SIZE AND LOAD EFFECT ON SETTLEMENT OF FOOTINGS IN CLAY

EFFET DES DIMENSIONS ET DE LA CHARGE SUR LE TASSEMENT DES SEMELLES SUR ARGILE

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SYNOPSIS A dimensional analysis is made on the effect of size and bearing pressure on the settlement of footings. The analysis shows that while for cohesionless soils, $q/\gamma d = f(\Delta/d)$, the settlement of clays is related to the size of footings d, and the bearing pressure q in accordance to the expression $q/c = f(\Delta/d)$. The results of the theoretical analysis are verified with the experimental data obtained by various investigators as well as with those obtained by the author. The design of geometrically similar footings in the same clay but carrying different loads to meet the requirement of minimum differential settlement, is shown.

INTRODUCTION

Plate bearing tests have been used for foundation investigations where the soil within the zone affected by the foundation loading is homogeneous and similar to that beneath the test plates. However, the cost of carrying out field tests with plates close in size to that of the proposed foundations is normally prohibitive and test results obtained with small plates are generally regarded with disfavour. There is, therefore, the need to examine the problem on a dimensional basis and to see how test results obtained with model plates might be extrapolated to predict settlement behaviour of the prototype.

DIMENSIONAL ANALYSIS

Cohesionless Soil Consider two circular footings of diameters d_1 and d_2 resting on the surface of the same homogeneous cohesionless soil. If their respective settlements are Δ_1 and Δ_2 when under the same intensity of pressure q, then

$$\Delta_1/d_1 = \Delta_2/d_2 \qquad (1)$$

That is, geometrical similarity requires that Δ/d be equal for model and prototype.

Using the pressure bulb concept to define the stressed zone within the homogeneous mass under the footing, it is clear that the size of the bulb is dependent on the diameter of the footing. Hence in the case of sand, the gravitational stresses within the stressed zone are represented by the quantity γd where γ is the unit weight of the material. Dynamic similarity, therefore, requires that $q/\gamma d$ be equal. Hence for settlement tests with footings of different diameters in a cohesionless soil to be represented in correct dimensional form, the relation

$$q/\gamma d = f(\Delta/d) \qquad (2)$$

should hold. If these settlement measurements are made on the same sand, i.e. with γ the same for all the tests, then

q/d is a function of Δ/d (3)
or Q/d^3 is a function of Δ/d

where Q is the load corresponding to a settlement Δ. In other words, if settlement measurements are made in the same sand with footings of different diameters d, then the plots Q/d^3 against Δ/d will produce a single curve.

Clay In the case of a cohesive material, surface - force effects predominate. Dynamic similarity therefore requires that q/c be equal, where c is the cohesion of the clay. Hence for settlement tests with footings of different diameters in clay to be represented in correct dimensional form, the relation

$$q/c = f(\Delta/d) \qquad (4)$$

should hold. If these settlement tests are made in the same homogeneous clay, i.e. with the cohesion c the same for all the tests, then

q is a function of Δ/d (5)

and the plots of q against Δ/d will produce a single curve. Eq. (5) therefore spells out the effect of size and bearing pressure on the settlement of footings in clay. The precise form of this function or relationship for any given clay has to be established by load bearing tests.

The validity of the conclusions of this dimensional analysis is confirmed by the published results of settlement measurements made by a number of investigators.

Bond (1961) made settlement observations on sand using model footings of diameters 3, 6 and 12 inches. The experimental results shown in Fig. 1 confirm that the plots of Q/d^3 against Δ/d produce a single curve as is indicated in Eq. (3). The validity of this equation is also confirmed by the experimental results which Koegler and Scheidig (1938) obtained with bearing plates of diameters 10, 20 and 40 cm in dense sand (Fig. 2).

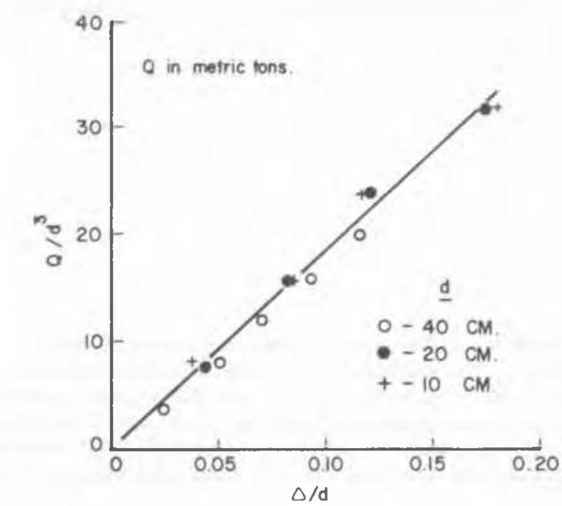

Fig. 2 Plate Bearing Tests by Koegler and Scheidig (1938) in Dense Sand.

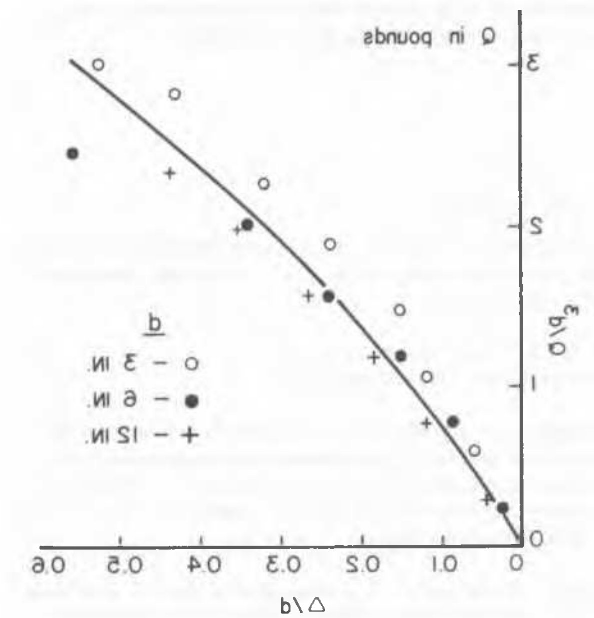

Fig. 1 Plate Bearing Tests by Bond (1961) in Air Dry Sand of Medium Density, R. D. = 0.439

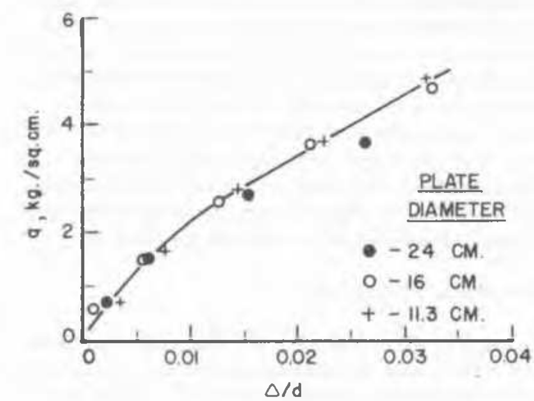

Fig. 3 Plate Bearing Tests by Recordon (1957) in Remoulded Clay

The experiments of Recordon (1957) on remoulded clay with plates of 11.3, 16 and 24 cm (Fig. 3) show that the plots of q against Δ/d produce a single curve as is indicated in Eq. (5); so do those of Perloff and Rahim (1966).

MODEL TESTS

Load bearing tests were carried out with square and circular footings of various sizes in remoulded lateritic clay from various sites. For the purpose of this paper some of the tests using circular mild steel footings of diameters 1, 1.25, 1.5 and 2 inches are presented. The model footing is connected by means of a steel rod to a proving ring which registers the applied load. An outer casing serves as a guide and keeps the steel rod from contact with the soil when tests are carried out with the footing at some depth below the surface.

The clay was thoroughly mixed to the required moisture content and then compressed in four layers into cylindrical moulds ten inches in diameter and 20 inches deep. A 100-ton Avery Universal testing machine was used to compress the soil to the required dry density. After compression the soil was equilibrated for 24 hours before the load bearing test was performed. One sample was used for each load test.

The load was applied by means of a lever system which allowed an applied load to be maintained at a constant value. The settlements of the footing were measured by using dial gauges graduated in divisions of 0.0001 inch. The load was increased after no change in settlement was registered. The surface of the soil surrounding the outer casing was covered with a layer of wax to prevent possible lose of moisture by evaporation.

Fig. 4 gives the plots of q against Δ/d for a clay which was remoulded to a dry density of 104 lb per cu ft at a moisture content of 15 per cent. It is clear from this figure that the experimental results obtained with the four different sizes of footing define a single curve.

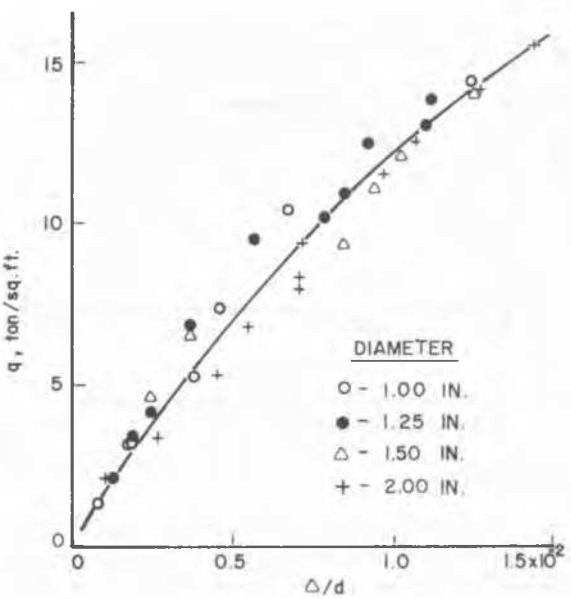

Fig. 4 The Relationship between q and Δ/d for Remoulded Lateritic Clay - γ_d = 104 lb per cu ft, w = 15 per cent

The use of such a curve for the purpose of determining the sizes of footings is illustrated by the following example:-

Example The loads of two adjacent circular footings A and B are 96 tons and 50 tons respectively. Determine the diameters of the footings if the allowable bearing stress is limited to 4 tons per sq ft and there should be no differential settlement.

Let the diameter of footing B be d_B ft.

Then $\frac{\pi}{4} \times d_B^2 \times 4 = 50$, giving d_B = 4 ft.

From Fig. 4, the value of Δ/d corresponding to a bearing pressure of 4 tons per sq ft is 25×10^{-4}.

Therefore the settlement of footing B is $4 \times 25 \times 10^{-4} = 100 \times 10^{-4}$ ft.

If the diameter d_A of footing A is say 6 ft, then $\Delta/d_A = (100 \times 10^{-4})/6 = 16.6 \times 10^{-4}$ for equal settlement of the two footings, for which q is 2.7 tons per sq. ft. from Fig. 4. The allowable load on footing A is then $\frac{\pi}{4} \times 6^2 \times 2.7 = 76$ tons which is not equal to the required load. By further trial it can be shown that the diameter of footing A should be 7 ft.

If the clay below footings is liable to changes in moisture content, the settlements and differential settlements which may result can be assessed from the q - Δ/d relationships for the moisture contents concerned. Fig. 5 gives the q - Δ/d plots from tests carried out with a lateritic clay which was remoulded to a dry density of 100 lb per cu ft but at three different moisture contents, viz: 9.1, 11.6 and 13.7 per cent.

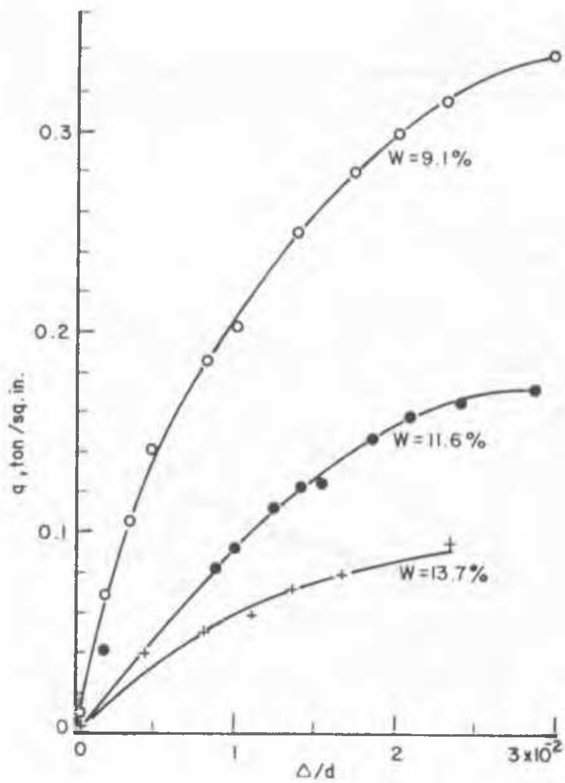

Fig. 5 The Relationship between q and Δ/d (γ_d = 100 lb per cu ft), at Three Different Moisture Contents

BEARING PRESSURE - SETTLEMENT RELATIONSHIP

In the range of small penetrations, Osterberg (1948) found that a logarithmic plot of load - sinkage produced a linear relationship for load tests on clay.

Konder and Krizek (1962) considered a hyperbolic relationship as most appropriate to fit their own data. Perloff and Rahim (1966) carried out constant-rate-of-penetration tests with model footings of various shapes and sizes on saturated Kaolin. They found that their experimental results were in accordance to the following two-constant rectangular hyperbola:-

$$\sigma / q_u = (z/\sqrt{A})/(M + Q_z/\sqrt{A}) \qquad (6)$$

where σ is the unit pressure on the footing, q_u the unconfined compression strength of the clay, z the depth of penetration of the footing, A the area of the footing and M and Q are constants.

The various expressions for pressure-settlement were studied and it was found that for the experimental results obtained with the lateritic clays concerned, the two-constant rectangular hyperbola seems most appropriate. Written in the form

$$\frac{\Delta/d}{q} = M + Q\frac{\Delta}{d} \qquad (7)$$

a plot of $\frac{\Delta/d}{q}$ against an abscissa of Δ/d produces a straight line (Fig. 6). As in the Southwell plot the

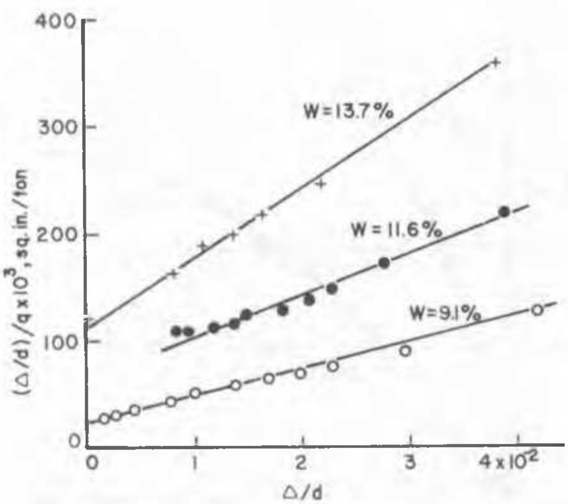

Fig. 6 The Relationship between $(\Delta/d)/q$ and Δ/d

inverse slope of this line gives the bearing pressure of the footing at failure. This would mean that in plate loading tests on the clays concerned, the ultimate bearing capacity could be predicted without having to load the plates to failure. Therefore if load-settlement observations are made at each phase as the construction of a building progresses, the ultimate bearing capacity of the footings may be assessed from the plots of $\frac{\Delta/d}{q}$ against Δ/d.

For short bored-piles in lateritic clay, the load-settlement relationship for both loading and unloading are also in accordance with Eq. (7). Fig. 7 shows the results of a load-settlement test on a bored-pile used in a low cost housing project. The pile was 14 inches in diameter and was buried 5 ft in lateritic clay. The duration of this loading test was 5 days.

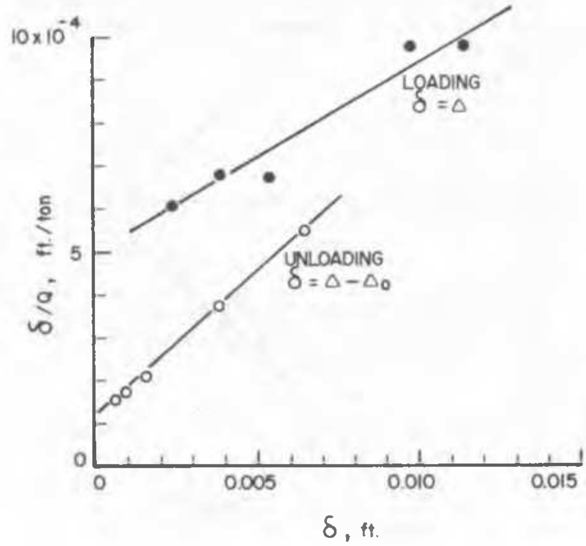

Fig. 7 Test on Bored-Pile: the Relationship between δ/Q and δ/d.

CONCLUSIONS

From the dimensional analysis and the results of experiments carried out by various investigators and by the author, it can be concluded that for footings in the same homogeneous clay, the relation between bearing stress, size and settlement is given by the expression $q = f(\Delta/d)$. This function which is established from load bearing tests can be used to determine the size of geometrically similar footings in the same clay to meet the requirements of any specified differential settlement.

The pressure-settlement relationship is a rectangular hyperbola for foundations in lateritic clay used in the experiments. The ultimate bearing stress can be predicted from the bearing tests without having to load the foundation to failure.

REFERENCES

BOND, D. (1961), The influence of foundation size on settlement, Geotechnique, Vol. 11, No. 2, pp. 121-143.

KOEGLER, F., and A. SCHEIDIG (1938), Baugrunde und Bauwerk, Ernst, Berlin, 288 pp.

KONDNER, R. L., and R. J. KRIZEK (1962), Correlation of load bearing tests on soils, Highway Research Board Proc., Vol. 41, p. 557.

OSTERBERG, J. O. (1948), Disc. of Symposium on load tests of bearing capacity of soils, ASTM Spec. Tech. Publ. No. 79, p. 128.

PERLOFF, W. H., and K. S. A. RAHIM (1966), A study of the pressure-penetration relationship for model footings on cohesive soil, Highway Research Board Proc., Vol. 45, pp. 28-59.

RECORDON, E. (1957), Determination des caracteristiques des terres necessaires au calcul des fondations sur sols elastiques, Proc. 4th Int. Conf. Soil Mech. and Foundation Engrg., Vol. 1, pp. 414-418.