3/46

Oblique Loading Resulting from Interference between Surface Footings on Sand

Charge oblique due à l'interférence entre les empattements de surface sur le sable

J. M. WEST, B.SC., PH.D., *Department of Civil Engineering, Queen's University of Belfast, Northern Ireland*

J. G. STUART, B.SC., PH.D., A.M.I.C.E., *Department of Civil Engineering, Queen's University of Belfast, Northern Ireland*

SUMMARY

This article describes an investigation of the increase of bearing capacity which occurs when two parallel strip footings are placed at various distances from each other on sand. The work has also included the study of the eccentricity and inclination of the soil reaction. The theoretical method, which has allowed for the effect of soil self-weight, has been compared with the results of model tests made in the laboratory.

SOMMAIRE

Cet article décrit une étude de l'augmentation de la capacité portante de deux semelles parallèles sur le sable lorsque l'espacement entre les semelles varie. On a étudié aussi les forces tangentielles et l'excentricité des contraintes normales. Les calculs théoriques qui tiennent compte du poids propre du sol sont comparés avec les résultats obtenus en laboratoire avec les modèles réduits.

IMPORTANT CHANGES in the ultimate bearing capacity and settlement characteristics of foundations occur when they are placed in groups. These problems are particularly important in pile group design, and in an effort to isolate the factors involved, a model study of pile group behaviour in sands has been in progress at Queen's University for some years (Stuart, Hanna, and Naylor, 1960; Hanna, 1963). It has been found that the most significant variable influencing group behaviour is the centre to centre spacing of the individual piles, although surface roughness, soil density, and group shape have important secondary effects on the group characteristics.

The complexity of pile group behaviour has, however, prevented a theoretical solution, and it has therefore been necessary to consider the simpler problem of small groups of parallel strip foundations both on the surface and at depth. Such foundations exhibit similar general characteristics to the pile group, particularly the interrelationship between group ultimate bearing capacity and spacing of the individual foundations. As a result of this study Stuart and Hanna (1961) and Stuart (1962) have proposed modifications of the familiar Terzaghi and Meyerhof isolated foundation failure mechanisms which account satisfactorily for the observed increases in bearing capacity.

In both the shallow and deep foundation cases, the individual foundation failure mechanisms become distorted as a result of the presence of an adjacent foundation thereby causing the resultant soil reaction on the foundation base to become both eccentric and inclined. The present paper is concerned with the particular case of a pair of shallow rough based strip foundations, and a simple method of estimating the eccentricity e and inclination λ of the resultant soil reaction acting on each foundation is described. Tests have been carried out at a number of spacings between $1.02B$ and $3.28B$ on a pair of parallel strip foundations resting on a medium density sand. The experimental results are compared with those calculated using Stuart's analysis and a similar approach where the Sokolovski numerical procedure has been used (Sokolovski, 1960).

THEORETICAL CONSIDERATIONS

When considering the case of interference at shallow depths ($D/B < 1$), Stuart has suggested that the Terzaghi/Prandtl solution for the isolated rough based foundation becomes modified to the form shown in Fig. 1. Because of the presence of a second footing, the normal symmetrical

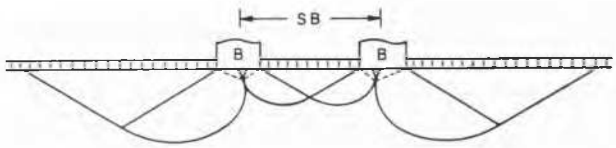

FIG. 1. General interference mechanism for shallow rough based strip foundations.

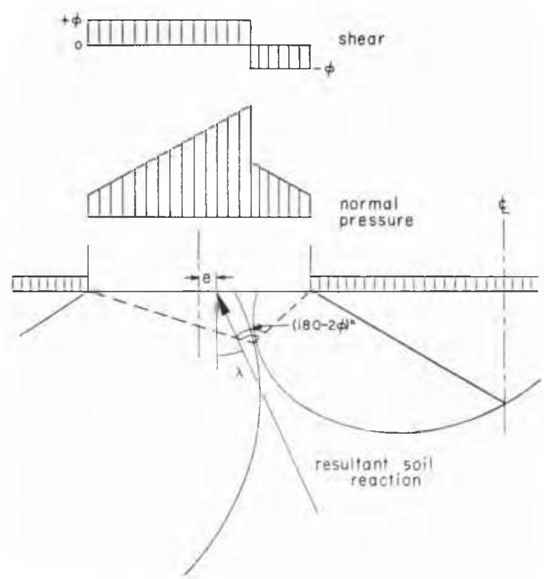

FIG. 2. Method used to calculate forces acting on interfering foundations.

failure pattern of logarithmic spiral radial shear and plane Rankine passive zones cannot develop; as a result the failure pattern becomes asymmetric and failure occurs predominantly to the free side of each foundation. The general method of computing the foundation bearing capacity under these conditions is illustrated in Fig. 2. The geometry of the smaller, or curtailed radial shear zone is fixed by the spacing S of the foundations, and consequently the extent of the larger radial shear zone may also be calculated since both are tangential at a point subtending an angle $(180-2\phi)^\circ$ from the foundation base. The remainder of the bearing capacity calculations are now performed using the established procedures, where the effects of soil self-weight are taken into account by trial and error (Terzaghi, 1943; Meyerhof, 1951).

By defining efficiency as the ratio of the ultimate bearing capacity of the foundation group to that of an equal number of identical isolated foundations, the above analysis shows that below a spacing of approximately $4B$ the efficiency rises until a maximum value considerably in excess of 200 per cent is reached at a spacing in the region of $1.25B$.

Mandel (1963) has also offered solutions concerning large groups of foundations, but although these were based on plastic theory, the effect of soil self-weight was not considered. To supplement Stuart's work the Sokolovski method has also been used to compute the efficiencies caused by interference, thereby taking soil self-weight effects into consideration more precisely. Here a pair of perfectly rough based foundations have again been considered, and as before the zones of radial shear are assumed to extend back to the base of each foundation.

When soil self-weight is considered, the former straight radial and logarithmic spiral failure surfaces are replaced by two families of curved slip lines, the stress conditions on the foundation base being determined by a numerical integration procedure working from the known boundary conditions along the adjacent passive zones. The results of this analysis show a similar general relationship between efficiency and spacing to Stuart's work, although efficiency values are considerably reduced. Both efficiency/spacing relationships are shown in Fig. 6.

The form of the normal pressure and shear distribution on the foundation base suggested by both the above analyses is shown in Fig. 2 and indicates that when interference takes place the resultant soil reaction will become both inclined and eccentric. Moreover, the amount of eccentricity e and inclination λ will be a function of the degree of asymmetry of the failure mechanism and hence will be directly related to the efficiency characteristics of the pair of foundations. The maximum values of λ and e would therefore be expected to coincide with the spacing where maximum efficiency is generated; in this case $\lambda = \phi$, while e may be as large as $B/6$ depending on the relative magnitude of surcharge effects. Both parameters λ and e have been computed over the experimental range of spacings using Stuart's analysis (analysis A) and the modified Sokolovski method (analysis B).

EXPERIMENTAL INVESTIGATION

The experiments were carried out in the testing apparatus shown in Fig. 3, where the soil is contained in a rigid steel tank 4 ft square and 3 ft deep. Stress-controlled loading of the foundations under test is achieved using a simple lever loading mechanism. Loads are transmitted through a rigidly located frictionless guide pin with a stiff plate attached to the lower end of the pin. In order to compensate for foundation settlement, and consequent deviation of the loading lever from the horizontal, a small hydraulic ram is carried in the lever directly above and in line with the guide pin. The magnitude of the applied loads are recorded on a sensitive proving ring placed between the base of the hydraulic ram and the guide pin, while settlements are measured by a dial gauge bearing directly on the loading plate.

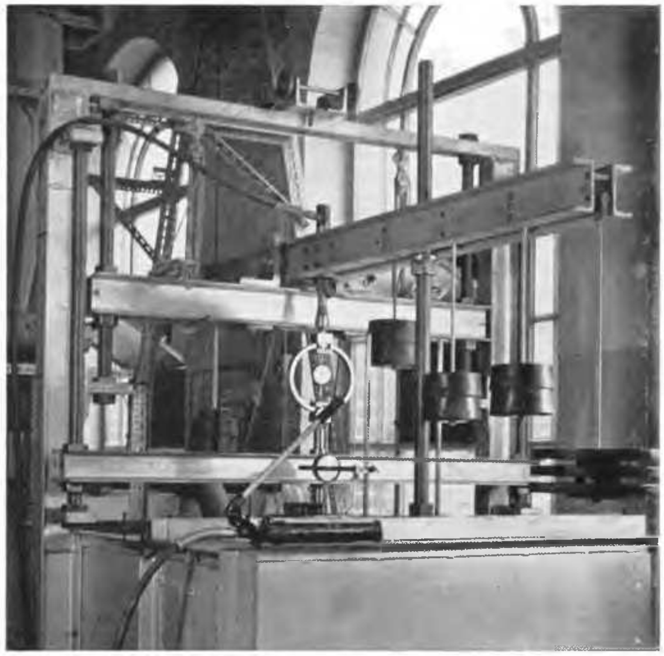

FIG. 3. Testing apparatus.

A white fine and medium Lough Neagh sand was used (γ_{max} = 105 lb/cu.ft., γ_{min} = 86 lb/cu.ft.), carefully compacted to an average bulk density of 95 lb/cu.ft. At this bulk density triaxial and shear-box tests indicated that an angle of shearing resistance of 35° was likely under plane strain conditions (Bishop, 1961) and accordingly this value has been used in all the computations.

The strip foundations were extruded aluminium alloy I sections, each 24 in. long and 4 in. deep, with 1.75 in. flange and 0.187 in. web. One flange of the I section forms the strip foundation, while the other is rigidly attached to a 0.75-in.-thick aluminium locating plate. Slots were milled in the locating plate so allowing any spacing between B and $3.28B$ to be selected as desired. In order to simulate the rough based foundation, sandpaper strips of similar texture to the sand used were glued to each footing. The basis of the

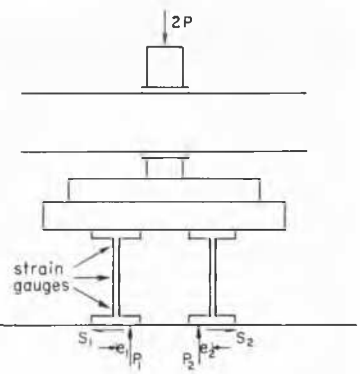

FIG. 4. Experimental measuring technique.

experimental determination of the eccentricity e and inclination λ of the resultant soil reaction is illustrated in Fig. 4. The resultant soil reactions on each foundation are split up into components P_1, P_2 and S_1, S_2 respectively, so that

$$S_1/P_1 = \tan \lambda_1;\ S_2/P_2 = \tan \lambda_2.$$

The eccentricity and inclination of the resultant soil reaction sets up bending stresses in each foundation, and providing elastic distortions are small, the bending moment diagram will be linear in the web of each I section. Therefore assuming that the applied load $2P$ is shared equally between the foundation, i.e. $P_1 = P_2 = P$, the values of e_1, e_2, $\tan \lambda_1$, and $\tan \lambda_2$ can be computed by simple statics if the bending moment is known at two points in each foundation web. In the experiments, bending stress was measured at 3 different levels in each foundation web using ¼ in. gauge length electric resistance strain gauges at sections 8 in. from either end of each footing.

Three measures of bending moment were obtained in order to increase accuracy and provide an independent check on the linearity of the bending moment diagram; in all cases the mid-level bending moment was closely equal to the mean of the extreme values. Sensitivity of measurement was increased by attaching active and dummy gauges of opposite sides of the foundation web, an arrangement also giving improved temperature compensation. All the strain gauges were directly calibrated against known applied bending moment and the calibration data was frequently checked. To prevent soil coming into contact with the strain gauges, thin metal shields were attached to the flange of each foundation, and Fig. 5 shows the complete footing assembly

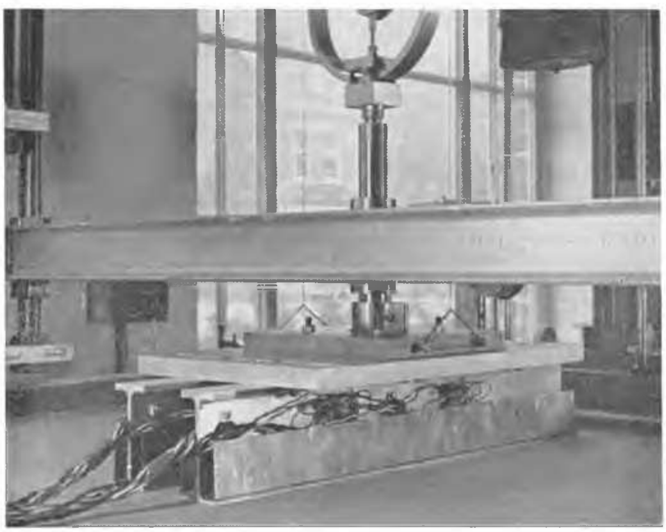

FIG. 5. Foundations under test.

under test. Great care was taken to ensure that a completely uniform mass of sand was used in each test, and particular attention was paid to the preparation of the sand surface. To achieve a perfectly level surface, the top 1 in. of the compacted sand was removed in ¼ in. layers using a scraping device running on carefully levelled rails.

TEST RESULTS

Loads, settlements, and bending stresses were measured in a total of 8 tests at spacings in the range $1.02B$ to $3.28B$. Tests were also carried out on an isolated footing for comparison purposes. Experimental values of efficiency were obtained from the load/settlement diagram in the manner already described in Hanna (1963), and the experimental and theoretical results are summarized in Fig. 6 at $D/B = 0.5$. These results confirm the earlier work of Stuart at smaller scale and show a satisfactory measure of agreement between theory and experiment.

In the case of the experimental determination of λ, it is essential to analyse the validity of the assumption (Fig. 4) that $P_1 = P_2 = P$. On this basis the experimental variations

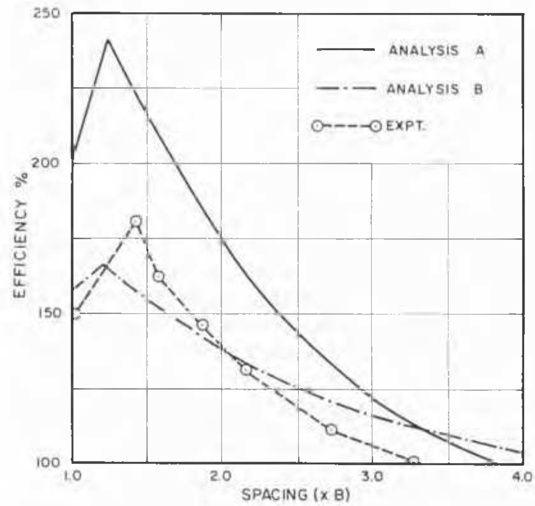

FIG. 6. Efficiency/spacing characteristics.

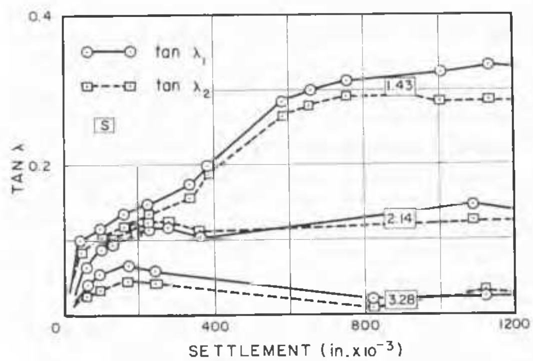

FIG. 7. Experimental variation of tan λ with settlement.

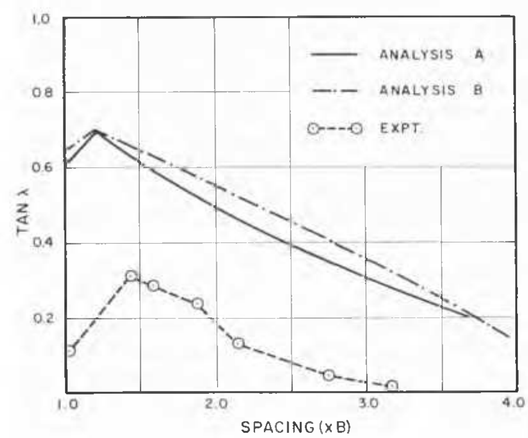

FIG. 8. Experimental and theoretical values of tan λ.

of tan λ_1 and tan λ_2 with settlement in 3 typical tests are shown in Fig. 7. Examination of these results indicates that symmetrical behaviour does occur within reasonable experimental limits. The mean experimental values of tan λ are compared with the calculated values in Fig. 8.

As had been anticipated, the form of these results recall the earlier efficiency/spacing characteristics, although in this case the experimental values are approximately 50 per cent of those predicted by analyses A and B. When considering the experimental values of eccentricity it was again found that each foundation could be assumed to carry half the applied load. However the observed eccentricity results do not follow any clearly defined trend as have efficiency and inclination. The theoretical failure mechanisms both suggest that the point of application of the resultant soil

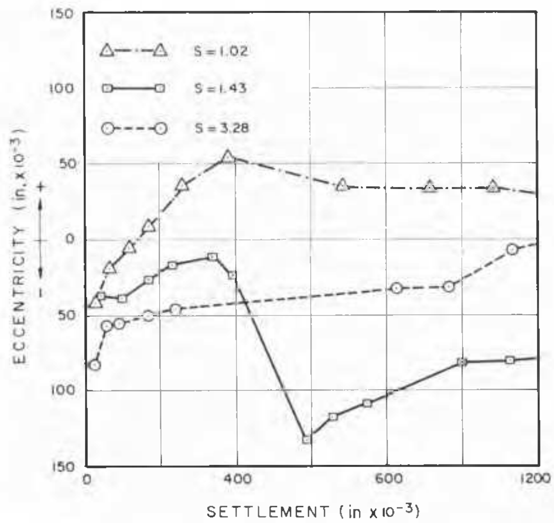

FIG. 9. Experimental variation of eccentricity with settlement.

reaction should move towards the centre of the foundation group as a result of mechanism interference, reaching a maximum value at the spacing corresponding to the peak efficiency. In the experiments, however, such an eccentricity was only observed at a spacing of 1.02*B*. Typical eccentricity/settlement relationships are plotted in Fig. 9 for spacings of 1.02*B*, 1.43*B*, and 3.28*B*.

DISCUSSION

The theoretical solutions described previously suffer principally from the basic assumption that soil may be considered to behave as a rigid plastic material, whereas Figs. 7 and 9 show that considerable strains are required to mobilize the peak values of efficiency, λ, and *e*. However, because efficiency is evaluated as a relative term these deficiencies are not apparent when comparing theoretical and experimental efficiency values (Fig. 6). The experimental values of λ and *e* are absolute measurements, however, and thus give some indication of the unsatisfactory nature of current bearing capacity theory. The experimental measurements are also affected to some extent by the small flexural strains in the pair of foundations as they are loaded to failure. Although it is not possible to make any allowance for this effect, it is likely to influence the eccentricity values considerably.

It can be concluded however from the experimental results that the proposed interference mechanism for a pair of closely spaced shallow strip foundations is basically correct within the limitations imposed by current bearing capacity theory. Until the advent of a generally accepted stress/strain theory for soils little further progress is possible with this problem.

ACKNOWLEDGMENTS

The work described in this paper forms part of a general study of foundation behaviour in sands at Queen's University, Belfast. The authors wish to acknowledge the interest shown by their colleague, Mr. J. Graham, by Professor T. M. Charlton, and by his predecessor Professor A. H. Naylor.

REFERENCES

BISHOP, A. W. (1961). Discussion on soil properties and their measurements. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 3, p. 99.

HANNA, T. H. (1963). Model studies of foundation groups in sand. *Géotechnique*, Vol. 13, pp. 334–51.

MANDEL, J. (1963). Inteférence plastique de fondations superficielles. *Proc. International Conference on Soil Mechanics* (Budapest).

MEYERHOF, G. G. (1951). The ultimate bearing capacity of foundations. *Géotechnique*, Vol. 2, pp. 301–32.

STUART, J. G., and T. H. HANNA (1961). Groups of deep foundations—a theoretical and experimental investigation. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp. 149–53.

STUART, J. G., T. H. HANNA, and A. H. NAYLOR (1960). Notes on the behaviour of model pile groups in sand. *Symposium on Piled Foundations I.A.B.S.E.* (Stockholm).

STUART, J. G. (1962). Interference between foundations, with special reference to surface footings in sand. *Géotechnique*, Vol. 12, pp. 15–23.

SOKOLOVSKI, V. V. (1960). *Statics of soil media.* London, Butterworth Press.

TERZAGHI, K. (1943). *Theoretical soil mechanics.* London, Chapman and Hall.