A Cell to Measure Small Soil Pressures in Model Tests

by

S. Venkatesan*

R.L. Kureel**

Introduction

CARRYING out model tests is an important step between theoretical considerations and active construction and vice versa. Even though this is true for all branches of civil engineering, it is particularly true in the case of soil mechanics where many aspects still need scientific approach, based on sound observations. The distribution of stress on a soil structure interface is one such aspect where there is plenty of scope for research and which will find immediate application in design.

Model tests on footings, retaining walls, abutments, etc., all have necessity to measure soil pressures. One important thing to note here is that the pressure in these model tests are smaller to what are encountered in the field. Particulary "the earth pressure at rest" or the horizontal pressure due to such overburden is just a small fraction of that in field. Hence the pressure cells to measure such pressures must :

(*i*) have a low range but high sensitivity,

(*ii*) be quite small in size compared to the models,

(*iii*) capable of being used in any desired position,

(*iv*) capable of using again and again ; and above all,

(*v*) quite cheap.

The present paper describes a small soil pressure cell meeting these requirements and also suiting mass production.

Design

In the present work the authors had to design a cell to measure low range of pressures such as 0 to 0·1 kg/cm^2 (about 0-1·5 PSI).

In fact the design of such low range pressure cells will be quite easy provided one can make use of a very sensitive detecting element and a suitable measuring system such as semi-conductor strain-gauges and suitable strain bridges. But this was not possible due to non-availability of indigenous semi-conductor strain-gauges. It was not advisable also to use imported strain-gauges because of their prohibitive cost which could make a pressure cell more a prestige piece than an utility in numbers.

---

*Scientist.
**Junior Scientific Assistant.
} Central Building Research Institute, Roorkee.

This paper (modified) was received on 9 August 1973. It is open for discussion up to March 1974.

With electrical strain-gauges of gauge factor (2·0) and strain bridges of least count 10 microstrain option was limited to beam type pressure cells (Nandakumaran, 1970) and diaphragm type pressure cells.

One disadvantage of the beam type pressure cell is that there will be a gap between the deflecting beam and the non-deflecting sides. Even if the beam is designed to give this gap smaller than the smallest size of the soil particle used, the angular ends of the particles entering into the gap will make repeatability of performance very difficult. Moreover, sealing against moisture ingression of such an instrument with gap is very difficult. Above all the greatest disadvantage of the beam type cell is that the deflection of the beam causes a sudden discontinuity in the face of the cell in a direction perpendicular to the axis of the beam (Figure 1). The degree of this discontinuity is itself varying along the beam and is maximum at mid span. The disturbance in the soil pressure distribution caused by this discontinuity would make the measurement unreliable.

In case of diaphragm type of pressure cells it would have been excellent if the cell could be designed with the diaphragm integral with the body. But it was not practicable because, the small pressure cells to be used in model tests to measure very low pressures should have very thin diaphragms. To machine such diaphragm out of rod stock without impairing their function is well neigh impossible with the available machines. So it was decided to design cells with attached diaphragms in such a way that each cell would be complete by itself.

The diaphragm of the cell is designed on the basis of the formulae (Roark, 1954) :

Stress at centre

$$S = \frac{3W\,(m+1)}{8\,\pi\, mt^2} \qquad ..(1)$$

and

Deflection at centre $\partial = \dfrac{3W\,(m^2-1)\,a^2}{16\,\pi\, E\, m^2t^3}$ ...(2)

Where,

W = Total load on the diaphragm.

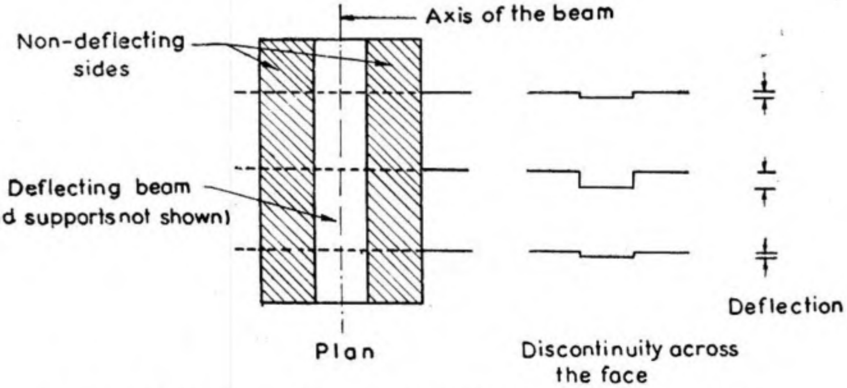

FIGURE 1 : Discontinuity across the face of a beam type pressure cell.

m = Reciprocal of Poisson's ratio.

E = Young's modulus.

a = Radius of the diaphragm and

t = Thickness of the diaphragm.

In order to exploit the full potential sensitivity of the diaphragm it was designed such that the central deflection of diaphragm (when the full designed pressure is applied) is equal to 1/4th of the thickness of the diaphragm itself. Any further attempt to make the diaphragm more sensitive will cause the diaphragm to behave more like a membrane than as a diaphragm and may cause permanent set. Discontinuity would set in and the formula would no longer hold good.

Applying the above criterion and the relevant values of the material (phosphor bronze), the above formulae reduce to

$$p_o = 0{\cdot}28 \times 10^8 \left(\frac{t}{d}\right)^4 \qquad \ldots(3)$$

$$\epsilon_o = 3{\cdot}23 \left(\frac{t}{d}\right)^2 \qquad \ldots(4)$$

Where,

p_o = Design pressure (kg/cm^2)

ϵ_o = Strain at the centre at design pressure (cm/cm)

d = Diameter of the diaphragm (cm).

Construction

The cell consists of a thin phosphor bronze diaphragm bonded to one face of a brass ring (Figure 2). Two electrical resistance strain-gauges (grid

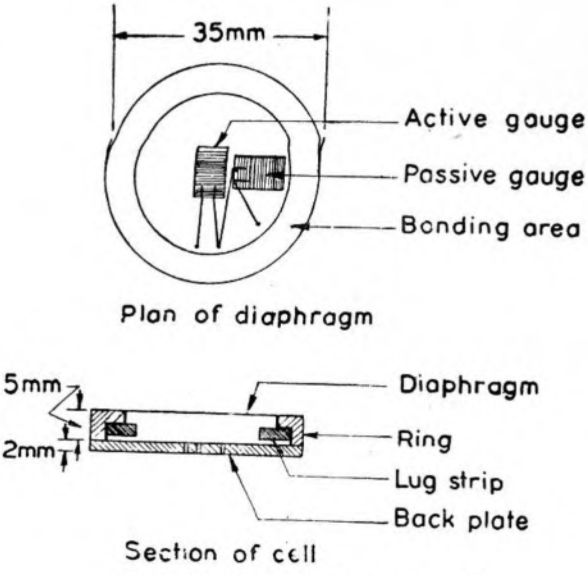

FIGURE 2 : Construction of the cell.

size 1×3 mm) bonded to inner side of the diaphragm, one at the centre and other tangentially near the edge, constitute the sensing elements.

The leads of strain-gauges are properly soldered to 3 points in a lug strip. The cable is soldered to these points and taken out through a back plate. The entire cell is then hermetically sealed.

The bonding of the diaphragm all around its edges makes it behave more like a diaphragm with fixed edges than like a freely supported diaphragm. Under such boundary conditions the application of uniform pressure on the outer surface of the diaphragm causes tension in the central gauge and compression in the edge gauge. When these gauges are connected to the opposite arms of a strain bridge, namely, active and compensating gauges respectively, two advantages result. The first is, of course, usual thermal compensation, the second is that the sensitivity is slightly increased because of the compression in the edge gauge.

Calibration

Each cell was calibrated with air or water and then with sand up to design range of pressure.

(a) FLUID CALIBRATION

A very simple and cheap instrument was made for this purpose. In a thick wooden base, two cylindrical recesses were made side by side just to accommodate two cells (Figure 3). The small gap between the rim of pressure cell and the inner surface of the recess was filled in with moulding clay. When the cells were thus set in the recesses their faces were flush with the upper surface of the base.

The cables projecting axially from the bottom were taken out of the base through holes at the centre of the recess. The surface of the base plate was covered by a thin poleythene sheet over which a flat annular rubber gasket was placed. A hollow lid was inverted over the gasket and clamped to the base.

Cells of ranges 1·0 kg/cm² were calibrated by pumping air into the lid and reading pressure against a mercury manometer. (The mercury manometer itself was made to read directly in kg/cm² instead of height difference in cm).

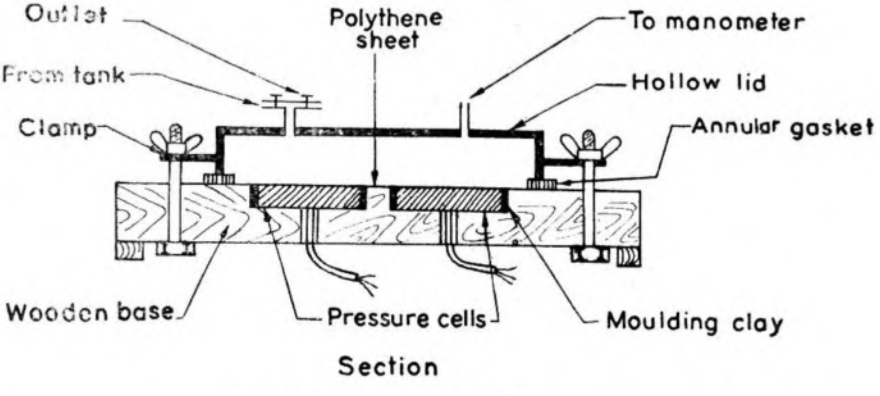

FIGURE 3 : Set-up for fluid calibration.

Cells of ranges 0·1 and 0·2 kg/cm^2 were calibrated by pumping water into the lid and the pressure measured against a vertical stand pipe, the zero of whose scale was in level with the face of the cells.

Calibration graphs were linear with little or no hysteresis and possessed excellent repeatability.

(b) SAND CALIBRATION

This is done in a special chamber (Figure 4).

The pressure cell is embedded with the face flush with the top surface of a thick circular wooden disc which itself fits tightly at the bottom of the chamber. The cable passes through the wooden disc and is taken out of the chamber. Clean sand is filled in the chamber to the required density up to level of flange surface. A thin polythene sheet is placed over its surface and a hollow lid is tightened on it as before. Air pumped into it exerts pressure on the cell through the soil medium. The pressure is read on manometer and a corresponding reading of the pressure cell is taken.

Sand calibration graphs were almost linear with negligible hysteresis. The factor of sand calibration was about 92 percent of that of air calibration.

Usage

The cells after development were immediately used in a research project on rigid well foundation of square section in a series of model tests (Kapur, 1971). They were buried in clean sand to various depths and loaded vertically and laterally. The pressure distribution along the loaded surface was measured by embedding these small pressure cells in the model. Circular recesses of diameter slightly larger than that of the pressure cells

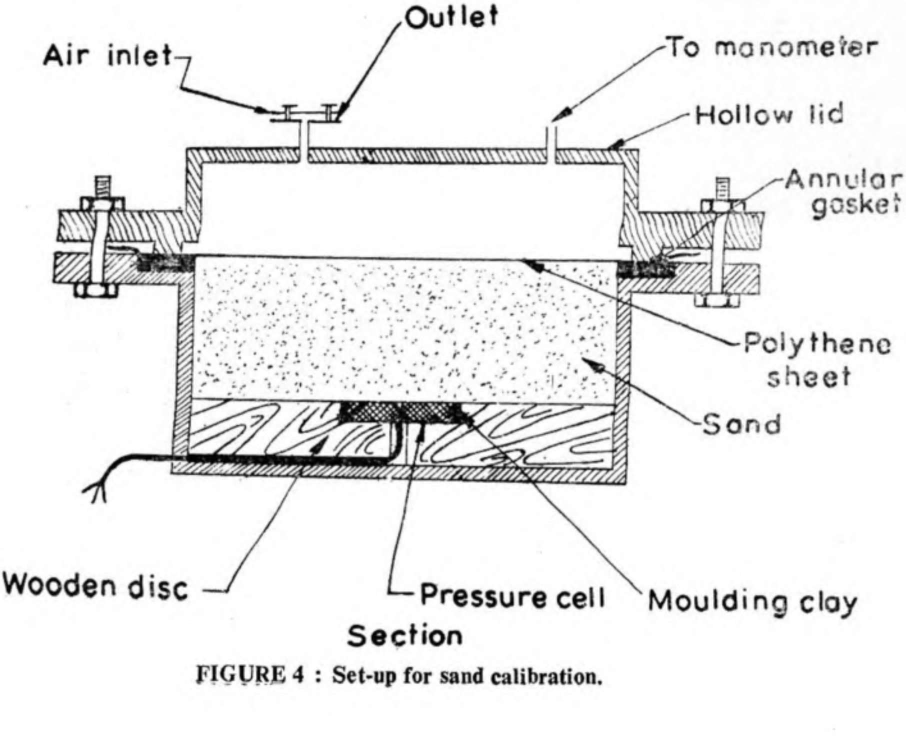

FIGURE 4 : Set-up for sand calibration.

were made in the models in the required positions, coated inside with plaster of paris and the pressure cell embedded with its face flush with the wooden surface. The cable passed through a hole in the recess and was taken out through the hollow interior of the model.

This arrangement proved excellent because of complete protection of pressure cells and cables. Since all these pressure cells were exactly of the same external dimensions irrespective of the ranges there was no difficulty whatsoever in changing the pressure cells from location to location or from model to model. Thus each cell could be used any number of times. Also since the pressure cells were of different ranges it was possible to fix the right cell in the right place (Pressure cell of large range was fixed at the place where the anticipated pressure was large and so on). Thus the design of the pressure cell enables lot of flexibility in the uses.

Discussion of Performance

Table I gives the performance of all these cells in a nutshell. Since

TABLE I

Performance of the cells.

Cell No.	Range (kg/cm²)	Air calibration characteristics			Full scale reading in sand calibration (micro-strain)	Least count of sand pressure (kg/cm²)	No. of models in which used	Total No. of tests in which used
		Linearity	Hysteresis	Repeatability				
1	2	3	4	5	6	7	8	9
C-1	0-1	G	C	G	680	0·015	1	24
C-2	0-1	G	S	E	550	0·018	2	62
C-3	0-1	G	S	E	740	0·014	3	73
C-4	0-1	G	S	E	760	0·013	3	73
C-5	0-1	G	S	E	800	0·013	3	73
C-6	0-1	G	S	E	670	0·015	3	73
C-7	0-0·5	E	S	E	440	0·011	3	73
C-8	0-0·5	E	S	G	480	0·010	2	35
C-9	0-0·5	E	N	E	510	0·010	1	24
C-10	0-0·5	E	S	G	480	0·010	3	73
C-11	0-0·5	E	Nil	E	300	0·017	3	73
C-12	0-0·5	G	Nil	E	310	0·016	2	35
C-13	0-0·5	E	Nil	E	470	0·011	2	35
C-14	0-0·2	P	L	P	540	0·0037	1	24
C-15	0-0·1	G	N	E	180	0·0056	2	35
C-16	0-0·1	G	S	E	150	0·0067	3	73
C-17	0-1	E	C	E	—	—	1	38
C-18	0-1	E	Nil	E	—	—	1	38
C-19	0-1	E	Nil	E	—	—	1	38
C-20	0-1	G	C	G	—	—	1	38
C-21	0-1	E	N	E	—	—	1	38
C-22	0-1	G	S	E	—	—	1	38
C-23	0-1	E	N	E	—	—	1	38

E = Excellent, G = Good, P = Poor,
N = Negligible, S = Slight, C = considerable and L = Large,

the cells could be read down to 10 microstrain (1 division) the least count of cell is given by

$$\text{Least count} = \frac{\text{Range} \times 10}{\text{Full scale reading}}.$$

Each model with all the embedded pressure cells intact was used several times (buried in a new filling, loaded to failure, removed, etc.). After that series of tests was over, the cells were removed from that model and put in a different model and a new series of test started. This way each cell has been in more than one model, and has undergone several tests. This is how column Nos. 8 and 9 in Table I have been obtained.

Naturally after repeated use, the calibration of the cell changed slightly. This could be overcome by calibrating again.

Specialities of the Present Design

(1) The diaphragm of the cell, by itself, has been designed to its maximum possible sensitivity, by putting $\partial = t/4$.

(2) By means of ordinary wire resistance strain-gauges and conventional strain bridges a high overall sensitivity has been achieved.

(3) The ratio, $\frac{\text{Deflection}}{\text{Diameter}}$ for these pressure cell is of the order of 2 to $3{\cdot}5 \times 10^{-3}$ which is more than what is recommended by W.E.S. (1953) but still their performance has been reliable.

(4) The design of these pressure cells is simple and standardised and suitable for mass production.

(5) The design allows flexibility in its use.

(6) All these have been achieved out of readily available indigenous material at low cost.

Acknowledgement

The authors are thankful to Shri Ramesh Kapur, Scientist for calibrating the cells, with sand and using them extensively in model tests. The work is a part of research programme of Central Building Research Institute and the paper is published with kind permission of the Director.

References

KAPUR, R. (1971) : "Lateral Stability Analysis of Well Foundations." *Ph. D. Thesis submitted to the University of Roorkee, Roorkee.*

NANDAKUMARAN, P. and DHIMAN, H.C. (1970) : "Miniature Earth Pressure Cell." *Journal of the Indian National Society of Soil Mechanics and Foundation Engineering* 9:3-11.

ROARK, R.J. (1954) : "*Formulas for Stress and Strain.*" McGraw Hill Book Company, Inc., New York.

W.E.S. (1955) : "*Pressure Cells for Field Use.*" Corps of Engineers, U.S. Waterways Experiment Station, Vicksburg.