THE LATERAL CAPACITY OF DEEP AUGERED FOOTINGS

LA FORCE PORTANTE HORIZONTALE D'UNE FONDATION PROFONDE FOREE

НЕСУЩАЯ СПОСОБНОСТЬ НА ГОРИЗОНТАЛЬНУЮ НАГРУЗКУ БУРОВЫХ ОПОР

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SYNOPSIS. The available methods of analyzing laterally loaded piles are generally based on an earth pressure theory or on the concept of modulus of subgrade reaction. In the case of rigid pier foundations that are subjected to large overturning moments as in the case of a steel pole foundation, these methods tend to produce an overly conservative design.

The results of a testing program carried out both on scaled models and full-size footings confirm that the elastic theory of subgrade reaction considerably overestimates the lateral deflection and rotation of the foundation. The ultimate capacity of test footings was in fair agreement with that indicated by earth pressure theories. However, the recorded soil pressures distribution was not according to the earth pressure theory. The load-deflection response of a laterally loaded rigid footing is shown to be non-linear and is greatly influenced by the footing width, the deflection decreasing markedly with the footing width. An improved method of predicting the deflections of the footing is indicated by considering the soil as a layered mass and selecting the modulus of subgrade reaction value for each layer based on the considerations of stress level and degree of non-linearity in the soil response.

INTRODUCTION

The use of tall steel poles to support high voltage transmission lines has come into fairly common use by power utilities in North America. Their use has been brought about by the increasing scarcity of right-of-way land particularly in built-up areas and by the quest to improve the appearance of transmission line structures. A major foundation problem in the design and construction of the single-pole structure is the provision of adequate lateral soil support to resist the high overturning moment due to wind and ice loads which reach magnitudes in excess of 5 million foot-lbs. A common design requirement is to limit the horizontal movements at ground level to between 1/2 to 1 inch under maximum loading.

The foundation normally considered for this type of structure is a cylindrical augered footing 6 feet or more in diameter varying in depth from 15 to 40 feet, depending on the type of soil and loading. The theories available for the design of these foundations include those of passive earth pressure and those utilizing the theory of horizontal subgrade reaction. The earth pressure theories provide a means of estimating the ultimate capacity while the subgrade reaction theory provides a means of calculating the deflections at ground level. The latter method assumes elastic behaviour of the supporting soil. The correlation between the modulus of horizontal subgrade reaction and conventional soil properties is not well developed which results in an overly conservative approach in selecting these parameters.

Due to the uncertainties in the design of steel pole foundations a comprehensive study of the problem was undertaken by the Ontario Hydro (Canada). Initially the literature on the subject was reviewed in detail. Model tests were conducted in silica sand in which the width and eccentricity of loading were varied. Full-scale field tests were then carried out in two different soil conditions in which footing sizes were varied and measurements of load-deflection and soil pressure were obtained. In this paper the results of the field and laboratory tests are presented and discussed and the discrepancies between theoretical and actual behaviour are brought out.

REVIEW OF THEORIES

In determining the ultimate capacity and the load-deflection behaviour of the steel pole foundation it is assumed that the foundation member is rigid and, therefore, the properties of pier do not have to be considered. This assumption is reasonable for reinforced concrete footings if the depth to width ratio is 5 or less (Broms, 1964). The principal forces and reactions acting on the foundation are shown in Figure 1.

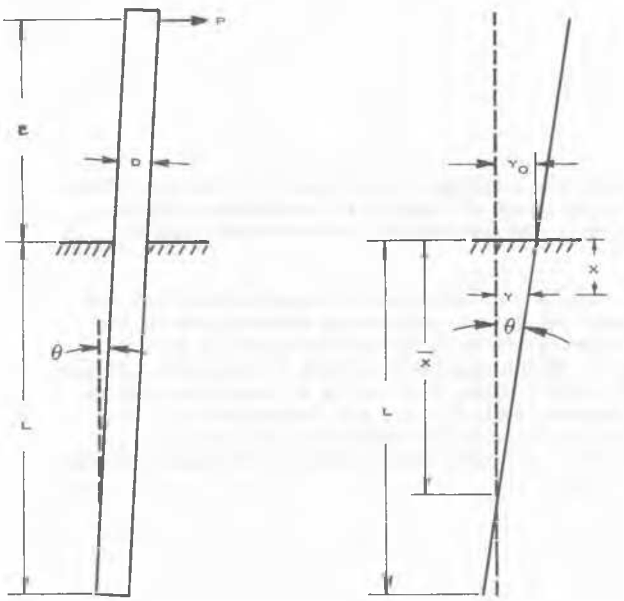

Figure 1 - Soil-Pole System and The Geometry of Pole Rotation

The ultimate capacity of a rigid pier under a lateral load is determined from the considerations of limiting equilibrium between soil resistance and the applied overturning forces by making an assumption of the mode of soil failure. In sand the ultimate soil resistance is calculated by the passive earth pressure theory modified for the three dimensional geometry of the footing. Broms (1964) assumed a triangular pressure distribution and used the passive Rankine's earth pressure coefficient multiplied by a factor of three to calculate the ultimate soil resistance against the pier foundation. He assumed the centre of rotation at failure to be at the bottom of the footing and the high negative earth pressure developed close to the heel of the footing was replaced by a concentrated load. In clays by assuming a bearing capacity type of failure Broms (1964) calculated the ultimate soil resistance to be uniform with depth and equal to nine times the undrained shear strength.

Hansen (1961) calculated the ultimate soil resistance against the pier foundation in both cohesive and granular soils by considering a general mode of soil failure changing from a passive earth pressure type at shallow depths to a bearing capacity type at greater depths. He derived earth pressure coefficients N_c and N_q similar to that of bearing capacity factors expressed as functions of depth and angle of internal friction.

Hansen's theory of ultimate soil resistance is well suited for the calculation of ultimate soil resistance in a layered soil with different values of soil parameters c and $\emptyset$. When the effective strength parameters c' and $\emptyset'$ are used in the calculation, the soil pressures correspond to the long-term resistance.

The main disadvantage of the methods based on modifications of the passive earth pressure theory or bearing capacity theory is the necessary simplifications regarding the zone of soil under stress and the complex pattern of the mobilized soil resistance with depth below the ground surface. Furthermore, the amount of footing movement at ground level required for the full development of ultimate soil resistance may be in terms of feet rather than inches and therefore the pole foundation design is invariably governed by the allowable deflection rather than the ultimate capacity.
In computing the deflection at ground level most investigators have utilized the theory of subgrade reaction in a form similar to that used for the design of grade beams and floor slabs resting on soil. For piles, Terzaghi (1948) defined the modulus of horizontal subgrade reaction as $k_h = \frac{p}{y}$, where p is the soil pressure at the soil-pile interface and y is the resulting deflection at the point under consideration. Terzaghi (1955) also showed that k_h, the modulus of horizontal subgrade reaction within a uniform soil deposit varies inversly with the width of the pile. For piles in clay he proposed $k_h = \frac{K_h}{D}$, where K_h is the modulus of subgrade reaction for a vertical beam of unit width and D is the width or diameter of the pile. In sands he assumed k_h to increase uniformly with depth, ie, $k_h = n_h \frac{X}{D}$, where n_h is the constant of horizontal subgrade reaction and X is the depth below ground surface. By using k_h and n_h parameters Broms (1964) derived expressions for the deflection of rigid piles at ground surface which indicated that the deflections are independent of the pile width. This is based on the assumption of purely elastic behaviour of soil for the entire depth of the footing and the mass of soil under stress being proportional to the pile width. These assumptions are not valid for all stress levels and therefore a marked departure from theory and practice may be expected.

The modulus of subgrade reaction values are generally inferred from the deformation modulus 'E' and Poisson s ratio, ν of the soil determined in the laboratory tests or from field plate load tests. The pressuremeter tests in boreholes provide a direct measurement of the horizontal deformation modulus of the soil from which the horizontal subgrade modulus values can be inferred, Menard (1962). A method of calculating the deflections of a laterally loaded rigid pile in a layered soil deposit was presented by Mori and Tajima (1964) which divides the soil into a number of layers having different values for modulus of subgrade reaction. By solving the equations of equilibrium between the applied forces and resisting forces, the centre of rotation and footing deflection are calculated for various depths and widths of footing. This method lends itself well to computer application. In this method the modulus of subgrade reaction is not considered as inversly proportional to the footing width as suggested by Terzaghi (1956) and therefore the calculated deflections are in inverse proportion to the footing width.

The major faults in the subgrade reaction approach are the assumptions of purely elastic behaviour of the surrounding soil and the load-deflection behaviour being independent of the footing width. The laboratory and field load test program described in this article were carried out to resolve these discrepancies and to indicate a more realistic design procedure.

LABORATORY MODEL TESTS

A series of model tests were carried out on three different sizes of cylindrical model footings partially buried in sand. The model footings were made of 2-inch, 3-inch and 4-inch diameter steel pipe about 32 inches in length which were buried about 18 inches in sand. The 2-inch and 3-inch pipes were filled with cement grout to make them rigid. The sand used for these tests was uniformly graded silica sand. The properties of sand are summarized in Table I.

pressures against the footing. These cells consisted of a thin metal diaphragm braced to the solid brass cell 2 inches in diameter in such a way that the surface of the diaphragm conformed with the cylindrical surface of the test footing in which it was housed. These cells operated on a simple principle of volume change due to the deflection of the metal diaphragm under external pressure.

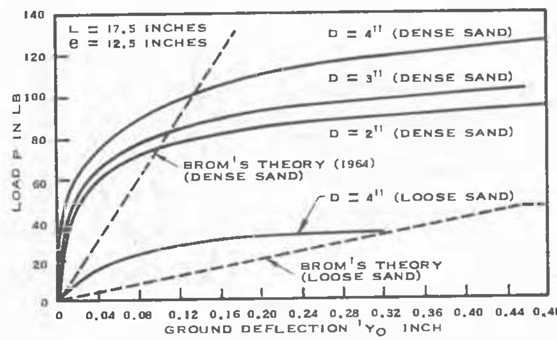

Figure 2 - Load vs Deflection Curves
From Model Tests in Sand

Typical load-deflection curves are shown in Figure 2. Also shown on these plots are the predicted load-deflection relationships using Brom's theory (1964) and subgrade modulus values suggested by Terzaghi (1955). Typical soil pressure distributions measured in the dense sand and loose sand are shown in Figure 3.

FULL-SCALE TESTS

Two test locations were selected on a proposed transmission line at London, Ontario, one in sand and another in dense till. The soil conditions

TABLE I

Properties of Silica Sand Used For The Model Tests

Condition	Dry Unit Weight lbs/cft	Angle of Friction (degrees)	Effective size (mm)	Uniformity Coefficient
Dense	110.0	45	0.45	1.45
Loose	97.8	31	0.45	1.45

The model footings were initially positioned in the test tank and the sand was packed around in 6 inch thick layers to the required density by means of plate vibrator. Almost all the tests were carried out in dense sand with the relative density of nearly 1.0 and only two tests were carried out in loose sand. The 4-inch diameter test footing was instrumented with pressure cells to measure the soil

at these locations are summarized in Figures 4 and 5. The results of in-situ pressuremeter tests are carried out at the two test locations are also shown on these figures.

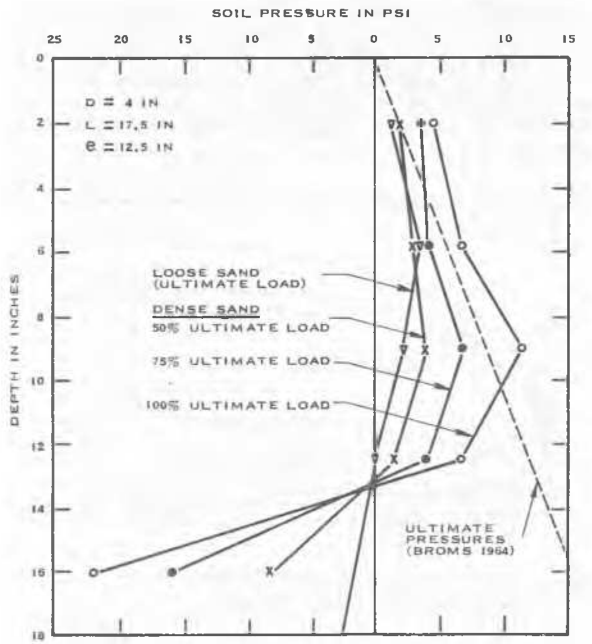

Figure 3-Distribution of Soil Pressure Against Model Footings in Sand

The test program consisted of installing two augered footings at each site, 3 feet and 5 feet in diameter. The footings were heavily re-inforced and installed 15 feet apart and extended 20 feet below ground level and 10 feet above ground.

The loading equipment consisted of two 100-ton jacking systems as shown in Figure 6 in which loads were applied to simulate a moment to shear ratio of 80 which is approximately the loading eccentricity for a typical single pole structure. The lateral movement of the test footings was measured at ground level by means of a pair of micrometer dials. The rotation of the footings was measured by means of a plumbline on each footing.

The soil pressures in front and back of the 3 foot diameter footings were recorded by means of hydraulic type displacement pressure cells similar to those used in the model tests. These were 1/8 inch thick stainless steel diaphragm 6 inches in diameter braced to a solid stainless steel backing and fabricated to conform to the shape of the 3-foot augered hole. The cells were mounted in the augered holes prior to concreting such as to be in full contact with the soil. A plastic line connecting each cell to a terminal above ground was used as a standpipe for measuring the volume change of the cell which corresponded to a known soil pressure.

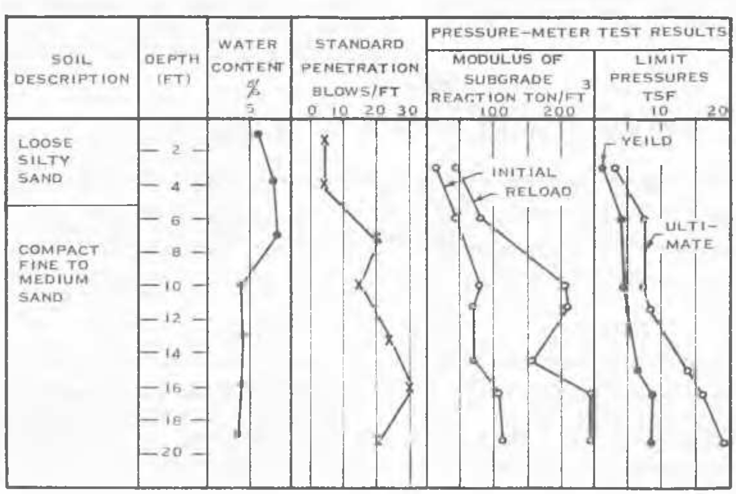

Figure 4 - Soil Conditions at Test Site No 1

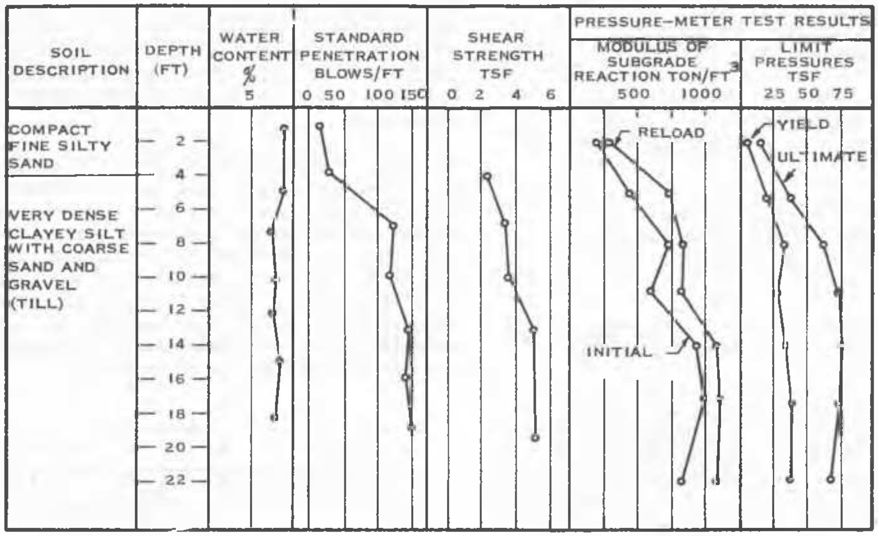

Figure 5 - Soil Conditions at Test Site No 2

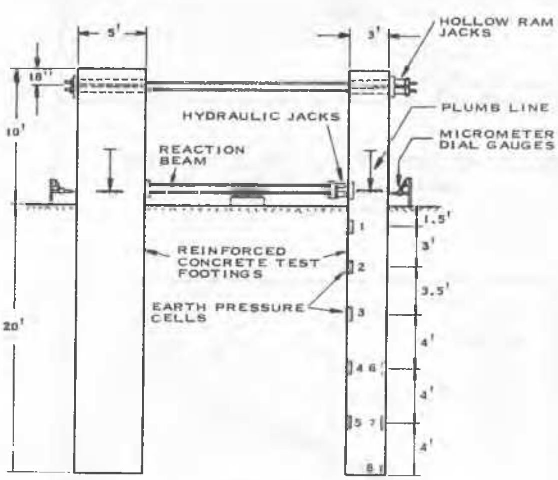

Figure 6 - Loading Arrangement for Full-Scale Tests

The loads were applied simultaneously to each jack in about 5000-lb increments and held steady until all the dial and cell readings were obtained. At a stress level corresponding to a frequent loading condition for the 5-foot diameter footing, five complete load-unload cycles were carried out. Loading was then continued to the maximum design loading condition. At this point, in order to obtain a significant overload condition, the lower strut was removed and load was applied at the top to the limit of the jacking system.

DISCUSSION OF TEST RESULTS

The results of the full-scale tests are discussed along with the laboratory scale test results and the results of the in-situ pressuremeter tests. A comparison between the predicted behaviour on the basis of elastic theory and the actual behaviour indicates the limitations of the existing theories and suggests modifications that may be considered in their use.

Lateral Deflection

The lateral deflections of the test footings were estimated by the layered theory (Mori and Tajima 1964) using moduli of subgrade reaction values obtained from the initial and reload portions of the pressuremeter tests as shown in Figures 7 and 8.

The following observations can be made from the comparison between the predicted and actual deflection behaviour shown in these Figures.

1. The actual load-deflection is obviously non-linear in the sand although in the till the behaviour is close to linear particularly at low stress levels.

2. The load-deflection is highly dependent on footing diameter, the deflection varying disproportionately with diameter for the same load.

3. The measured deflections for both sizes of footing are very much smaller than the predicted values.

These observations are in general agreement with the results of the model tests in sand and indicate that the present method of calculating lateral deflections of pier-type foundations based on elastic theory will seriously overestimate the lateral deflection.

The soil reactions on the 3-foot diameter footings are plotted for each soil type in Figures 9 and 10. The limit pressures at which the soil yielded in the pressuremeter tests are compared with the soil reaction measured in the full-scale tests in Figure 9. The soil reactions in sand at maximum loading are at or close to the yield stress for most of the footing depth whereas the till is stressed to a low proportion of the yield stress except near to the ground surface.

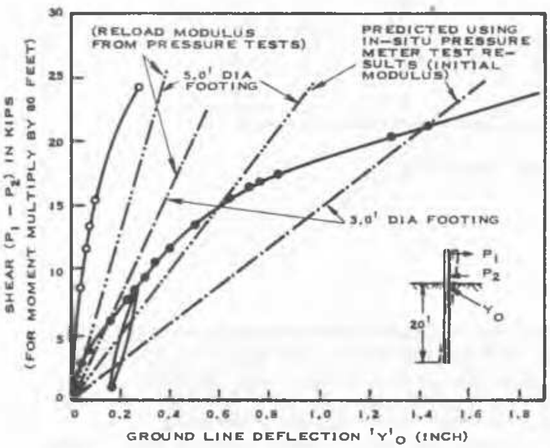

Figure 7 - Load-Deflection Curves For Full-Scale Test Footings In Sand

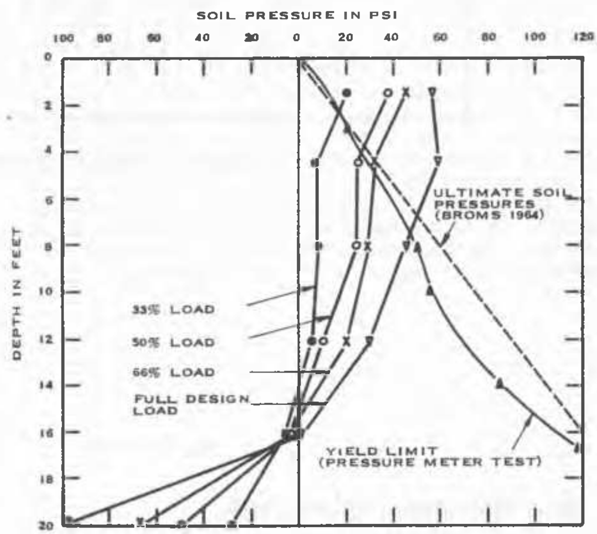

Figure 9 - Distribution of Soil Pressures Against 3-foot Diameter Test Footing in Sand

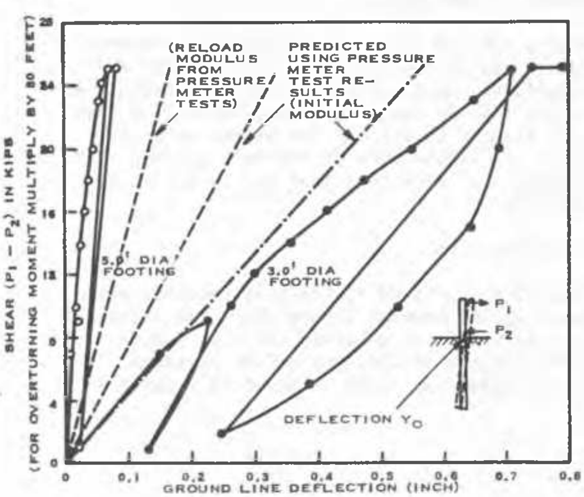

Figure 8 - Load-Deflection Curves For Full-Scale Test Footings in Till

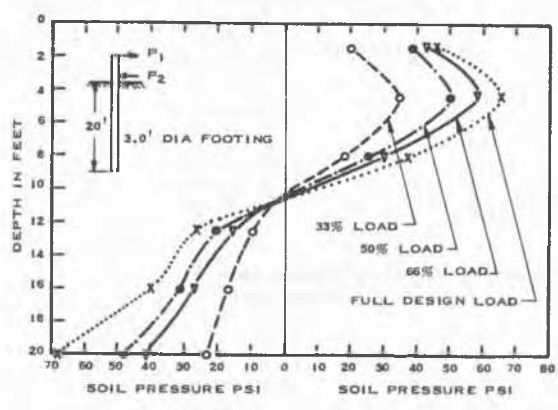

Figure 10 - Earth Pressure Distribution Against The Test Footing In Till

Pressure versus deflection curves are shown in Figures 11 and 12. In sand the pressure-deflection curves exhibit a degree of non-linearity depending on the position of the cell in relation to the centre of rotation and the ground surface, the greater the distance the more the degree of non-linearity. In till the curves show better linearity at all locations with the exception of the cell closest to ground level.

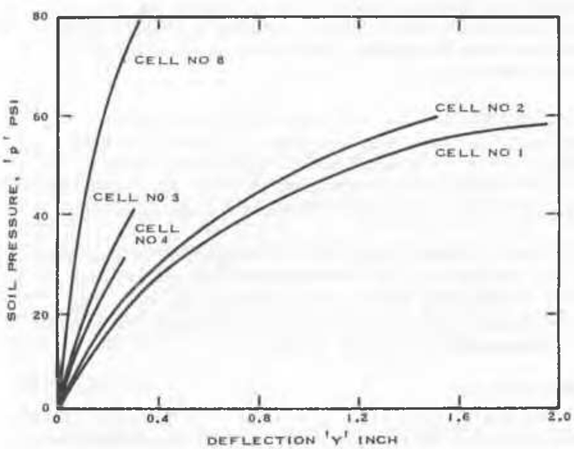

Figure 11 - Soil Pressure vs Deflection Curves For 3-Foot Diameter Test Footing in Sand

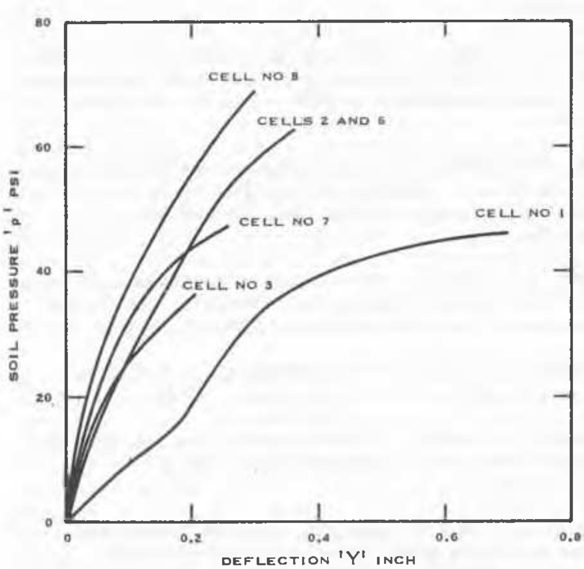

Figure 12 - Soil Pressure vs Deflection Curves For 3-Foot Diameter Test Footing in Till

The non-linear behaviour is believed to occur due to plastic yielding of the soil which occurs progressively downwards from the surface with increasing rotation. At very low stress levels the behaviour may be close to linear, however, at normal stress levels a distinctly non-linear behaviour may be expected. In the case of the compact sand a relatively high stress level occurred particularly for 3 foot diameter footing resulting in a distinctly plastic type of deformation for the entire loading curve. In the case of the dense till a much lower stress level occurred during the entire test even for the 3 foot diameter footing and the deformation was closer to being linear.

Effect of Footing Width

The elastic theory implies that the modulus of subgrade reaction of both sand and clay varies in inverse proportion to the width of the footing and thus in the analysis of a pole foundation the deflection and rotation are predicted to be independent of the footing width (Broms 1964). In the layered theory (Mori and Tajima 1964) which considers individual areas of contact,the deflection is predicted to be in inverse proportion to the footing width.In both the laboratory and field tests the deflection is shown to decrease disproportionately with increase in footing width.In sand,the lateral deflection of the 3-foot diameter pier was six times that of the 5 foot diameter pier, while in till the ratio was twelve to one. A possible explanation of this behaviour is that the ultimate soil resistance increases in direct proportion to the width of the pier which has the effect of reducing the stress level with increasing footing width.Where the behaviour is not purely elastic the modulus of subgrade reaction will be larger for lower stress levels depending on the degree of non-linearity.This is particularly true for the soil near the ground surface which reaches a plastic state at an early stage of loading.The beneficial effects of footing width at shallow depths have been noted in earlier investigations (Davison and Gill,1963).

Coefficient of Subgrade Reaction

The values of coefficient of subgrade reaction calculated from the pressure-deflection curves (Figures 11 and 12) are plotted against the depth ratio X/L as shown in Figure 13. The linear relationship between the coefficient of subgrade reaction and depth suggested by Terzaghi (1955) for compact sand is also plotted on this Figure. The calculated values of coefficient of subgrade reaction at low stress levels are considerably higher than Terzaghi's values. Only under the maximum load do the calculated values show some agreement with the conventional values. In the case of till the modulus of subgrade reaction values decrease only slightly with stress level. This further suggests that in soils showing significant non-linear behaviour, the selection of subgrade modulus values should be governed by the anticipated stress levels. The footing deflections calculated using the modulus of subgrade reaction values obtained from the reloading portion of the pressuremeter tests, showed a fairly good agreement for the 5-foot diameter footings for all stress levels but only for the initial part for 3-foot diameter footings.

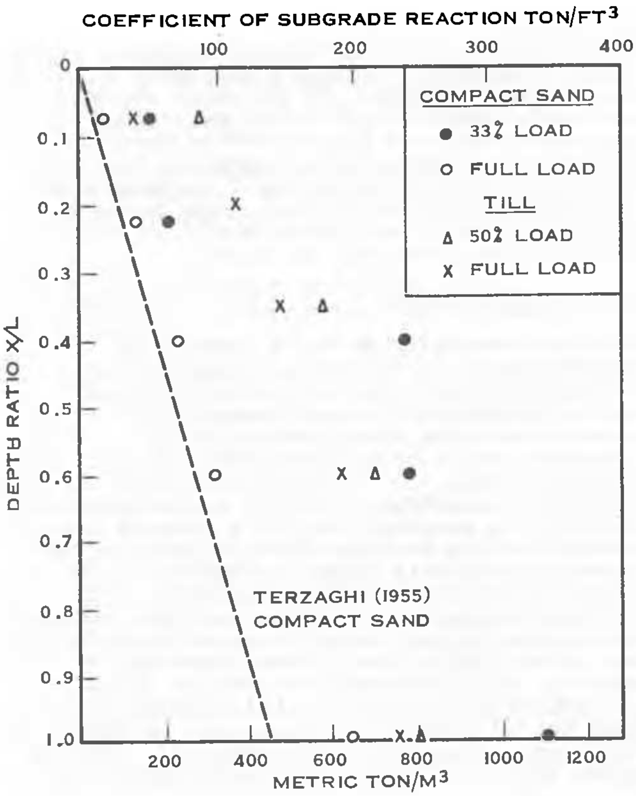

Figure 13 - Relationship Between The Modulus of Subgrade Reaction and Depth Ratio (Full-Scale Tests)

Ultimate Capacity

In the full-scale tests ultimate capacity was not reached except for the 3-foot diameter footing in compact sand. The recorded soil pressure distribution under the maximum load, shown in Figure 9 has no resemblance to the triangular distribution assumed in conventional theory. Similar observations were made in the laboratory model tests in dense sand as shown in Figure 3. The ultimate lateral load capacity calculated on the basis of Brom's theory would tend to be on the safe side and is probably adequate for the problem of pole foundation considering its simplicity and the fact that in the working load range the deflection criteria ensures a wide margin of safety against the soil failure.

CONCLUSIONS

The load-deflection behaviour of a laterally loaded pier foundation was found to be essentially elasto-plastic and the actual deflections were considerably less than those predicted from purely elastic considerations.

The width of the pier was shown to significantly influence the lateral deformation causing a disproportionate reduction in deflection with increase in width. This dramatic departure from predicted behaviour can be partly explained in that the modulus of subgrade reaction is shown to be highly sensitive to stress level which is influenced by footing width.

The subgrade theory is relatively simple in application and it is proposed that the predictions of footing deflection can be considerably improved if the selection of coefficient subgrade reaction is based on considerations of the anticipated stress levels and degree of non-linearity in the soil response. A careful interpretation of the in-situ pressuremeter test results provide a range of values for the coefficient of subgrade reaction. The use of the reloading modulus values for calculating the footing deflections at relatively low stress levels merits the consideration, particularly for large diameter footings.

A more rigorous solution to the problem of pole foundation with the possible use of finite element analysis should bo sought which will take into account the non-linear behaviour of the soil and the complex pattern of the soil pressure distribution.

The ultimate lateral capacity although not a critical factor in design of pole foundation does provide a means of estimating the working stress level. The theories based on passive and bearing capacity theory appear reasonable for this purpose.

ACKNOWLEDGEMENTS

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