Experiments to determine the distribution of pressure over a foundation

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VIII 2

Experiments to Determine the Distribution of Pressure over a Foundation.

Versuche zur Bestimmung der Spannungsverteilung in Gründungssohlen.

Essais pour déterminer la distribution des efforts dans la surface d'appui d'une fondation.

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1) *Object of experiments.*

Boussinesq's solution of the problem of a solid which is limited by a horizontal plane in which a perpendicular force is applied through the medium of a rigid cylinder (Fig. 1) is already known. If the vertical displacements of all the points at the base of the cylinder are equal, the force at any point M is given by

$$v_M = \frac{a}{2\sqrt{a^2 - x^2}} \cdot p,$$

where p is the mean value of the pressure. The corresponding expression for a two-dimensional problem, due to *Sagowsky*, is

$$v_M = \frac{2\,a}{\pi\sqrt{a^2 - x^2}} \cdot p.$$

These two equations serve to give the distribution of pressure as indicated by the line v in Fig. 1. The minimum pressure is at the centre C, and may be of any value between p/2 and 0.637 p according to the shape of the bearing surface. Actually the forces cannot be infinitely great. Close to the edge of the compressed surface there will be modifications caused by plastic strains, and the dotted line v′ must be taken as an approximate indication of the true distribution of pressures. The curve is, therefore, saddle-shaped, the two maxima of pressure being close to the edge of the loaded area and being dependent on the sliding movements which arise within the two bodies in mutual contact.

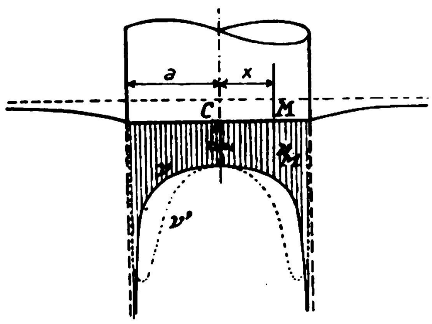

Fig. 1.
Theoretical distribution of stresses.

Is this true also of foundations carried on compressible ground? This question is one which has been under active discussion for some years past. The tests by

Kögler and *Scheidig*[1] made on the surface of a mass of sand have indicated that the maximum pressures occurs at the centre of the loading slab, but on the other hand measurements of the forces arising over the bearing surface of piers at Ludwigshafen[2] and Niederfinow[3] clearly show the saddle-shaped curve of pressure which agrees with the theory of an elastic solid, and finally the experiments carried by Press[4] appear to confirm that under certain conditions either case may occur.

In the design of large foundation slabs it is of great importance to understand the true distribution of the reaction from the ground, and with a view to assisting in the elucidation of this problem, the Czechoslovak Research Association have carried out the tests of which a brief account will now be given.

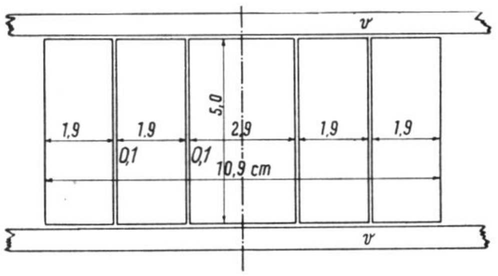

Fig. 2.
Loading plate with five subdivisions.
v = glass plate.

2) *Arrangement.*

The settlement of a foundation is due to two distinct phenomena:

1) the elastic compression of the ground, and

2) irreversible changes in the internal structure, depending on the relation between the total principal stresses due to the action of the load and the weight of the upper layers of the surrounding ground carried by the plane of the bearing surface. In order, then, to study the action of the ground in a small scale model, it is essential that the test soil should be subjected to the same conditions of stress as will occur in an actual foundation; in other words, not only is it necessary to use testing material with a degree of compactness corresponding to that which occurs in nature, but further, a weight must be applied to the edges of the loading slab which will serve as a substitute for the superincumbent mass. The model here used was designed in accordance with this principle, to imitate a section of a long wall founded at the usual depth. The materials chosen for the test were fine sands of the kind to which a permissible stress of approximately

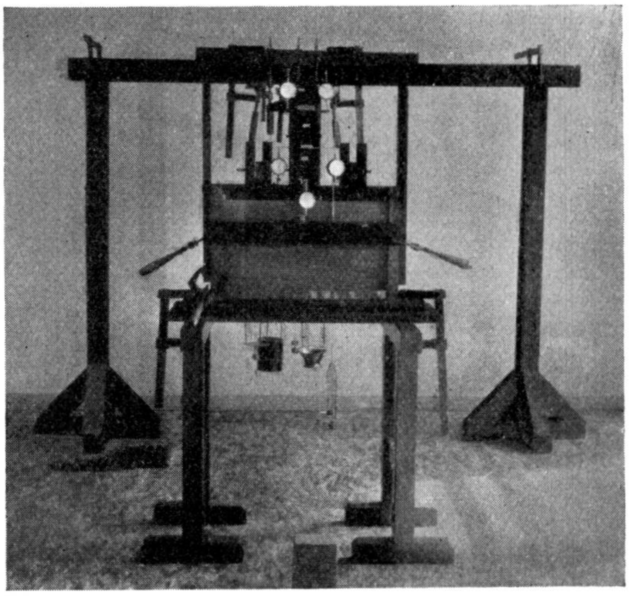

Fig. 3.
General arrangement of test.

[1] Bautechnik 1929, pp. 268, 828.
[2] Ibid 1932, p. 595; Bauingenieur 1933, pp. 242, 473.
[3] Ibid 1934, p. 522.
[4] Ibid 1934, p. 569.

1 kg/cm² is usually attributed. A similar series of tests were carried out on a layer of rubber. The arrangement of the test was as follows.

The loading slab was divided into five portions (Fig. 2) capable of being loaded through the medium of three small rigid tables and of being depressed independently of one another. Their displacements were measured by six instruments reading directly in hundredths of a millimetre and allowing thousandths of a millimetre to be estimated. The photographs, Figs. 3 and 4, show the details of the arrangement. In this way it was possible to study the displacements of the several sections of slab by applying various loads to them and measuring both their total depressions during the period of action of the pressure and the irreversible displacements which remained after the pressure had been removed. Up to July 1936 sixteen series of tests were carried out, indicated by the letters A, B, etc., each series comprising several measurements a, b, etc. The material had to be prepared anew for each series because the compressibility of the sand is modified as a result of each loading process. It is clear that zones of increased resistance are formed, and the amounts of the irreversible deformation differ as between one section of plate and another, the consolidation of the material being different according to the mode of distribution of pressure.

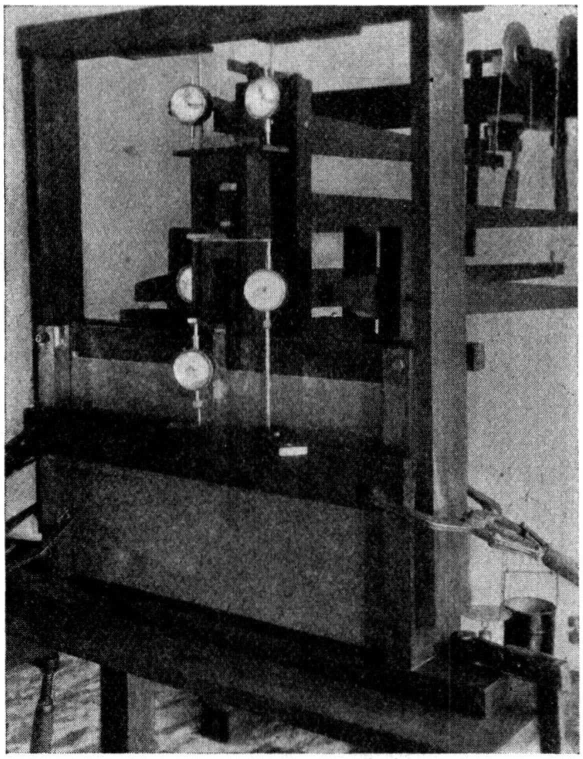

Fig. 4.

Arrangements of measuring apparatus.

3) *Characteristics of the materials used.*

Designation	Specific weight	Granulometric composition: left on screen of size in mm						Water content	Vol. of voids	Voids index
		2.0	1.0	0.5	0.25	0.1	<0.1	% of weight	% of total vol.	ε
	kg/dm³	%	%	%	%	%	%			
Sand I	1.583	—	4.3	47.8	44.8	2.2	0.9	3.6	41.8	0.718
„ II	1.672	—	4.3	47.8	44.8	2.2	0.9	3.6	38.4	0.624
„ III	1.741	—	4.3	47.8	44.8	2.2	0.9	1.8	34.7	0.532
„ IV	1.768	24.6	20.7	26.7	25.5	2.0	0.5	0.9	33.2	0.497
„ V	1.567	—	4.3	47.8	44.8	2.2	0.9	0.5	40.9	0.693

The limit of proportionality p_o in the penetration under the middle of the loading plate was observed to occur when the mean pressure over the bearing surface reached nearly $2^1/_2$ times the value at the edge.

The rubber test specimen measured $45 \times 14.3 \times 5.1$ cm and was stuck down with bands having a mean thickness of 0.68 cm over a layer of heaped sand IV, which was 20 cm deep at the side of the bearing surface. It was not loaded.

4) *Uniform distribution of the load.*

Fig. 5 shows the compression of the rubber layer. The lines T or I indicate respectively the total (or the irreversible penetrations) of the various portions of the plates due to the uniform load of 0.53 kg/cm². The difference in properties

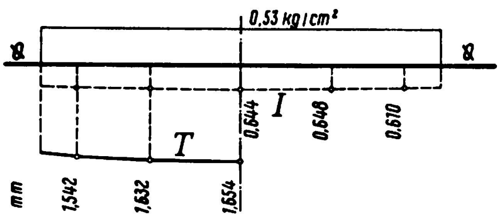

Fig. 5.
Uniformly distributed load over the layer of rubber. Experimental Qa.
T = total penetration.
I = permanent penetration.

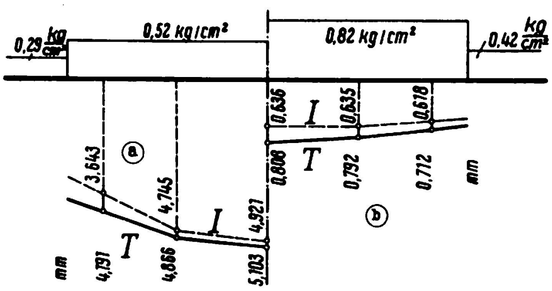

Fig. 6.
Uniformly distributed load.
a) Sand I, test Eb ($p_o \approx 0.5$ kg/cm²),
b) Sand III, test Ha ($p_o \approx 1.0$ kg/cm²).
T = total penetration.
I = permanent penetration.

of the sand are reflected in the preponderance of the irreversible penetrations which have given the shape to the curve T (Fig. 6). The result is that the distribution of forces under a rigid slab depends mainly on the state of equilibrium of the ground around the edge, that is to say on the ratio $p : p_o$.

a) When the arrangement of the test was such as to reproduce the general circumstances encountered in constructional practice, the proportion between the total depression around the edges of the plate to that at the centre was 0.68 to 0.98 (the mean value being 0.88 in 11 experiments wherein the load over the bearing surface was 0.5 to 1.1 kg/cm² and the load around the edges 0.23 to 0.49 kg/cm². These conditions correspond to those arising in foundations at a depth of 1.53 m in a ground of similar nature to that examined in the experiment).

b) If a particularly heavy load is applied to the free surface of the sand, the result is a reversal of the line T, the minimum of the penetration being now under the centre of the plate. Fig. 7 gives an example of this, as observed. In the case of a rigid plate the distribution would then follow a line of approximately parabolic shape, as found in *Kögler*'s experiments.

5) *Distribution corresponding to equal penetration.*

Even in the case of an elastic solid the distribution would depend on irreversible movements around the edges of the plates. It is not possible, therefore, to calculate the mutual relationship between the partial loads by reference to the increase occurring in one of them, and it is necessary to proceed by experiment and direct observation. Fig. 5 shows the final result obtained on the rubber, the difference between the penetrations as measured being only 0.003 mm (0.3 %)

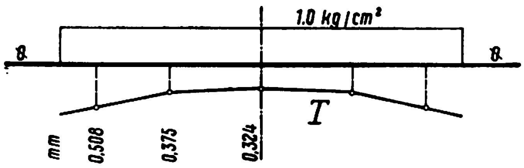

Fig. 7.
Load uniformly distributed over free surface.
Sand III, test Oa ($p_o = \phi$).

which represents the limit of accuracy of the measuring apparatus. From the amounts of load applied the curve of distribution of pressures may be traced, as indicated by v in Fig. 8. These measurements indicate that the pressure at the centre is a little higher (approximately 5 % higher) than is indicated by theory.[5]

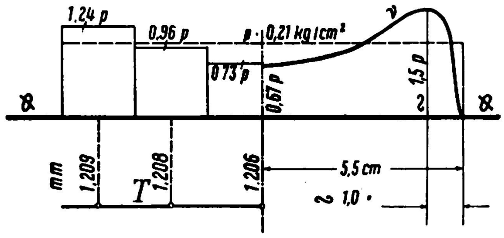

Fig. 8.
Distribution of load causing equal penetrations. Layer of rubber loaded for the first time, test Qh.

In the case of the sands it was not possible to obtain this degree of accuracy and the results were less regular. In order to trace the curves of distribution a small correction calculated from other tests was added to the partial loads. The examples (Fig. 9) show the distribution obtained with the average pressure

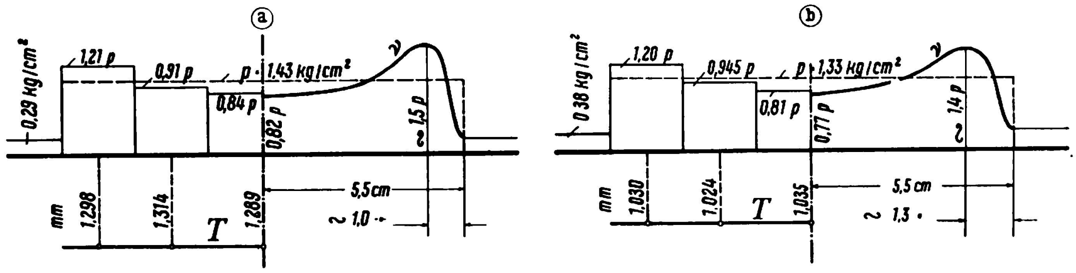

Fig. 9.
Distribution of laod causing equal penetrations.
a) Sand II, test F_n ($p_o \approx 0.8$ kg/cm²).
b) Sand III, test B_l ($p_o \approx 0.9$ kg/cm²).

already exceeding by 50 % the limit of proportionality, which represents the maximum obtainable in practical construction. Where the loads are less heavy the shape of the line v will be more nearly similar to that obtained with rubber. These numerical results do not, however, admit of generalisation, each being dependent on the experimental data. Preparations are in hand for continuing the experiments on other kinds of soil and to a larger scale as in nature.

[5] It should be noticed that even rubber gives a slightly different line if the loading is repeated.

In order to observe the change produced when the loading exceeds that generally permissible a series of tests was made with the sand dry and only lightly loaded at the edges of the bearing surface. Here the limit of proportionality was found to be approximately 0.5 kg/cm², which implies a permissible strength of 0.75 kg/cm². When the sand was subjected to a mean pressure of 1.24 kg/cm² (that is to say 2.5 p_o) the distribution necessary to equalise the penetrations was obtained, as indicated in Fig. 10, where the reduction in pressure towards the centre will be noticed. It would appear that with loads increasing at an excessive rate a distribution curve approximating to the shape of a bell would ultimately be reached, similar to that observed with a free surface.

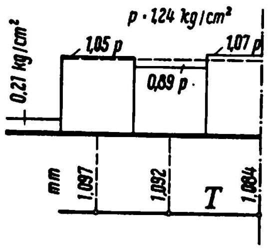

Fig. 10.
Distribution of load causing equal penetrations.
Sand V, test Ng ($p_o \approx 0.5$ kg/cm²).

6) *Conclusions.*

Since the model used was of small dimensions, it is necessary to examine whether the results so obtained agree with measurements on actual foundation slabs as mentioned above. This is in fact found to be the case, since in a three dimensional problem (with a square bearing surface, or a rectangular bearing surface not too long) the load at the centre should amount to approximately one half of the mean pressure. These tests incidentally afford an explanation of the different shape of the pressure curve found in different cases.

It may be further added that the very numerous measurements on different foundation soils carried out by the Institute with which Mr. *Klokner* is associated have served to determine the amounts of the elastic and of the irreversible compressions. Calculation shows that the bending under a reinforced concrete foundation causes a deflection which is much smaller than the amount of the non-elastic settlement in a compressible soil, and if this is true it follows that all foundation slabs may be regarded as rigid.

Assuming a foundation over a stratum which is practically homogeneous, the following conclusions may, therefore, be drawn:

The distribution of load over an element of a foundation varies according to the conditions of equilibrium of the soil. Up to the point where the mean pressure does not exceed the limit of proportionality by more than 50 % the curves of pressures is in the shape of a saddle, and its maximum points are found within the external quarters of the width of the loaded surface. If the loading is in excess of this amount, the maximum pressure occurs at the centre.