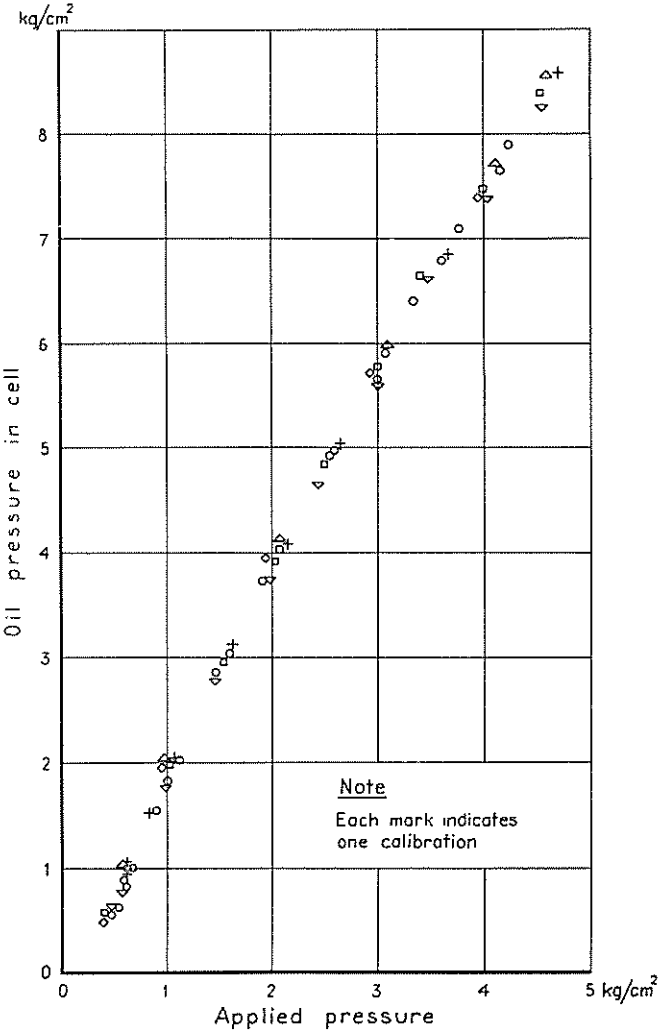


Fig. 7. Mechanical calibration curves for test cell.

§ 6. Test Cell in Contact with Soil

After having been thoroughly calibrated mechanically, the test cell was calibrated in contact with soil. The purpose of these calibrations was to study the influence of the cell on the soil pressure and the behaviour of the cell itself.

§ 6 a. Final Test Set-Up

The test set-up (Figs. 8 and 9) should reproduce as closely as possible the conditions in soil resting on a wall. Strictly speaking, this would require a triaxial apparatus of very great dimensions. As this would greatly complicate the test, it was decided to use an available test tank apparatus, namely, the "50 cm compressometer" (13). It is a kind of oedometer, whose cylindrical wall

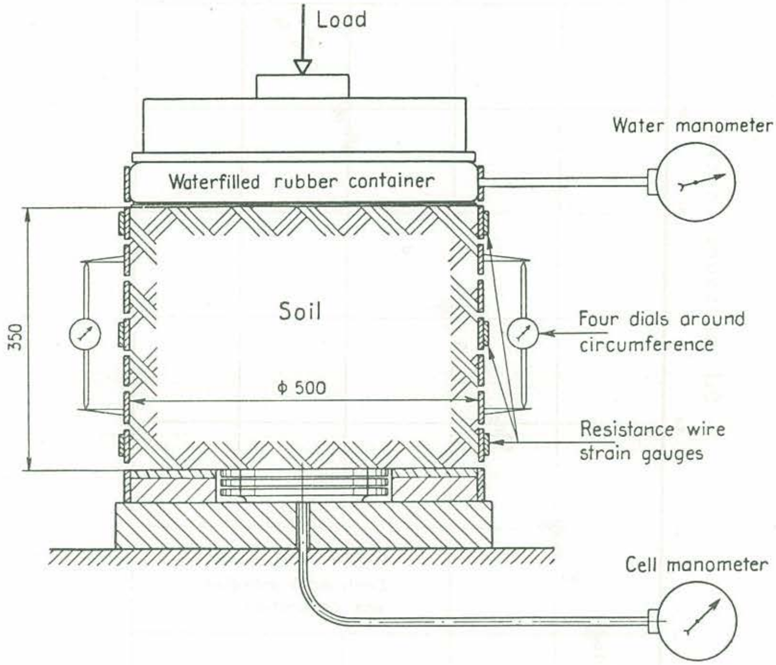


Fig. 8. Set-up for calibration of test cell in contact with soil.

consists of separate rings—5 cm in height and 50 cm in diameter each. The rings are separated by 1 mm spaces, and would permit axial compression of the soil without appreciable friction if no forces were transmitted between the rings. The stress distribution in the 50 cm compressometer will be dealt with in detail in § 8.

The cell was installed in the same way as in the mechanical calibrations (*cf.* Fig. 6 with Fig. 8). The ring-shaped steel plate lying on the surrounding plaster of Paris flush with the cell cover ensured the same type of surface of cell cover and wall (§ 4 b).

The vertical load was applied by means of an Amsler hydraulic jack controlled by a pendulum manometer. In order to obtain a uniform distribution of the load, the water-filled rubber container—the same as in the mechanical calibrations—was placed between the soil and the pistonlike plate to which the load

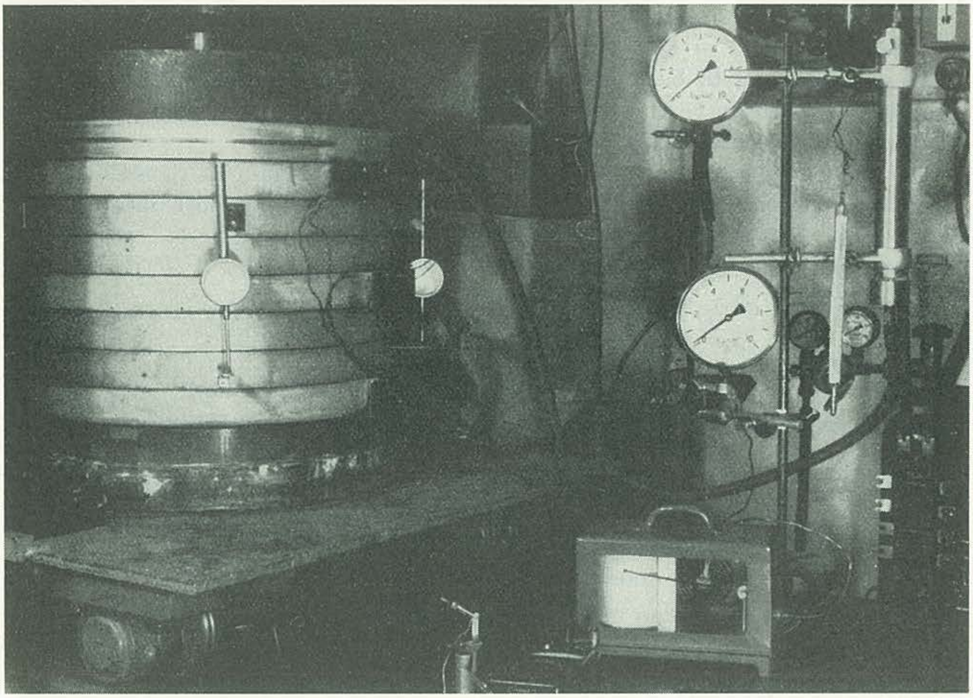


Fig. 9. Set-up for calibration of test cell in contact with soil.

was applied. Thus the load was applied in the same way during both types of calibration, the only difference being the intermediate soil in the calibrations in contact with soil.

The tank diameter, 50 cm, and the height of soil above the cell, 35 cm, were of course far too small to permit unlimited stress conditions in the soil.

As to the diameter, it is to be noted that the rings form a cylindrical wall, which can be regarded as rigid in a horizontal direction. In the case of unlimited extension, we should have horizontal deflections caused by the cell cover movement. These deflections are prevented by the cylindrical wall, and therefore the soil seems now to be more rigid than in the unlimited case.

Moreover, our ring-shaped steel plate prevents vertical displacement of soil surrounding the cell (§ 4 b). This effect also makes the soil in the test tank to seem more rigid as to the effect on the cell than in the case of unlimited medium discussed in § 2.

As to the height of soil above the cell, it is to be observed that the transmission of the load via a water-filled rubber container makes the distribution of vertical stresses very uniform. On the other hand, the vertical stresses at the centre are partly transmitted to the periphery by means of interior shear stresses.

A strict theoretical solution of the general case, in which the diameter ($2\ R$) and the height (H) of the test tank can be given optional values, was found to be intricate and to be dependent on too many assumptions to be of much practical use. We have therefore confined ourselves to calculations made with special reference to our test conditions.

The calculations[1] were based on equations of equilibrium of stresses in each horizontal cross-section, which also took into account the horizontal stresses in the soil.

This gives

$$\frac{d^2\,\delta_{\mathrm{av}}}{dx^2} = \frac{(m+1)(m-2)}{m\,(m-1)} \cdot \frac{R^2}{R^2 - a^2} \cdot \frac{2\,G\,\gamma}{E \cdot a} \quad \ldots\ldots\ldots\ldots (6\,\mathrm{a})$$

where x = distance between top of tank and cross-section

δ_{av} = difference between average vertical dilatation of circular surface with radius a, and average dilatation of surrounding ring at distance x

γ = angle of shear at radius a

G = modulus of shear

E = average modulus of elasticity

The type of deformation curve of originally plane horizontal sections in the soil was obtained from special tests. It seems that in our case an acceptable approximation will be

$$\gamma \approx c \cdot \frac{\delta_{\mathrm{av}}}{a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6\,\mathrm{b})$$

where c can be given probable values checked by these tests.

By inserting Eq. (6 b) in Eq. (6 a) we can get the average change in normal stress

$$\varDelta\,\sigma = \frac{\delta}{2\,a} \cdot E \cdot f\,(m, a, R, H) \quad \ldots\ldots\ldots\ldots\ldots\ldots (6\,\mathrm{c})$$

Eq. (6 c) is similar to Eq. (1). We have therefore chosen to evaluate our test results by means of

$$\underline{\varDelta\,\sigma_{\mathrm{test}} = \frac{\delta}{2\,a} \cdot E_{aw} \cdot \frac{m^2}{m^2-1} \cdot C} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

which is the same as Eq. (1) except that the real modulus of elasticity of the soil [E in Eq. (1)] has been replaced by "the apparent working modulus of elasticity" (E_{aw}) of the soil in the test tank. Here E_{aw} contains all the differences between Eq. (1) and Eq. (6 c). The value of E_{aw} for our test tank was found to be

$$E_{aw} \approx 1.7\ E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

This means that the calibrations in the test tank should give stress deviations caused by cell cover travel which are about 1.7 times as high as

[1] Made by Mr Justus Osterman, now head of the Institute.

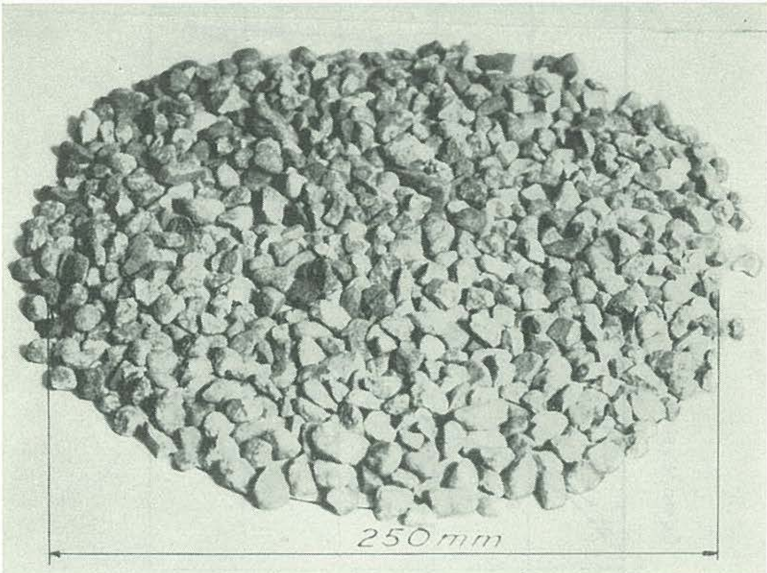


Fig. 10. The test soil.

those which might be expected in an unlimited soil. Such a large correction is not dangerous, provided that the pressure deviation is sufficiently small.

The soil characteristics were determined by measurements on the compressometer rings. Thus the compression was measured by means of dial gauges, and the horizontal pressures by the aid of resistance wire strain gauges fitted on the rings. Temperature compensation was obtained by unstressed resistance wires on the same rings. The rings were calibrated separately for lateral pressure in a special pneumatic device.

§ 6 b. Test Soil

Most of the tests were made with dry gravel and, as the investigations were very time-wasting, only a few with normal sand.

The gravel consisted of hard granite grains with relatively rounded edges (Fig. 10). As the average grain diameter was 7 mm, an estimate formed in accordance with § 4 a 1 shows that the maximum possible error caused by random grain distribution is ± 4.4 %.

The soil was filled very carefully, always from the same level, and was not compacted. The procedure was tried out so as to ensure uniformity. Fig. 11 shows the compression and the expansion of the test soil during repeated loading cycles made in the test apparatus. After a few loading cycles the curves become very much alike. Fig. 12 shows the curves superimposed one upon another and starting from the same origin. The Authors believe that these observations

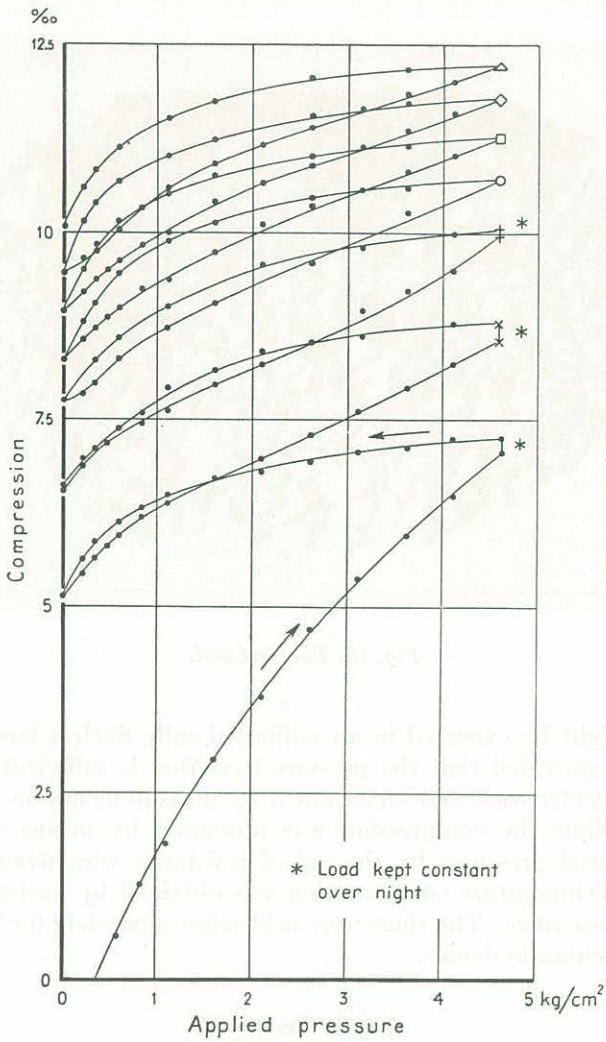


Fig. 11. Typical compression and expansion of test soil during seven loading cycles.

could be utilized to predetermine the behaviour of such a soil [*cf.* (28), p. 75]. Lack of time has prevented further investigation of this interesting problem.

On the basis of the curves for the first application and removal of load, the moduli of elasticity in compression (E_c) and in expansion (E_e) have been computed (Fig. 13) from the formula applicable in this case,

$$E = \frac{\Delta\,\sigma}{\Delta\,\varepsilon}\left[1 - \frac{2}{m\,(m-1)}\right]$$

where m, calculated in accordance to (13), p. 18, was taken to be 3.2 (Fig. 14). We observe that the moduli increase with the pressure. This fact is in agreement with the theoretical calculations (10) but has hitherto been neglected in calculating the corrections due to soil pressure cells.

' The unit weight of the gravel in unloaded state was 1.600 kg/dm^3 before, and 1.609 kg/dm^3 after a test comprising seven loading cycles. These values correspond to a porosity of 40 % before, and 39 % after the test.

§ 6 c. Outline of Calibrations in Soil

The calibrations of the test cell were divided into four different groups called A, B, C, and D. The total work amounted to about 30 test series, each comprising three loading cycles on an average. The first load increase curve was here used for actual calibration, the other curves were used for determining the soil properties. We have given only the main results for the sake of brevity.

§ 6 c 1. Test Group A—Preliminary Tests

These tests afforded the necessary experience for the following test groups. The test set-up differed from that described above (§ 6 a).

The soil was slightly compacted by means of a rod. But it was found that this method did not give the requisite reproducible soil characteristics. At the beginning, the cell had been filled with glycerine because of its low coefficients of thermal expansion and compressibility. This fluid, however, proved too viscous. It was not possible to get rid of air bubbles, and the time lags due to friction in the capillary were great. Afterwards the system was filled with kerosene and finally with silicone oil.

The cell was here not surrounded by the ring-shaped steel plate, and the plaster of Paris was flush with the cover. Great trouble was caused by the grain edges which entered into the surface of the plaster of Paris, so that the test results became unreliable. Furthermore, we had the impression that the plaster of Paris was compressed to a dangerously great extent under load during the first month or so.

In order to obtain smaller travel, we made a comparison between the behaviour of a non-prestressed cell and a cell which was prestressed by an internal pressure of 2.0 kg/cm^2. However, we did not find any obvious difference in recording (§ 5 c).

We observed that the rings of the compressometer moved a little irregularly, and we suspected that the edges of the grains might enter into the spaces between the rings and prevent them from free axial movement. The spaces between the rings were therefore covered by thin and narrow steel strips. Comparison was made between two tests with these strips and two tests without them. The results showed an obvious increase in the underregistration when use was made of steel strips thus indicating greater wall friction.

A comparison was also made between the test gravel (§ 6 b) and normal sand. The sand gave greater errors, but this may have been due to the test set-up.

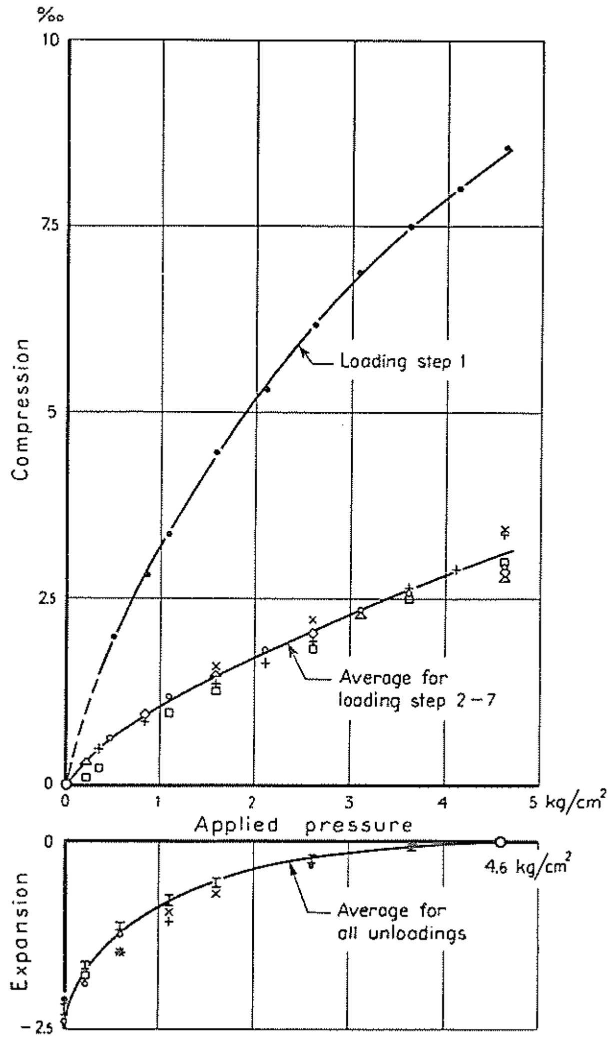


Fig. 12. Typical compression and expansion of test soil during seven loading cycles. The curves are superimposed one upon another and start from the same origin.

In all tests we observed that the cell pressure readings varied with time. Therefore, all readings were taken 30 minutes after a loading step had been applied. Then the load was sometimes allowed to act for three hours or more, and the observed increase in oil pressure readings varied from 0.1 to 0.3 kg/cm^2. A similar time effect was observed in measuring the compression of the soil.

These time effects may to some extent have been caused by vibrations (in the laboratory or in the hydraulic jack, the vibrations in the latter being caused by the plunger pump). To check this assumption, the compressometer

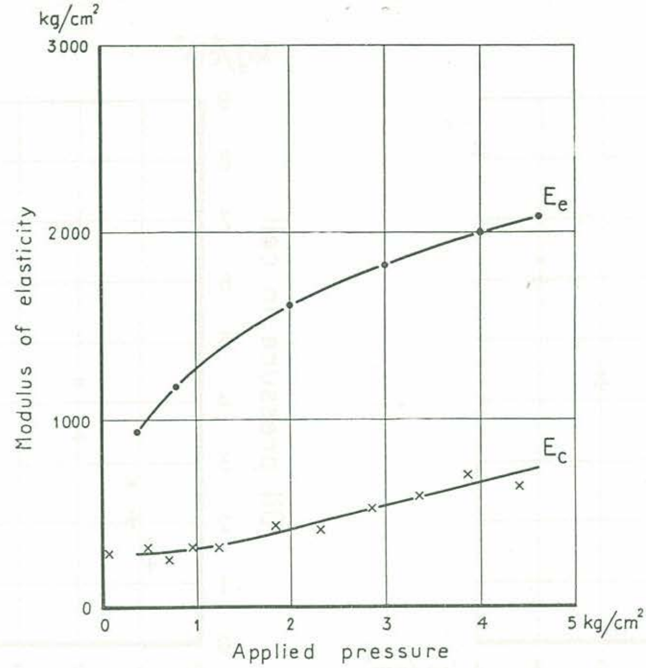


Fig. 13. Typical moduli of elasticity of test soil in compression (E_c) and in expansion (E_e). (First loading cycle.)

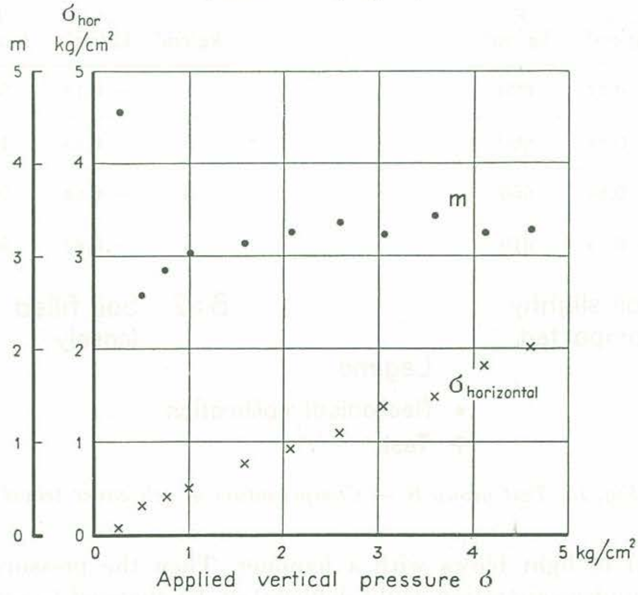
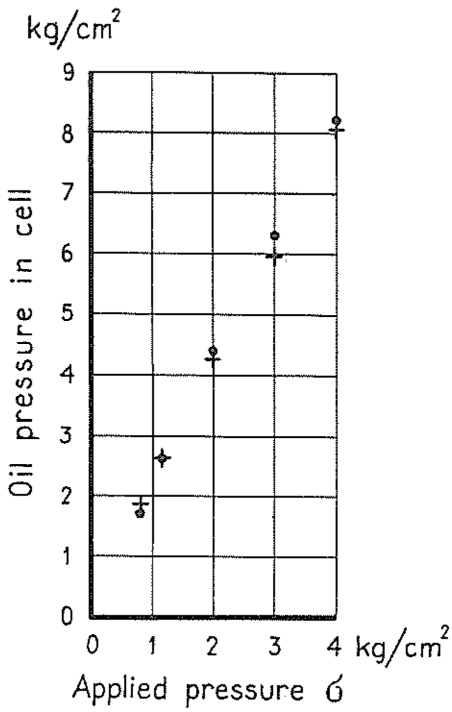
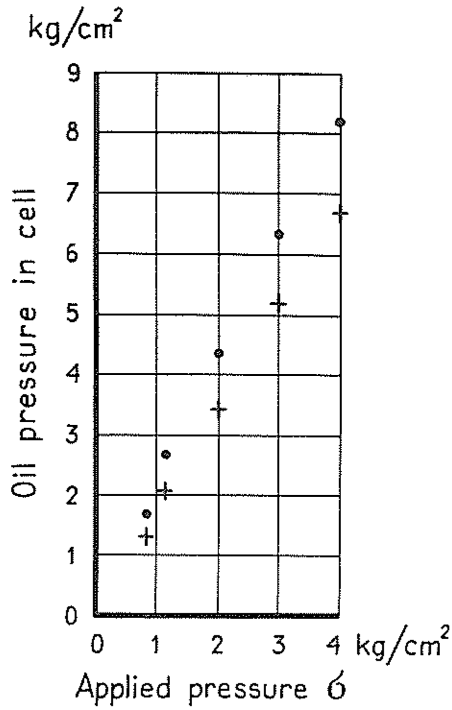


Fig. 14. Poisson's number m of test soil $\left(m = 1 + \dfrac{\sigma}{\sigma_{hor}}\right)$.



σ kg/cm²	$\Delta\sigma$ kg/cm²	E_c kg/cm²
1	+ 0.04	620
2	— 0.04	660
3	— 0.06	650
4	— 0.05	610

B : 1 Soil slightly compacted



σ kg/cm²	$\Delta\sigma$ kg/cm²	E_c kg/cm²
1	— 0.18	310
2	— 0.43	450
3	— 0.64	520
4	— 0.86	540

B : 2 Soil filled in loosely

Legend
• Mechanical calibration
+ Test

Fig. 15. Test group B — Compensation of cell cover travel.

was subjected to light blows with a hammer. Then the pressure readings increased, and underregistration could deliberately be changed to overregistration. This shows that vibrations affect the results very much by changing the distribution of stresses in the soil.

§ 6 c 2. Test Group B—Compensation of Cell Cover Travel

The test set-up used in this group was final except that the load was distributed by means of a heavy steel plate, and not by the waterfilled rubber container, which was used for all subsequent tests.

It was intended to reduce the cell cover travel to a minimum by using the built-in contact device and by filling extra fluid into the cell at frequent intervals (Fig. 4). The cell cover was permitted to deflect inwards not more than 0.003 mm. Extra fluid was filled under pressure until the cover had moved outwards to its original position. During the whole loading, about 125 such compensations were performed.

The results are shown in Fig. 15. Diagram B: 1 shows that the deviation from the applied pressure was $\sim \pm 4\%$ at small pressures and less than $\pm 2\%$ at higher pressures. Here the soil was compacted in the same way as in Tests A. On the other hand, when the soil was filled loosely, as in Test B: 2, the deviation was constantly negative, and was of a higher order. This seems to indicate that a loosely filled soil is compressed by the cell cover when the cover moves into the soil, and then the contact is partly disconnected when the cell cover moves in the opposite direction.

§ 6 c 3. Test Group C—Main Tests

In these tests, use was made of the final test and calibration set-up (Figs. 6 and 8). The soil was filled loosely, always from the same level, and this gave comparatively reproducible soil data. The loads were always allowed to act 15 minutes before taking readings and changing over to the next step. Neither prestressing nor compensation of cover movement were used during these tests.

The purpose of these tests was to express the cell correction as a function of the cover travel.

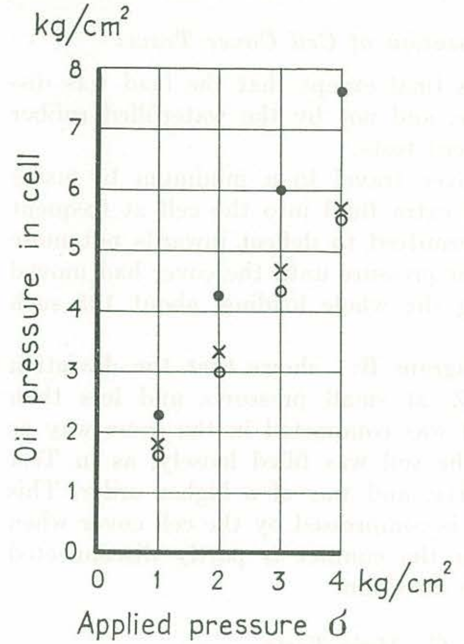
Tests were run with deflections of about 0.13 mm and 0.08 mm at a soil pressure of 4 kg/cm^2. The results are shown in Fig. 16. An influence of the cell cover travel is noticeable although the scattering of the results seems to be rather great—especially for the 0.08 mm travel. These tests will further be discussed in § 6 d.

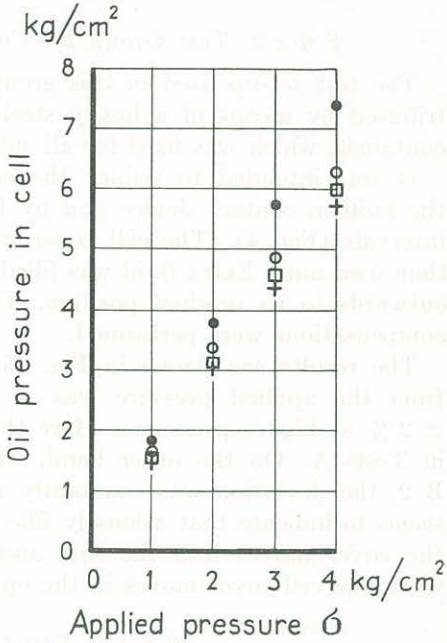
§ 6 c 4. Test D—Correlating Test

This test was performed to compare our results with those of Benkelman and Lancaster (1) and W.E.S. (19), (26), who had dealt with the influence of projecting cells. A special reason was that the influence of cell projection, as stated by the above authors, seemed to agree with our theoretical calculations more closely than the influence of cell deflection given by W.E.S.

We therefore mounted the cell on the base-plate without surrounding it with plaster of Paris. The cell then projected 51.2 mm into the soil (*i.e.*, the projection-diameter ratio was 0.205).

The results are shown in Fig. 17, and will be discussed in § 6 d.





σ kg/cm²	$\Delta\sigma$ kg/cm²	δ mm·10^{-3}	E_c kg/cm²
1	0.32	70	280
	0.24	74	350
2	0.64	99	530
	0.52	103	560
3	1.00	113	530
	0.80	119	620
4	1.30	129	580
	1.20	131	700

C:1 Max. cover travel
~ 130 mm·10^{-3}

σ kg/cm²	$\Delta\sigma$ kg/cm²	δ mm·10^{-3}	E_c kg/cm²
1	0.14	39	340
	0.06	40	260
	0.19	39	380
2	0.42	56	480
	0.19	60	400
	0.42	55	550
3	0.73	69	510
	0.44	74	660
	0.64	69	620
4	1.00	80	580
	0.66	85	720
	0.84	80	590

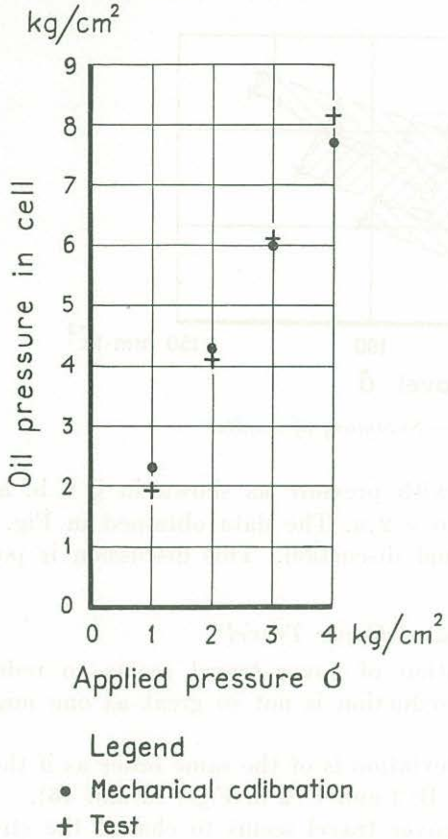
C:2 Max. cover travel
~ 82 mm·10^{-3}

Legend

• Mechanical calibration

+ □ × o Tests

Fig. 16. Test group C — Main tests.



σ kg/cm²	$\Delta\sigma$ kg/cm²	δ mm · 10^{-3}	E_c kg/cm²
1	− 0.14	50	390
2	− 0.08	77	500
3	+ 0.04	97	770
4	+ 0.30	113	660

Fig. 17. Test D — Projection error.

§ 6 d. Discussion of Test Cell Results

§ 6 d 1. Influence of Deflection

In Fig. 18 the underregistrations of the test results in Group C are given as functions of the cell cover travel for four different loads. It is obvious that the results are dependent on pressure. If the test results obtained from Goldbeck cells and W.E.S. cells are plotted in a similar way, the same tendency can be observed.

By examining the values relating to the same pressure and the same cover travel, we found that the test results scattered a little more than desired. Yet the tests had been made with an accuracy which is not attainable during measurements in practice.

However, three main kinds of pressure influence have not been considered in Fig. 18. The first is the possible friction in the test set-up. This will be discussed separately in § 8. The second is the boundary condition discussed in § 6 a (limited dimensions of the test tank). The third is the modulus of

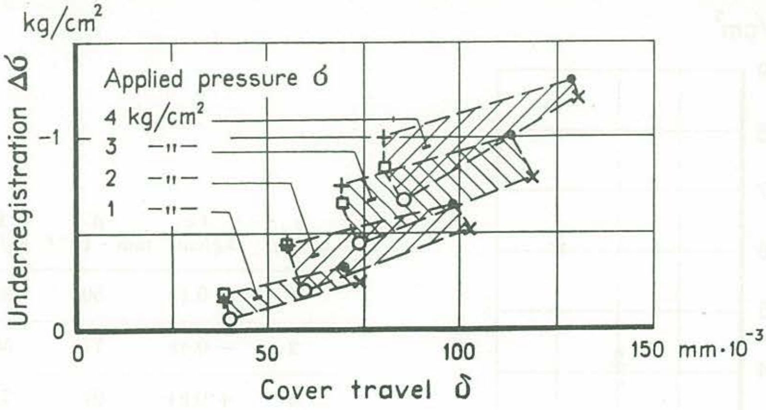


Fig. 18. Test group C — Summary of results.

elasticity of the soil, which increases with pressure as shown in § 6 b, and which influences the result according to § 2 a. The data obtained in Fig. 18 should therefore be corrected before final discussion. This discussion is postponed to § 7 c.

§ 6 d 2. Compensated Cover Travel

In a compacted soil, the compensation of cover travel seems to reduce the observed deviations, although the reduction is not so great as one might expect.

In a loosely filled soil, the observed deviation is of the same order as if there were no compensation at all (Diagrams B: 2 and C: 2 in Figs. 15 and 16).

On the whole, the compensation of cover travel seems to change the stress conditions in the soil in a rather unpredictable way. It should be used only with great care.

§ 6 d 3. Cell Projection

In Test D the cover travel was almost the same as in Group C: 1. It is difficult or even impossible to quite separate the influences of the projecting cell and of the deflecting cell cover.

We had, however, the condition of zero deviation for our projecting cell at the applied pressure of 2.6 kg/cm². At this point we made the simplification to assume

$$\Delta\sigma_{\text{projection}} + \Delta\sigma_{\text{deflection}} = 0$$

From Tests C: 1, $\Delta\sigma_{\text{deflection}} = -0.72$ kg/cm² was obtained at this pressure. Therefore, $\Delta\sigma_{\text{projection}}$ ought here to be $+0.72$ kg/cm².

If we use Eq. (1) and compute δ as the elastic compression of 5.12 cm of soil, we get

$$C = \frac{0.72 \cdot E \cdot 25 \cdot 0.91}{2.6 \cdot 5.12 \cdot E} = 1.23$$

which is in close agreement with Eq. (1) and Table 1.

The value of this superposition lies in the far-advanced separation of the friction of the test tank.

It is of interest to calculate the apparent working modulus of elasticity (E_{aw}) of the soil in the above case.

We had the condition

$$\Delta\sigma_{\text{projection}} = \Delta\sigma_{\text{deflection}},$$

which we transform into

$$\delta_{\text{projection}} = \delta_{\text{deflection}}.$$

$\delta_{\text{projection}}$ can be computed at $\dfrac{2.6 \cdot 5.12}{E_{aw}}$ cm and $\delta_{\text{deflection}}$ was calibrated so as to be 0.011 cm.

Thus, $E_{aw} = 1\,200$ kg/cm^2.

As the boundary conditions of the test tank have influenced the above (see § 6 a), the real modulus will be about 1.7 times smaller than E_{aw} (*i.e.*, 700 kg/cm^2 at 2.6 kg/cm^2), thus being a little above the E_c value in Fig. 13.

§ 7. Flexible Plates

The tests in § 6 had given results which scattered a little. This was believed to be caused mainly by differences in equalization of the high stresses in the soil near the periphery of the cell. This equalization is greatly dependent on the type of cell cover movement, and it was therefore decided to test plates whose

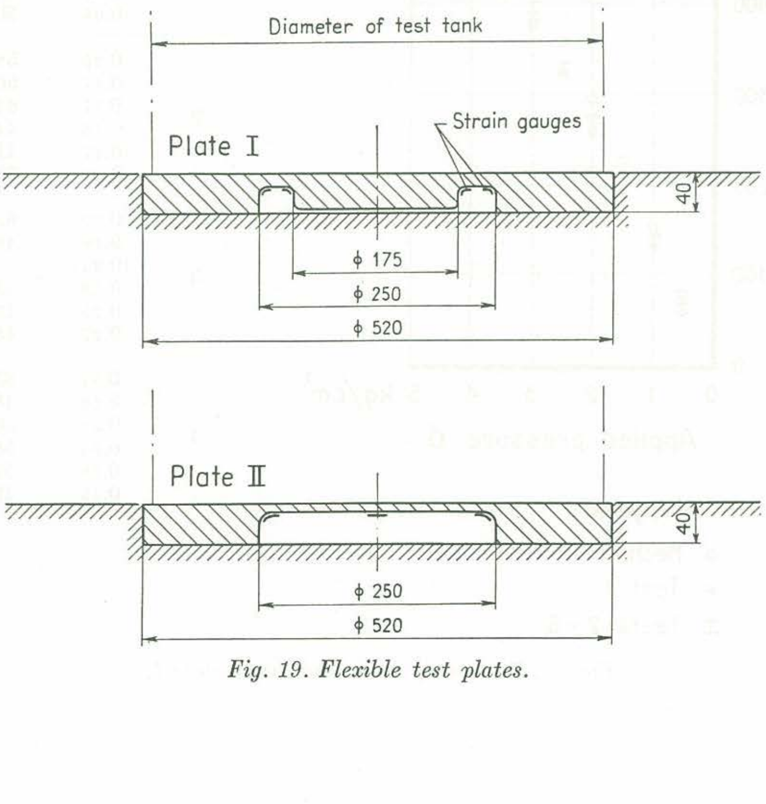


Fig. 19. Flexible test plates.

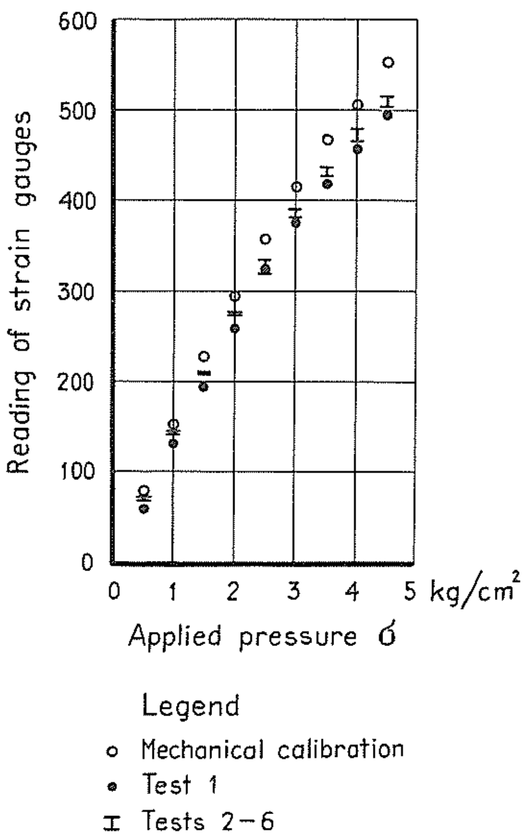
deformations at the periphery showed a continuous curve, so as to avoid great stress concentrations.

These tests were only short-time laboratory tests, and it was therefore decided to use electrical resistance wire strain gauges for the measurements.

Two different types of cover movement were tested in order to obtain the desired influence of the cell cover deflection. Therefore, two plates were made. The plates were 52 cm in diameter and 4 cm in thickness. Recesses, 25 cm in diameter, were turned in so as to form flexible membranes, see Fig. 19.

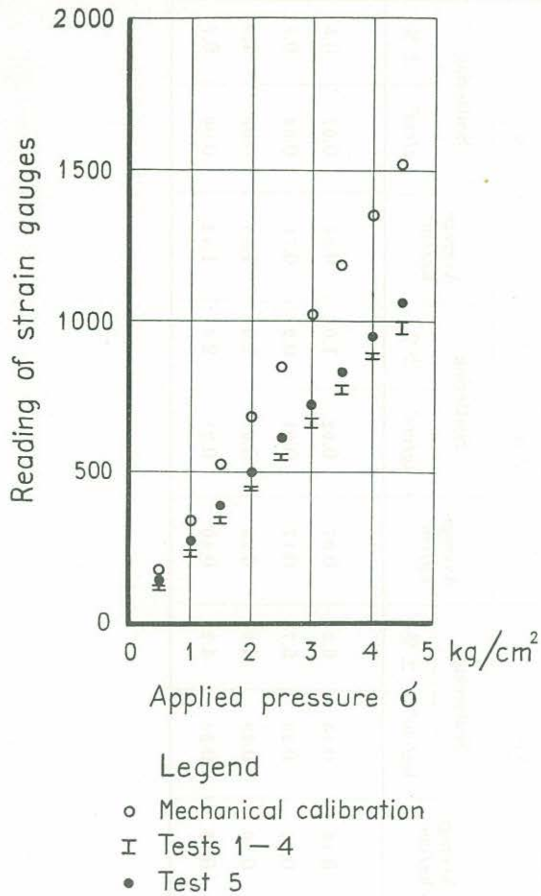
The first plate (I) was designed for a centre travel of only 0.004 mm at a soil pressure of 4 kg/cm^2 (§ 3 d). The second plate (II) was designed for a maximum deflection of 0.12 mm at the same pressure (§ 3 b). Strain gauges were glued at the points of maximum strain.

The test set-up was the same as in the main tests (*cf.* § 6). Only the test cell, the surrounding layer of plaster of Paris, and the steel-ring were replaced by the test plates. Calibration was carried out in the same way as before. The



σ kg/cm^2	$\Delta\sigma$ kg/cm^2	E_c kg/cm^2
1	0.15	390
	0.08	300
	0.08	320
	0.06	325
	0.06	310
	0.08	305
2	0.25	580
	0.17	505
	0.17	640
	0.16	440
	0.17	415
	0.17	380
3	0.32	630
	0.19	485
	(0.25)	
	0.19	330
	0.25	495
	0.27	480
4	0.54	630
	0.28	480
	0.49	505
	0.34	580
	0.38	525
	0.49	495

Fig. 20. Test group E — Tests with plate I.



σ kg/cm²	$\Delta\sigma$ kg/cm²	E_c kg/cm²
	0.32	285
	0.39	330
1	0.32	275
	0.32	290
	0.25	310
	0.70	470
	0.72	400
2	0.69	430
	0.72	400
	0.57	540
	1.02	540
	1.11	400
3	1.05	560
	1.07	460
	0.88	450
	1.38	535
	1.44	495
4	1.42	550
	1.44	610
	1.20	660

Fig. 21. Test group F — Tests with plate II.

variations in electrical resistance were measured by means of a carefully stabilized D.C. Wheatstone bridge with a light-spot galvanometer. Although the temperature compensation was performed with "dummies", all tests were nevertheless made in a room with temperature control.

§ 7 a. Test Group E — Tests with Plate I

For this plate, the radial stress near the circumference had been computed at 125 kg/cm² under a pressure of 4 kg/cm². Mechanical calibrations indicated that the average stresses were equal to 122 kg/cm², and it is justified to conclude that the cover was deformed in conformity with calculations.

Table 2. Average scattering of test results in per cent of applied pressure

Applied pressure uncorrected σ kg/cm²	Test group											
	C: 1			C: 2			E			F		
	$\Delta\sigma$			$\Delta\sigma$			$\Delta\sigma$			$\Delta\sigma$		
	Average kg/cm²	Scattering		Average kg/cm²	Scattering		Average kg/cm²	Scattering		Average kg/cm²	Scattering	
		kg/cm²	± %		kg/cm²	± %		kg/cm²	± %		kg/cm²	± %
1	0.28	0.08	4.0	0.13	0.13	6.5	0.07	0.02	1.0	0.34	0.07	3.5
2	0.58	0.12	3.0	0.34	0.23	5.7	0.17	0.01	0.2	0.71	0.03	0.7
3	0.90	0.20	3.3	0.60	0.29	4.8	0.23	0.08	1.3	1.06	0.09	1.5
4	1.25	0.10	1.2	0.83	0.34	4.2	0.40	0.21	2.6	1.42	0.06	0.7

Table 3. Average of test results, uncorrected and corrected

Applied pressure uncorrected σ kg/cm²	E_c average kg/cm²	Test group								
		C: 1				C: 2				
		Cover travel mm 10^{-3}	Underregistration $\triangle\sigma$			Cover travel mm 10^{-3}	Underregistration $\triangle\sigma$			
			uncorr. average kg/cm²	corrected for			uncorr. average kg/cm²	corrected for		
				tank friction (F_t) kg/cm²	$F_t + E_c$ kg/cm²			tank friction (F_t) kg/cm²	$F_t + E_c$ kg/cm²	
0.5	280	47	0.20	0.18	0.18	25	0.06	0.04	0.04	
1	300	72	0.28	0.25	0.25	39	0.13	0.10	0.10	
2	410	101	0.58	0.52	0.38	57	0.34	0.28	0.20	
3	540	116	0.90	0.81	0.45	71	0.60	0.51	0.28	
4	660	130	1.25	1.13	0.51	82	0.83	0.71	0.32	
		E				*F*				
0.5	280	0.5	0.04	0.02	0.02	10	0.19	0.18	0.18	
1	300	1	0.07	0.04	0.04	21	0.34	0.31	0.31	
2	425	2	0.17	0.11	0.08	42	0.71	0.65	0.46	
3	490	3	0.23	0.14	0.09	63	1.06	0.97	0.59	
4	550	4	0.40	0.28	0.13	84	1.42	1.30	0.71	

Six separate test series were run, and the results are shown in Fig. 20. The results of the first series lie a little away from the rest, and are indicated by points. The other test series lie so closely together that we have to indicate the results by lines enclosing all values.

§ 7 b. Test Group F — Tests with Plate II

The calibrations of this plate gave stresses at the periphery as calculated by means of the theory of thin plates. In the centre the stresses were 40 % of the computed values, which is reasonable. The maximum deflection at 4 kg/cm^2 is supposed to lie somewhere between 0.07 and 0.10 mm, but was not measured.

This group comprised five test series. The results are shown in Fig. 21. The scattering here is also smaller than in the tests described in § 6.

§ 7 c. Discussion of Plates versus Test Cell

The tests with the flexible plates were intended to give less scattering than Tests C. From Table 2 we can see that this was indeed the case. For the test cell, the percentual scattering decreases as the pressure increases (Tests C). This shows that the conditions at small pressures (or movements) are less stable than at higher pressures.

To make comparison possible, the average underregistrations at a pressure of 4 kg/cm^2 are assembled in Fig. 22. Here we observe that Tests F show greater underregistration than Tests C at the same cell cover travel.

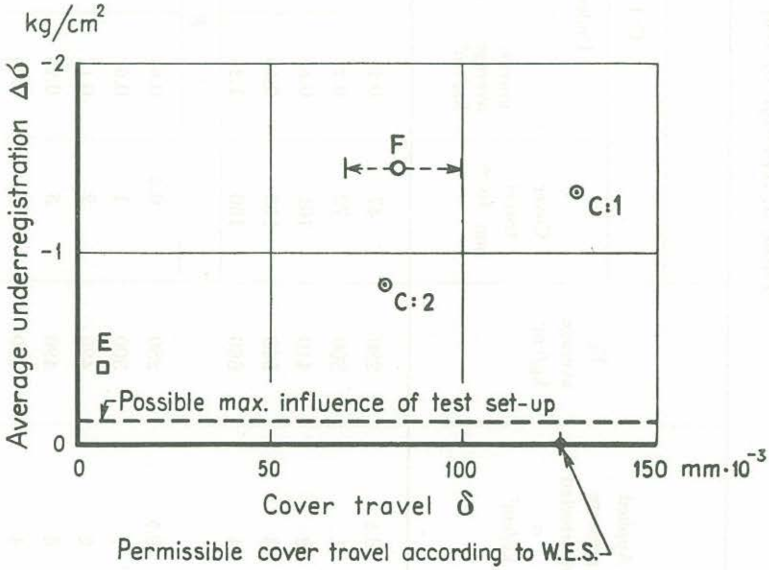


Fig. 22. Comparison of underregistration values for different cell covers at an applied pressure of 4 kg/cm^2.

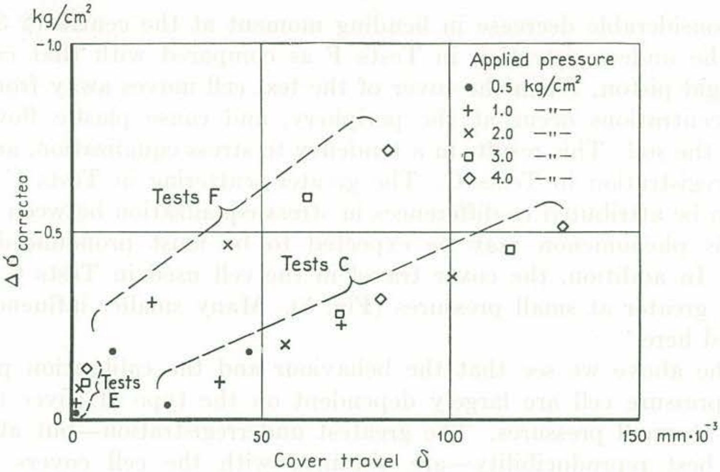


Fig. 23. Corrected average underregistrations.

Furthermore, Fig. 22 indicates that the underregistration at the extremely small cover deflections in Tests E is great. This can partly be due to the test set-up. It is discussed separately in § 8, and we may indicate in advance that the test set-up was affected by a reduction of 3 % in the pressure on the cell surface area. However, the effect observed in Tests E is greater than that attributable to this percentage.

Up to now we have deliberately not corrected the results of our measurements. We know, however, from the above (§ 2) that the modulus of elasticity of the soil influences the results. Fig. 13 shows that in our case this modulus increases with the vertical pressure. To be comparable, the results should be adjusted to a standard modulus of elasticity.

Table 3 shows the correction of the results of measurements in Tests C, E, and F for a test tank friction of 3 % of the applied pressure. Solely in order to make the results comparable, the results relating to the average observed modulus of elasticity (E_c) were reduced in this table to a standard modulus, which was taken to be 300 kg/cm^2. The corrected deviations are plotted in Fig. 23.

Fig. 23 shows that the corrected underregistrations in Tests E and F seem to form a continuous curve. The plates used in these tests had continuous deflection curves at the periphery of the cell area. We must bear in mind the high reproducibility of these tests (Table 2).

We also note that the average corrected underregistrations in Tests C (where the cell cover deflection curve was discontinuous at the periphery) now group very close together along a nearly straight line having a certain definite slope. However, the absolute values in Tests F are considerably greater than in Tests C. The main reasons for this are as follows. When the cover of Plate II deflects away from the soil, the normal stresses at the centre decrease, and this causes a considerable decrease in bending moment at the centre (§ 3 b). This increases the underregistration in Tests F as compared with that corresponding to a rigid piston. When the cover of the test cell moves away from the soil, stress concentrations occur at the periphery, and cause plastic flow or even rupture in the soil. This results in a tendency to stress equalization, and reduces the underregistration in Tests C. The greater scattering in Tests C (Table 2) might then be attributed to differences in stress equalization between individual tests. This phenomenon may be expected to be most pronounced at small pressures. In addition, the cover travel in the cell used in Tests C was comparatively greater at small pressures (Fig. 5). Many smaller influences will be disregarded here.

From the above we see that the behaviour and the calibration possibilities of a soil pressure cell are largely dependent on the type of cover movement, especially at small pressures. The greatest underregistration—but at the same time the best reproducibility—are obtained with the cell covers which are continuously bent at the periphery.

For deflections which are greater than, say 0.05 mm, both types of cell covers exhibit very similar tendencies to greater underregistration.

For instance, the average slope in Tests C indicates a change of 0.41 kg/cm² in underregistration when the change in cover travel is 0.1 mm. For the same travel and the same modulus of elasticity, Eq. (7) (§ 6 a), indicates an underregistration of only about 0.34 kg/cm². Thus the slopes in Fig. 23 indicate an influence of the cell cover travel which is about 20 % greater than that given by Eq. (7). This is due partly to the circumstance stated in § 2 b and partly to the possible arching. It is interesting to compare this result with the projection case in § 6 d 3, which represents a relative movement into the soil. We must keep in mind, however, that the influence of the test tank friction was eliminated in the latter case. Both theory and practice are too intricate to permit any far-reaching conclusions.

The above discussion shows the importance of the cell cover type and the soil elasticity. The good reproducibility in Tests E and F indicates that soil pressure measurements by means of cells are possible in the absence of vibrations, especially if the cover deflections are not discontinuous. It is very difficult to acquire adequate knowledge of the elastic properties and the boundary conditions (*e.g.*, those caused by a limited wall extent) in the soil in practice. Where, however, sufficiently reproducible soil properties can be obtained, when passing from laboratory to practice, most of these inconveniencies are avoided.

Some investigators, (8), (19), (26), have made tests with fairly great cell cover deflections, and obtained certain definite slopes of the test curves, which were then extrapolated rectilinearly to the line of zero deflection. The slope lines have indicated a certain deviation at zero deflection. This has been interpreted as due solely to test tank friction. Fig. 23 shows that this extrapolation is not permissible.

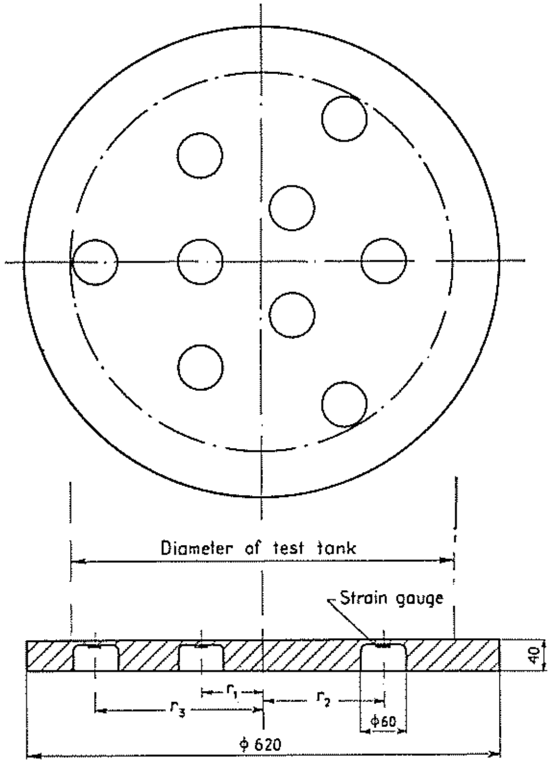


Fig. 24. Test plate III.

§ 8. Pressure on Bottom of Test Tank

As the compressometer rings did not touch the bottom plate, the whole load applied to the top must be transmitted to the bottom plate. Owing to frictional forces between the soil and the individual compressometer rings, a shear stress pattern is developed close to each ring. In another report of the Institute (Ref. 13, p. 10), the maximum influence of ring friction was estimated as an average over a horizontal section, and was found not to exceed 2 % of the applied load.

Non-uniform pressure distribution on the bottom plate may be due to various causes, for instance, to the fact that the soil is not quite homogeneous and also to the deflection of the bottom plate. Special tests, G and H, were therefore run to form an idea of the real stress distribution.

We made a bottom plate similar to that used in § 7, but this time it was provided with 9 test membranes placed at 3 different diameters (Fig. 24). The membranes were 60 mm in diameter and 5 mm in thickness. The membrane deflection was computed to be as small as 0.003 mm at a pressure of 4 kg/cm^2.

Resistance wire strain gauges were used in the same way as in § 7, and the calibrations and measurements were made similarly. The observed maximum

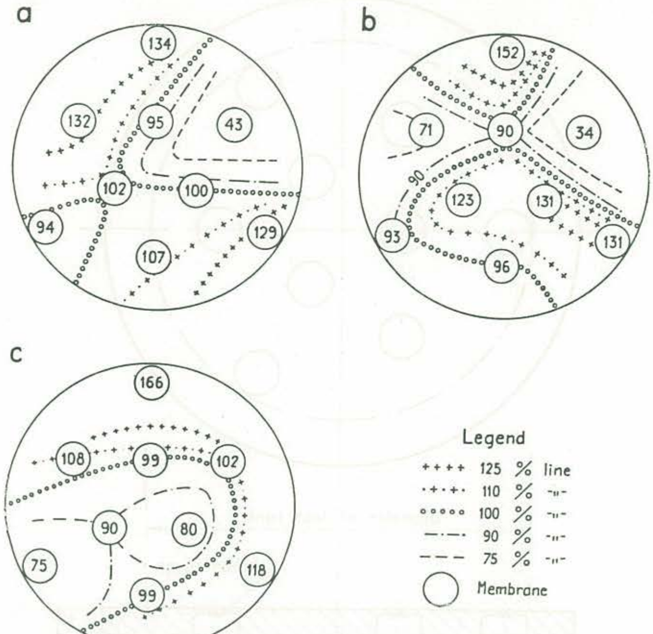


Fig. 25. Test group G — Pressure readings in per cent of mechanical calibration. Applied pressure 4.5 kg/cm².

stress in the membranes was about 70 kg/cm², corresponding to about 30 micro-strain in the measuring bridge. The zero point shift was probably not greater than 5 micro-strain. Thus we can safely estimate the results when the differences lie above 15 % of the maximum range.

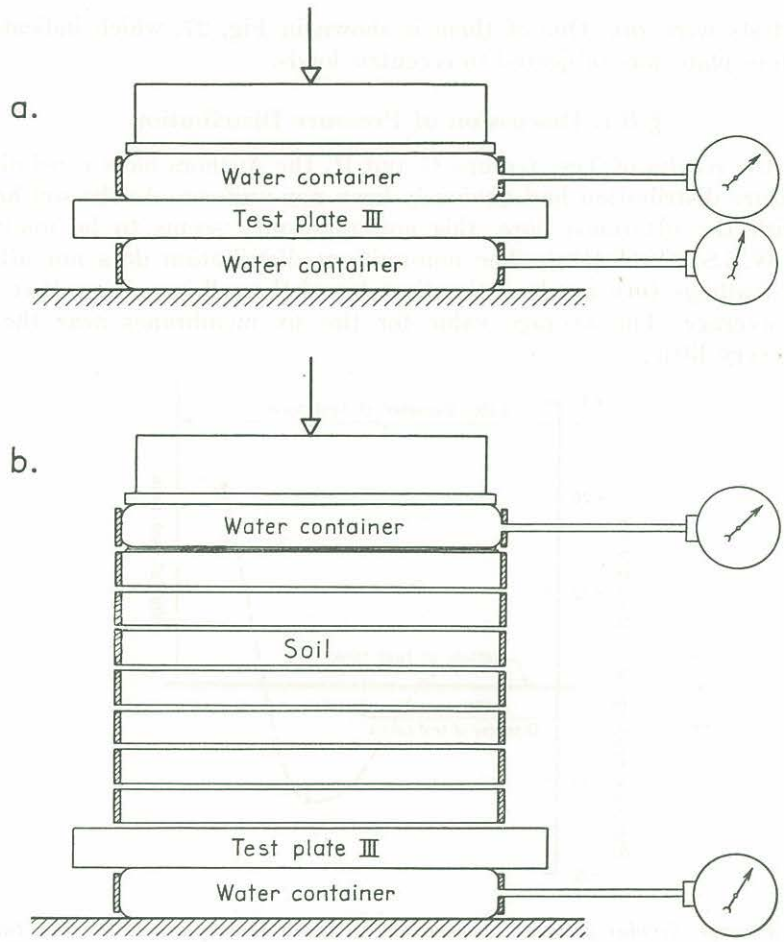
§ 8 a. Test Group G — Pressure Distribution

The bottom plate rested on the same base as in all earlier test groups. Three separate tests were run, each with new refill of the tank. The results obtained at the highest applied pressure (4.5 kg/cm²) without corrections are given in Fig. 25 in per cent of the mechanical calibrations.

It is interesting to note that the pressure distribution in these tests is highly non-uniform, although some regularity in the pressure distribution can be found. The differences are greater than the possible errors in measurements.

§ 8 b. Test Group H — Check Tests

In order to find out whether the non-uniform pressure distribution obtained in Tests G was due to bending of the test plate, we made check tests, in which the plate was placed on a water-filled rubber container (Fig. 26).



a) Mechanical calibration b) Soil test

Fig. 26. Test set-up for Test group H.

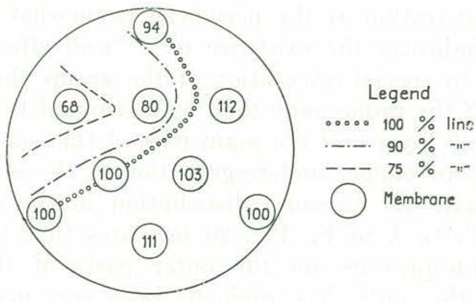


Fig. 27. Pressure readings in a test of Group H.

Four tests were run. One of them is shown in Fig. 27, which indicates that the bottom plate was subjected to eccentric loads.

§ 8 c. Discussion of Pressure Distribution

From the results of Test Groups G and H, the Authors have concluded that the pressure distribution had obviously been non-uniform. As the soil had been filled with the uttermost care, this non-uniformity seems to be unavoidable [*cf.* the W.E.S. Tests (19)]. The non-uniform distribution does not affect the test cell readings very much as the diameter of the cell is so large that it gives a good average. The average value for the six membranes near the centre changes very little.

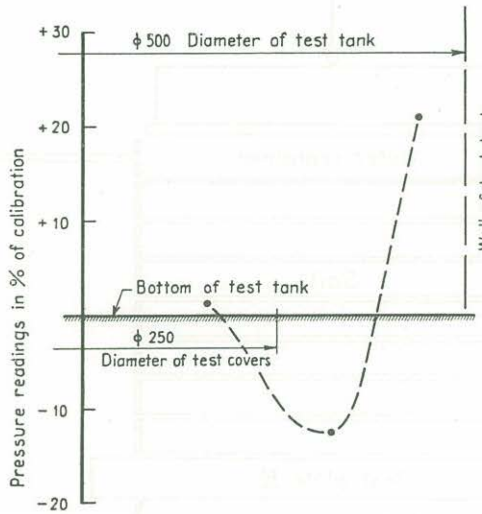


Fig. 28. Average circular pressure distribution on the bottom plate of the test tank at an applied pressure of 4.5 kg/cm² (Test group H).

In Fig. 28, the average test values from Test Group G are plotted as a function of the radius of the test-tank bottom. This curve is of qualitative interest. The overregistration at the periphery (somewhat exaggerated by the calibration set-up) indicates the existence of a "wall effect", which is in our opinion mainly due to special orientation of the grains close to the wall. The friction at about half the radius may then be attributed to relative movements of this more rigid wall layer and the main part of the soil mass. This also can explain the tendency to smaller underregistration at the centre.

Let us now estimate the pressure distribution in the area where a cover was placed in the Tests A to F. Fig. 28 indicates that there has existed an original average underpressure on the outer parts of this area, while the medium pressure at the centre has originally been very near the correct value. As a whole, the area was subjected to a slight underpressure.

We also had other means of estimating the friction in the test tank. As is seen from Fig. 18, the values in the Tests C were dependent on the pressure. For a travel of $75 \cdot 10^{-3}$ mm, all pressure groups lie close together, and can be compared. After reduction to a standard modulus of elasticity there will remain a pressure-sensitive influence. If we assume that this influence was friction, we can calculate its magnitude. It was found to be about 3 % of the applied pressure. Part of this friction may have been present between the cell cover and the soil, and will also exist in practice.

§ 9. General Conclusions

From the calculations and tests described in §§ 2 to 8, we can draw the following conclusions.

On the whole, we can state that the results of measurements are affected by deviations originating partly from the cell, partly from the soil, and even from the boundary conditions.

§ 9 a. Deviations Originating from Cell

Firstly, the cell cover travel has an influence on the results, which is of the same order as that given in § 2 if the boundary conditions of the test tank are taken into account (*cf.* § 6 a and § 7 c). However, it will not pay to make the travel extremely small. The Authors are of the opinion that a cell 25 cm in diameter should have a maximum travel of about 0.025 mm at a pressure of 4 kg/cm^2. This corresponds to a diameter-deflection ratio of 10 000.

Secondly, we recommend that the cover should have a continuous deflection curve in order to reduce the scattering of the results. The deviation from calibrations will then be greater, but, as it is computable, the real error will be smaller than in the case of a rigid piston.

Thirdly, the surface of the cell must have the same hardness as the wall in the immediate neighbourhood. Furthermore, friction between the soil and the cell should be a minimum.

Fourthly, the cell must be able to take eccentric loads, as has been proved in § 8.

§ 9 b. Deviations Originating from Soil

Firstly, the modulus of elasticity of a granular soil is not a constant, but changes with pressure and is probably of nonisotropic nature. This must be taken into account in the calculations, and is the main factor influencing the results (Fig. 23).

Secondly, a change in unit weight of the soil close to the cell surface can influence the results. Such a change evidently takes place when the cell cover (§ 6 c 2) is repeatedly moved in relation to the soil.

Thirdly, the distribution of stresses is not uniform because the soil is inhomogeneous. This is shown in § 8, and has also been noticed by other authors. The remedy is to use large cells or many cells. The grain size of the soil also has an influence on the results. Therefore, soil pressure cells cannot be used in coarse fills adjacent to structures (§ 6 b).

Fourthly, the stress conditions in any soil may change when the soil is subjected to vibrations. As has been said in § 6 c, the cell readings can then change and can even pass from underregistration to overregistration. In soils where vibrations occur, scattering of the results is inavoidable. The entire calibrated underregistration of a cell must here be regarded as a range of error.

§ 9 c. Deviations Originating from Surroundings

As has been pointed out in § 2 c and § 6 a, our results have been influenced by the test tank. Similar influences may occur in practice when a cell is installed close to a corner, a neighbouring structure, the soil surface, or rock. Such deviations may be considerable, and must be taken into account.

§ 9 d. Suitable Measuring Systems

The test cell described in § 5 proved to be reliable during some years. However, the results scattered a little (Table 2). Scattering was reduced by changing the cover design. If the maximum cover travel is reduced to 0.025 mm, the underregistration can be expected to be smaller. The above conclusions have resulted in a revised cell design, see Fig. 29, which is to be regarded as a typical long-time measurement cell. In a soil whose modulus of elasticity is known, this cell may be supposed to give reliable results.

We cannot see why the best type of resin-bonded electrical resistance wire strain gauges (a cell similar to our test plates may be a practical solution), or the vibrating-string method should not be used for measurements over a few years. What really matters, however, is the type of cell cover and its deflection curve.

§ 9 e. Some Considerations on Cell Application

As has been shown in § 7 c, the modulus of elasticity of the soil has a direct and great influence on the results of measurements. Even if the soil pressure cell is perfect, the results of measurements cannot be corrected more reliably than is made possible by the knowledge of this modulus. This is also true of projecting cells, which may apparently show small deviations, but nevertheless are dependent on the soil properties as well as cells flush in a wall.

If the procedure used in practice is such that the pressure cell is always calibrated in contact with the actual soil and in the actual pressure range, corrected for the distribution of main stresses, and possibly for the boundary

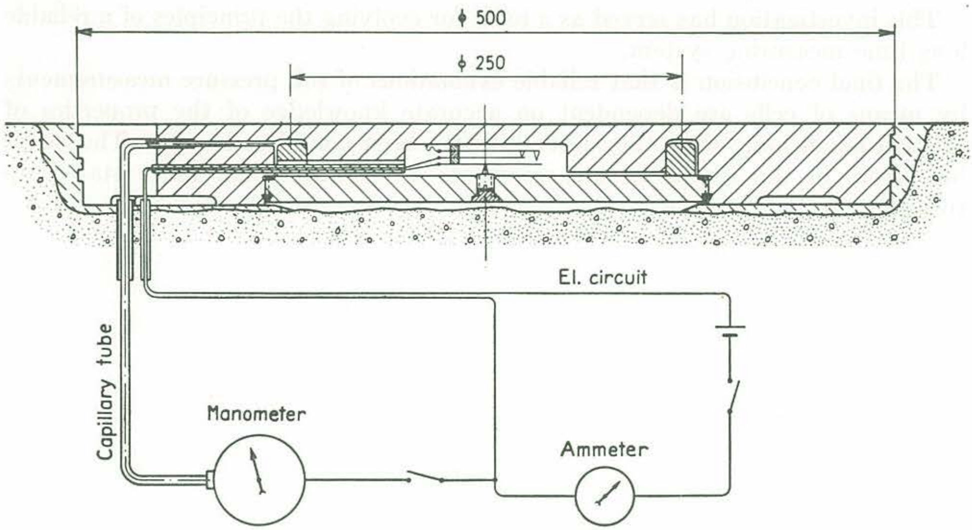


Fig. 29. Project of a soil pressure cell.

conditions, then the errors in cell recordings may be expected to be small. This procedure will have to be employed at present. A practical check is very expensive and time-wasting as large-scale field tests are necessary owing to the boundary conditions of test tanks.

§ 10. Summary

The Authors have investigated the conditions which govern the behaviour of pressure cells fitted in the surface of a wall and situated in a granular soil.

When a cell cover moves from the surface in a direction away from the soil, and when the soil does not vibrate, the cell will indicate pressure underregistrations, which can be corrected for. Laboratory tests have shown that the dominating factors which influence the underregistration are:

a) the *magnitude* of the cell cover travel
b) the *modulus of elasticity* of the soil
c) the *boundary conditions* in the soil.

Moreover, there is some scatter in the results obtained by means of the tested cell. The scatter has been reduced by using improved types of cell cover, and this shows the importance of

d) the *type* of cell cover movement.

This investigation has served as a basis for evolving the principles of a reliable long-time measuring system.

The final conclusion is that reliable evaluations of soil pressure measurements by means of cells are dependent on accurate knowledge of the properties of the soil much more than they have hitherto been considered to be. The possible errors in the results of measurements are greater than those stated up to now.

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