On the Deformation and Failure of Sand Underneath Deep Foundations

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SUMMARY. An experimental investigation on the deformation and failure mechanism of deep foundations in sand is carried out. It is shown that the mechanism of failure of sand underneath deep foundations is perfectly different from those obtained by the theory of rigid-plasticity. Vertical and horizontal strains in the zone of failure are measured, using soil strain gages, and the change of stresses in that zone during failure is estimated from a special strain-fitting test, performed in a triaxial cell.

1 INTRODUCTION

The bearing capacity of deep foundations is usually calculated from the slip plane analysis by the theory of rigid-plasticity. However, it has already been found that the mechanism of failure is different from those classical theories. Kerizel, in his large scale model test, has shown that the bearing capacity of deep foundations in sand does not increase linearly with depth, as by the theory, but becomes almost constant at a certain depth.[1] Berezantsev has found from the observation of laboratory and field investigations that the compressive failure of soil just underneath a pile tip is the main cause of the pile failure.[2] Vesic has referred to the mode of failure of deep foundations concerning the effect of the relative density and the confining pressure, and suggested that the slip failure occurs only in case of very small surcharge in dense sand.[3][4] BCP Committee (Committee on the Bearing Capacity of Piles, by Koizumi et al) has, by chance, found that there is no slip plane at the tip of a test pile, when the excavation of the whole surrounding ground up to - 12 m has been performed after the loading test of that pile.[5]

All these findings seem to show that the mechanism of failure in calculating the bearing capacity of deep foundations is different from those by the classical theories. The method of calculating the bearing capacity of deep foundations has, by no means, been established and there must be further investigations, especially on the deformation and failure of soil around deep foundations, in order to find out the right way to approach the problem.

2 MODEL EXPERIMENTS

In order to measure the strain and stress distribution in a soil mass underneath a deep foundation, a series of model tests has been carried out. Fig. 1 shows the outline of the apparatus. A sample container, 60 cm in diameter with a height of 50 cm, is filled with a compacted sand from the River Ohta. The diameter of the model footing is 10 cm and the surcharge on the surface of the soil sample is hydraulically loaded through a thin rubber membrane.

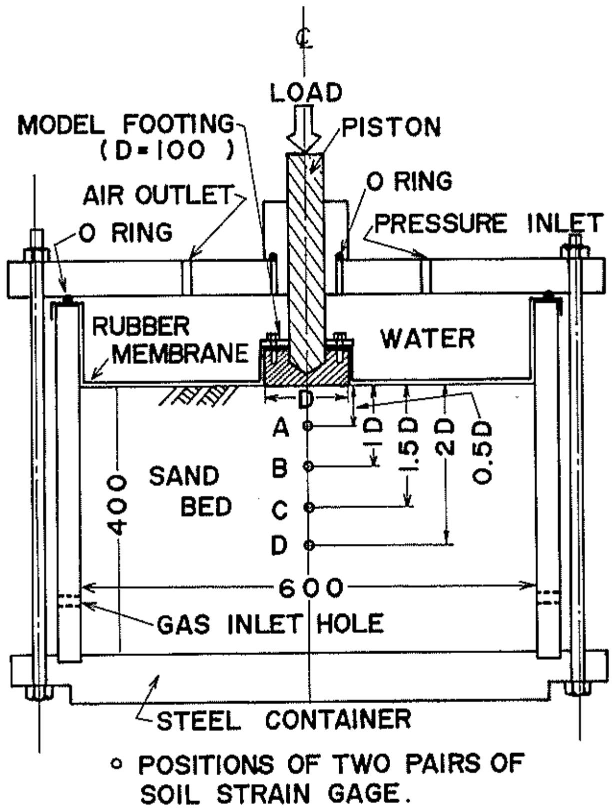

Fig. 1 Apparatus

Fig. 2 is the grain size distribution curve of the sample used. The density of the sample is kept constant at $\gamma d = 1.60$ t / m^3 in every tests.

From the result of triaxial compression tests, its angle of internal friction in the range of present experiments is $\varphi = 37^\circ$, as shown in Fig. 3.

Several pairs of soil strain gages are installed in the sand bed beforehand, to measure the change of strain in horizontal and vertical directions. The soil strain gage consists of a pair of flat disc-type coils, and there is no physical connection between them. The strain is measured by the change of mutual inductance caused by the change of distance between the two coils, as has been reported elsewhere.[6] In order to make clear the presence of slip planes in the soil mass after failure, a special technique is applied. When compacting the sand sample in layers, horizontal striped patterns are formed in it, using a colored sand. About 3 %, by weight, of liquid silicate of soda (water glass) has been mixed in the sand sample before compaction. After the loading test, carbon dioxide gas is poured into the sample from a pin-hole of the side wall, as a grouting material, to make the sand sample solidified. This solid sample taken out from the container, is cut in two carefully by a knife edge. The photographs of the cross section are shown in Fig. 4 and 5.

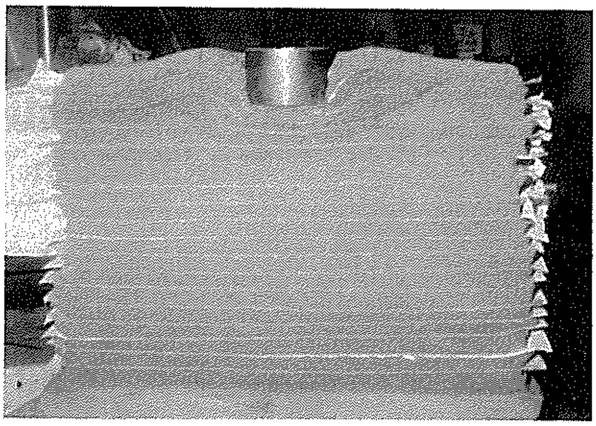

Fig. 4 Case of No Surcharge

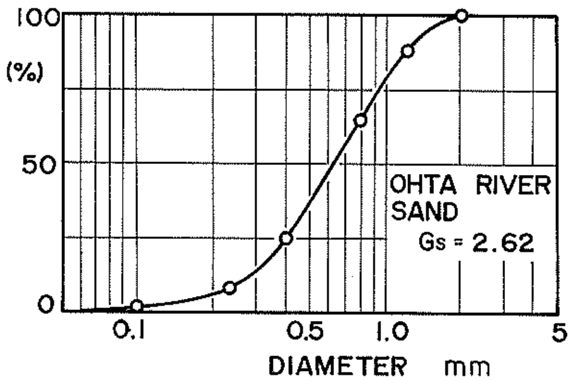

Fig. 2 Grain Size Distribution

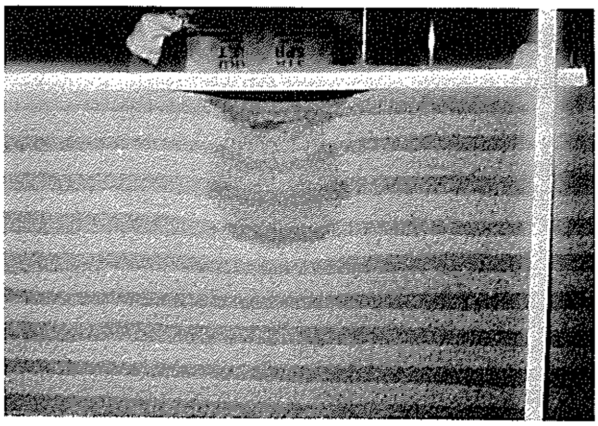

Fig. 5 Case of 10 KG/CM² Surcharge

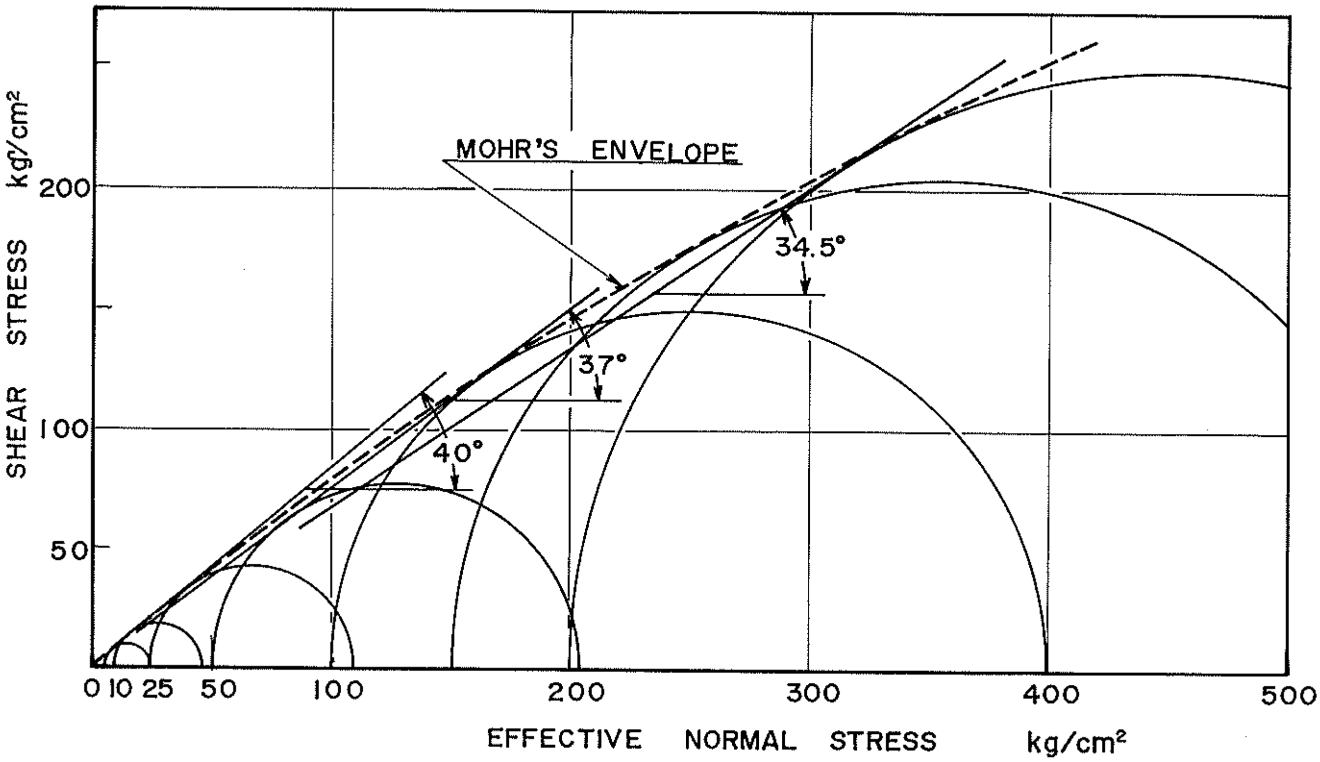

Fig. 3 High Pressure Triaxial Compression Test of the Sample

3 RESULTS OBTAINED FROM THE EXPERIMENTS

Loading of the model footing is performed in a strain controlled test, its penetration rate being 1.0 mm / min. A series of surcharges of 0, 0.3, 0.5, 0.8, 1.0, 2.0, 4.0, 6.0, 8.0, 10.0 kg / cm^2 are loaded.

In Fig. 4, which is a case of no surcharge and a model of shallow foundations, there are clearly observed slip planes under the footing. However, in FIG. 5, which shows a case of 10 kg / cm^2 surcharge, there is no definite slip plane. Even in case of a relatively small surcharge, there is no slip plane observed, and as in Fig. 5, a bulb-shaped failure zone appears. The change of color of the zone is thought to be caused by newly exposed surfaces of the constituent sand grains in the zone by their breakage.

As for the stress-strain relation, the peak stress is observed in case of no surcharge. However, in case of deep foundations,there is no peak stress, and the yield stress in each case is determined from the intersection of two straight lines in log-log plots. The relation between these yield stresses and surcharge loads is shown in FIG. 6. Deviation from the classical theory is clearly seen over a certain magnitude of surcharge. The settlement of footing at each yield stress is also shown in Fig. 7.

4 ESTIMATION OF INDUCED STRESSES IN THE SAND BED

It is very difficult to determine stresses, induced in the soil mass, directly from pressure cell measurements, especially in the zone of failure.

In order to estimate these stresses at several points on the axis of symmetry in the sand bed, vertical and horizontal strains at these points have been measured by the use of soil strain gages. Several examples are shown in Fig. 8.

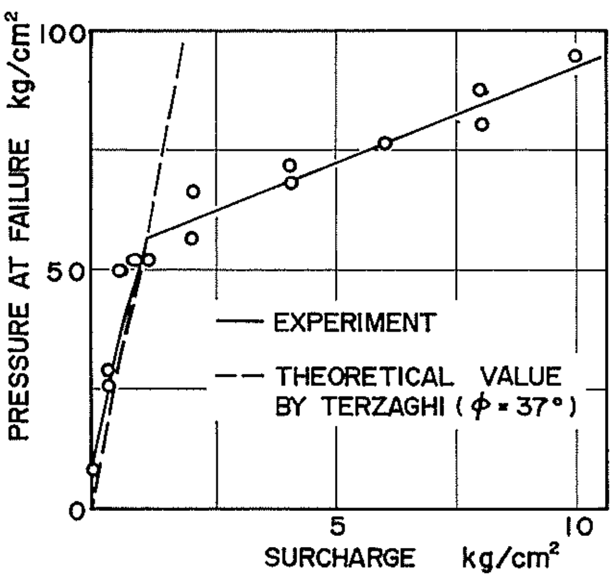

Fig. 6 Footing Load at Failure

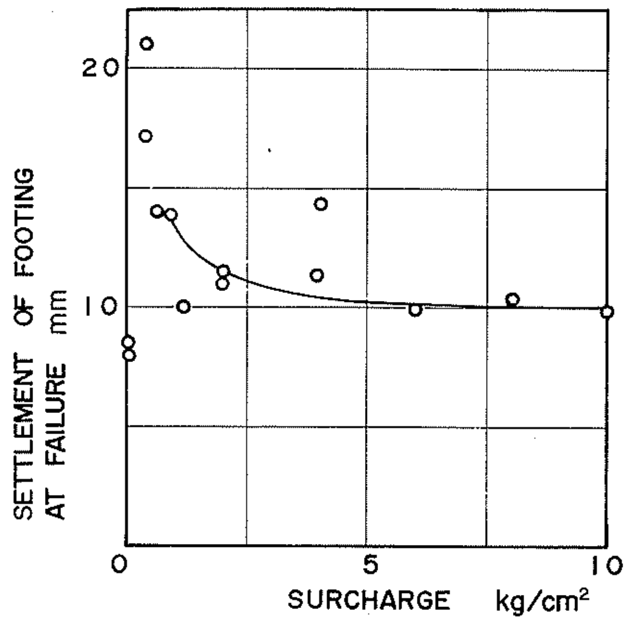

Fig. 7 Footing Settlement at Failure

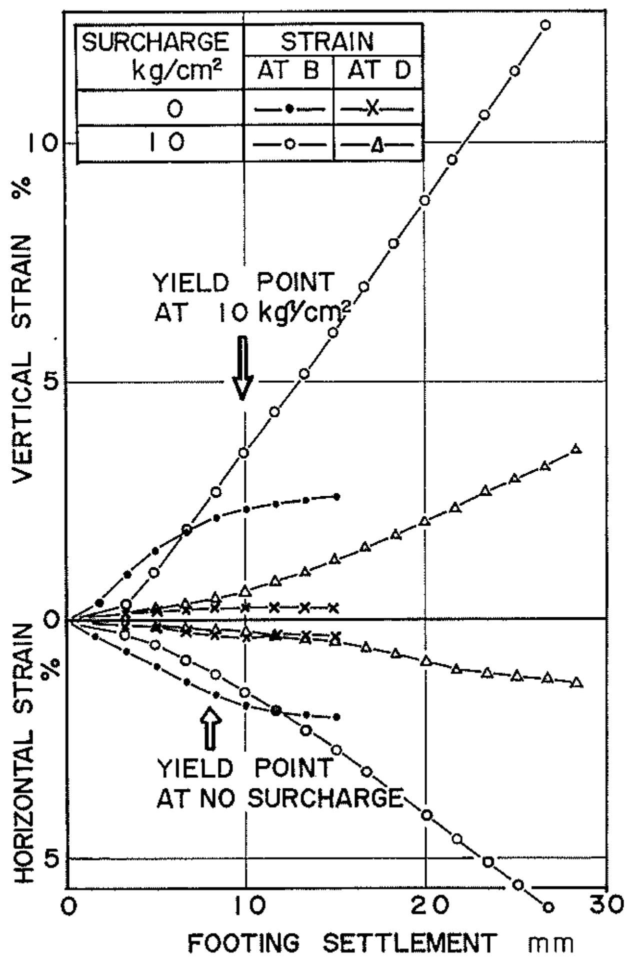

Fig. 8 Examples of Soil Strain Reading

Special strain-fitting tests have been performed. A sand sample, which is in the same condition with a certain point in the soil mass where the change of strain has been measured, is set in a triaxial cell. Starting from K_0 condition at each surcharge load, it is compressed in the same vertical strain rate. At the same time, horizontal confining pressure is controlled,

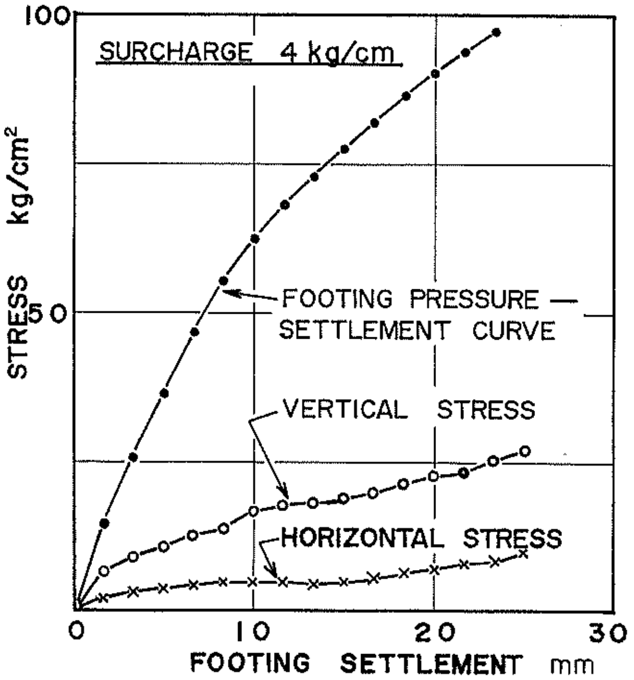

Fig. 9 Estimation of Induced Stress at Point B.

so that the strain in horizontal direction is also kept exactly same with the measured value. The vertical and horizontal stresses induced in the soil mass can be estimated from the stresses in these strain-fitting tests. One of the examples of these measurements is shown in Fig. 9. At the yield point in the load-settlement curve, the estimated stress also seems to yield, as in the figure.

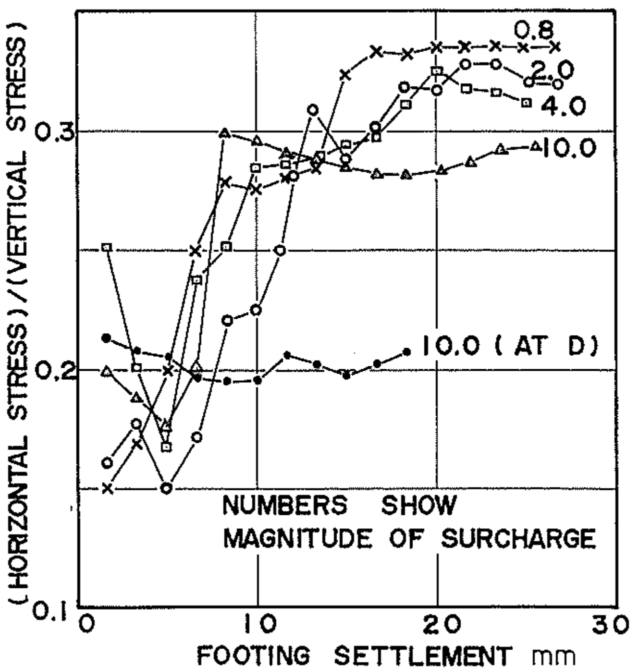

Fig. 10 Ratio of Induced Horizontal Stress to Vertical one at Point B.

5 ON THE MECHANISM OF FAILURE

As shown in the photograph, there is no slip failure in deep foundations. The mechanism of failure in these cases seems to be the compressive one, and it has been analysed from the measurement of soil strain gages. In Fig. 10, the change of the ratio of induced horizontal stress to vertical one at point B in each case of surcharge, has been followed up. This ratio converges to a constant value of 1/3, after the yield stress is reached, irrespective of the magnitude of surcharge. At point D, which is situated outside the zone of compression failure, this ratio is relatively smaller, and there is no significant change in this ratio at the yield point of the footing load.

Fig. 11 is an example of volume change, calculated from the strain at point B, obtained by soil strain gages. As the footing settles, the sand just underneath the footing is gradually compressed and decreases its volume, until it reaches to a constant volume at the yield state.

From the stress condition and the volume change, shown in Fig. 10 and 11, the state of soil underneath deep foundations at failure can be understood well. It also suggest that there is a possibility to estimate the bearing capacity of deep foundations by means of the compression failure test in a triaxial cell.

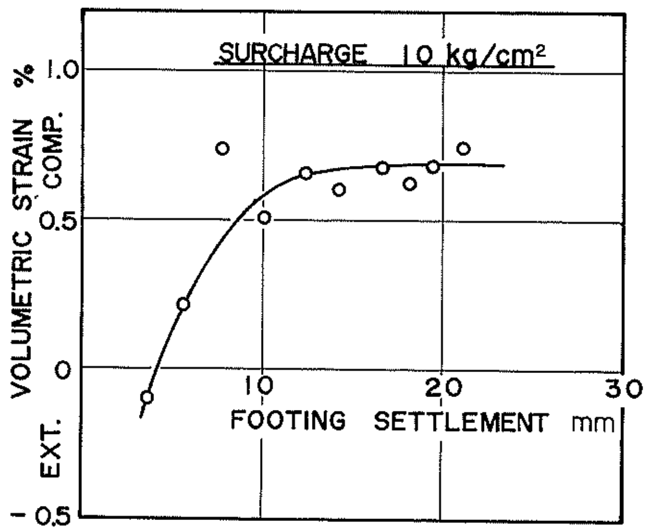

Fig. 11 Volume Strain at Point B

6 CONCLUSIONS AND ACKNOWLEDGEMENTS

The deformation and the mechanism of failure of sand bed just underneath a deep foundation have been investigated through a model experiment. The mode of failure is perfectly different from the one suggested by the theory of rigid-plasticity.

In order to clarify the mechanism of failure of deep foundations, the change of strain in the soil mass during failure has been measured by means of soil strain gages.

A special strain-fitting test has been

developed to estimate vertical and horizontal stresses from the strain readings.

The ratio of estimated horizontal stress to vertical one seems to converge to the value of 1/3, when the soil mass in the zone has reached to failure, irrespective of the magnitude of surcharge. And the volume of soil in the failure zone has gradually decreased , until it has reached a constant value, when the footing load has become to the yield state.

From these phenomena in the failure of deep foundations, the possibility of determining the bearing capacity by means of a compression failure test in a triaxial cell, has been pointed out.

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