Effect of pile-head enlargement on lateral and axial responses of a bored pile

Effet d'élargissement de la tête d'un pieu foré sur les chargements latéraux et axiaux

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ABSTRACT: Results of a full scale pile load test performed on a 42m long and 1.5m diameter bored pile are analyzed and presented. To increase the lateral and axial stiffnesses the diameter of the upper 3.0m of the pile was enlarged to 3.0m. Both axial and lateral load tests were performed, with continuous measurement of the pile head movement and the stresses which developed in the reinforcing bars. These stresses were used to determine the variation of axial forces and bending moments along the pile. Test results are compared to predictions of the axial and lateral response of the pile tested, obtained using the "*t-z*" and "*p-y*" methods of analysis, respectively. In addition, piles of constant diameter are analyzed and their behaviour compared to the behaviour of the enlarged-top pile.

RESUME: Les résultats d' un essai de chargement sur un pieu foré d' une longeur de 42m et d' un diamètre de 1.50m sont analysés et présentés. Afin d' augmenter la rigidité axiale et latérale du pieu examiné on a élargi de diamètre de 1.50m à 3.0m au niveau de la partie supérieure du pieu et jusqu' à une profondeur de 3.0m. Des essais axiaux et latéraux ont été réalisés avec enregistrement continu du déplacement de la tête du pieu et des contraintes développées le long des barres de renforcement. Ces contraintes sont utilisées pour le calcul des forces axiales et des moments fléchissants le long du pieu. Les résultats expérimentaux sont comparés à des calculs numériques (prédiction théorique) de la réponse axiale et latérale du pieu examiné, obtenus au moyen des méthodes d' analyse "*t-z*" et "*p-y*" respectivement. En plus, des pieux à diamètre constant sont analysés et leur comportement est comparé à celui du pieu élargi au niveau de la partie supérieure.

1 INTRODUCTION

It is well known that lateral pile movement is in inverse ratio to pile diameter (Poulos & Davis, 1980) and that the response of laterally loaded piles is mainly affected by the stiffness of the upper soil layers. This behaviour suggests that an increase of pile diameter in the upper pile section will have an important effect on reducing pile displacements. A parametric linear finite element study of an offshore 4.0m diameter monopile in cohesive soil (Magni & Michalopoulos, 1981) demonstrated that strengthening the top 8.0m of the pile with a collar caisson, reduced drastically lateral pile displacements.

On the other hand, pile top enlargement is not expected to have any major effect on the axial pile capacity and stiffness, unless a non-cohesive soil layer exists at the depth where the pile diameter changes. In this case, in addition to the increased soil friction which acts on the enlarged-diameter pile section, a significant axial soil reaction developes on the annulus which is formed at the base of the enlarged section.

To investigate the effect of enlarged pile top on lateral and axial pile responses, a full scale instrumented pile was tested at a site where a reinforced concrete bridge was to be founded on 1.5m diameter bored piles.

Figure 1. Pile load test arrangement

2 PILE LOAD TEST

A full scale pile load test was performed on a 42.0m long bored pile. The pile diameter was 3.0m from ground level to a depth of 3.0m and reduced to 1.5m below this depth. The materials used to construct the pile were C20/25 grade concrete and 40 steel bars (S500 grade) of 25mm diameter. The pile was initially subjected to an axial and subsequently to a lateral test using a system of six hydraulic jacks of 2.5MN maximum capacity each, four 1.5m diameter anchor piles and a heavy prestressed concrete reaction frame, shown in Figure 1.

The load was applied in steps which were kept constant for at least one hour in the axial load test and 15min in the lateral load test. The duration of each step was prolonged when the rate of pile movement was greater than 0.25mm/hr, as pile failure was approached.

In the lateral pile test the load was applied at a height of 200mm above ground level, resulting in the development of a small bending moment on the pile head. The vertical and horizontal movements of the pile head at ground level were continuously recorded using a set of four displacement transducers. The instrumentation also included ten reinforcing-bar stress transducers installed at several depths as shown in Figure 2, which recorded the tensile and compressive stresses of the reinforcing bars. These stresses were used to determine the variation of axial force and bending moment along the pile length.

The design soil profile shown in Figure 2 was derived from a geotechnical site investigation, which comprised soil laboratory and static cone penetration testing. A dense layer of sand exists to

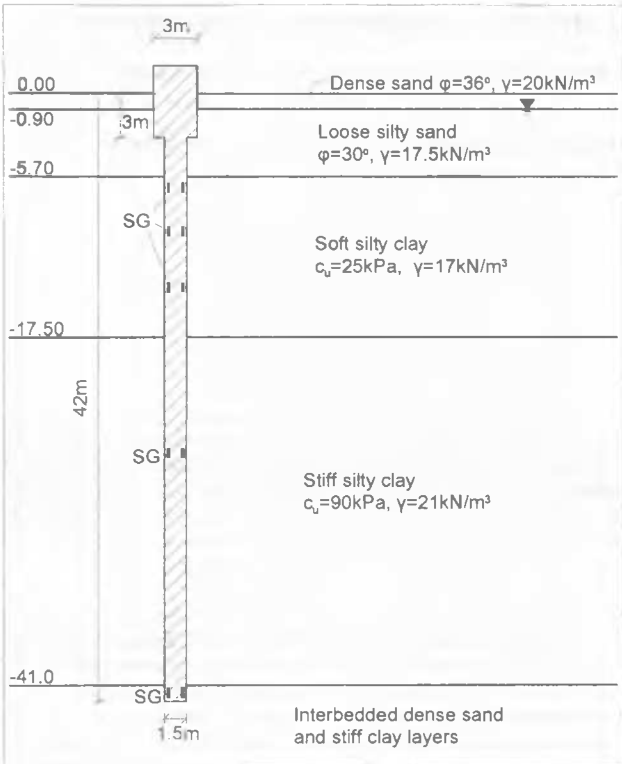

Figure 2. Instrumented pile and design soil profile

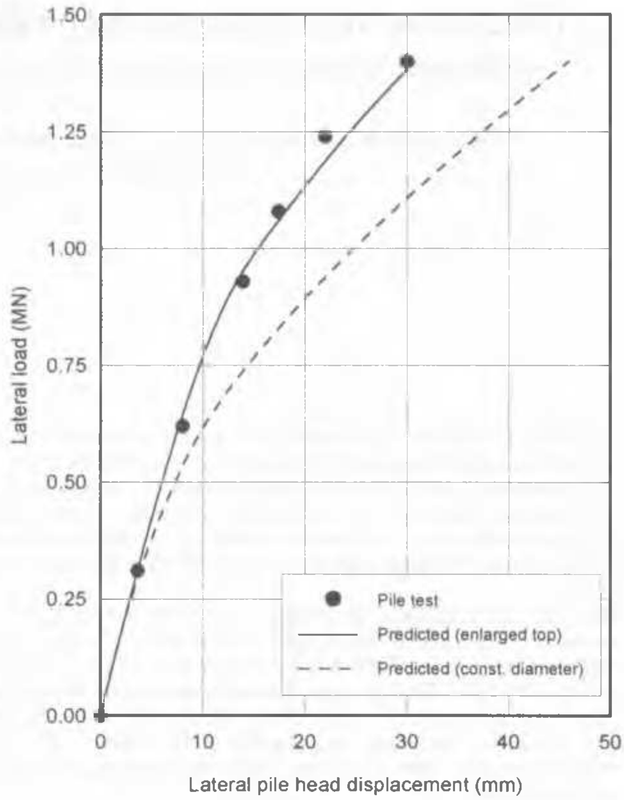

Figure 3. Lateral load versus lateral pile head displacement relationships

a depth of about 0.9m which also coincides with the elevation of the ground water table. This layer is followed by a loose silty sand layer from 0.9 to 5.7m, a soft silty clay layer from 5.7 to 17.5m and a stiff silty clay layer from 17.5 to 41.0m. Below this depth exist interbedded layers of dense gravelly sand and stiff clay which gave very high values of cone penetration resistance.

3 LATERAL PILE RESPONSE

The lateral pile load test provided relationships of lateral load versus lateral displacement and rotation of the pile head and bending moment diagrams for several values of the lateral load.

Figures 3 and 4 show the recorded non-linear variations of lateral displacement and rotation with applied load, respectively. On the same figures, the measured pile response is compared to predictions made using the design soil profile of Figure 2 and a lateral subgrade reaction "*p-y*" type of pile analysis in which the soil is represented by a series of non-linear horizontal springs and the pile is modelled as an elastic beam. Non-linear spring characteristics of "*p-y*" curves were developed using the Matlock (1970) criteria for piles in clay and the Reese et al (1974) criteria for piles in sand. Soil layering was taken into account using the method of equivalent layer thicknesses developed by Georgiadis (1983), which considers the effect of overburden pressure and strength of the overlying layers. Figures 3 and 4 present predictions corresponding to the actual pile geometry (increased diameter in the upper part) as well as to the geometry of a pile having constant diameter of 1.5m throughout its length.

Additional comparisons between measured and predicted lateral pile responses are made in Figures 5 and 6 with reference to the bending moments developed in the pile. Figure 5 shows the variation of bending moment with depth for piles loaded at ground level with a horizontal load H_o= 930kN and a bending moment M_o= 0.2x930= 186 kNm. Figure 6 presents the measured and predicted relationships of maximum bending moment versus applied lateral load.

Figures 3 to 6 show that the agreement between predicted and measured pile responses was remarkable. They also demonstrate

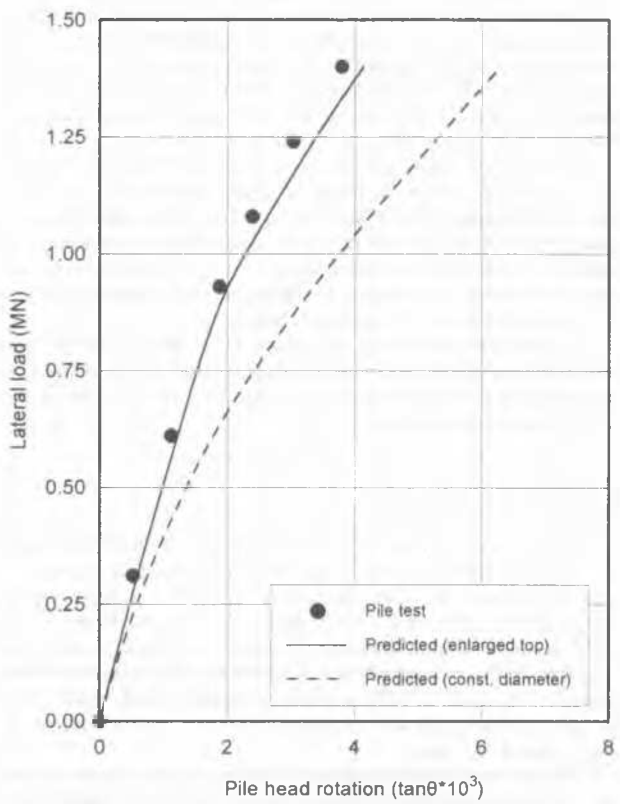

Figure 4. Lateral load versus pile head rotation relationships.

that enlargement of pile diameter from 1.5 to 3.0m over a relatively small length (two diameters) of the upper pile section reduces significantly lateral displacements, rotations and bending moments. Lateral displacements and rotations were reduced as much as 65%, while maximum bending moments (develop at a depth of about 5m) were reduced up to 23%.

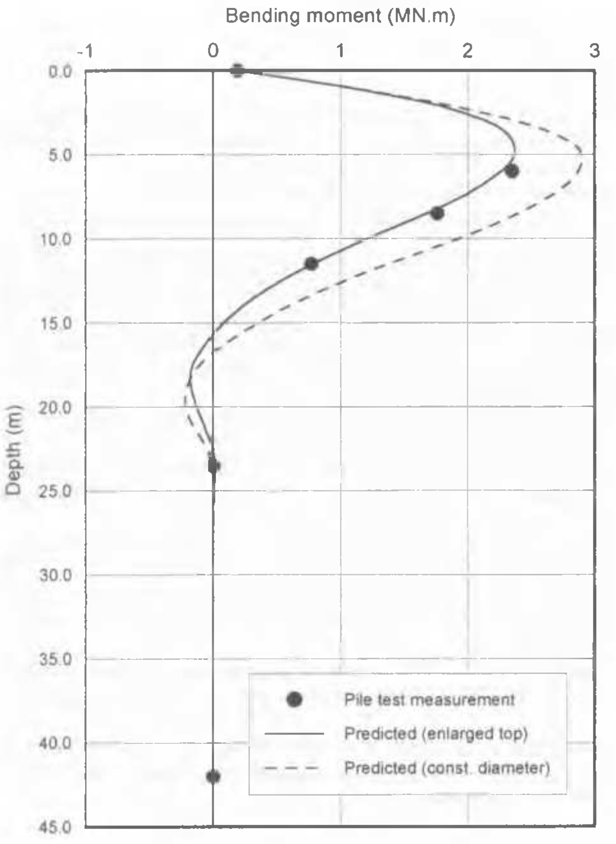

Figure 5. Bending moments with depth for Ho=0.93MN

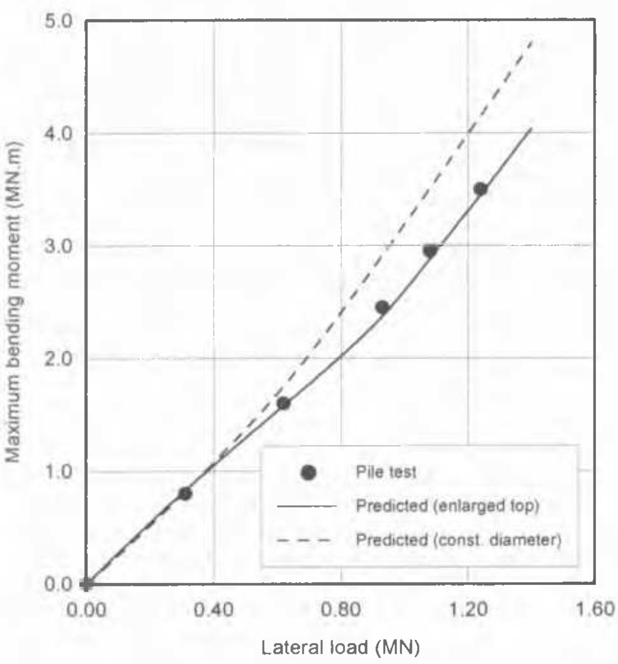

Figure 6. Lateral load versus maximum bending moment relationships

4 AXIAL PILE RESPONSE

Measured and predicted axial load versus pile settlement relationships are presented in Figure 7. To investigate the effect of pile head enlargement on pile settlement, predictions were made for both the actual pile geometry and for a pile of constant diameter equal to 1.5m. The analysis was performed using the "t-z" method in which the pile is considered as an elastic bar and the soil is represented by a series of non-linear axial springs. The predicted relationships shown in Figure 7 correspond to the following axial spring characteristics proposed by Vijayvergiya (1977):

* Shaft friction springs :

$$t = t_{max}[2(z/z_c)^{1/2} - z/z_c] \tag{1}$$

* End bearing springs :

$$q = q_{max}(z_b/z_{cb})^{1/3} \tag{2}$$

where t is the shaft friction mobilized on a pile segment at settlement z, t_{max} is the ultimate shaft friction on a pile segment, mobilized when settlement exceeds limit value z_c= 7.6mm, q is the end bearing at pile tip movement z_b, q_{max} is the ultimate end bearing which is mobilized when the tip movement exceeds the limit value z_{cb}= 0.05D and D is the pile diameter.
The ultimate shaft friction t_{max} was determined according to the following well-known for bored piles relationships (Tuma & Reese, 1974; Tomlinson, 1992) :

$$t_{max} = \alpha . c_u \quad \text{(for clay)} \tag{3}$$

$$t_{max} = 0.7 \tan\varphi . \sigma'_v \quad \text{(for sand)} \tag{4}$$

where c_u is the undrained shear strength, α is an adhesion factor for bored piles in clay, φ is the angle of internal friction and σ'_v is the effective stresses.

It should be noted that the value of a of the stiff silty clay layer (c_u=90kPa), obtained from the "α-c_u" relationship presented by Weltman and Healy (1978), predicted very accurately the shaft friction, while the shaft friction determined according to DIN4014 was about 20% lower than the measured value. For the soft silty clay layer (c_u=25kPa), the pile load test confirmed that the shaft friction is equal to the undrained shear strength (i.e. α=1), as suggested by both, Weltman and Healy (1978) and DIN4014.

The ultimate end bearing provided by the interbedded gravelly sand and stiff clay layers, proved experimentally to be only a small fraction of the ultimate axial pile capacity (on the order of 15%). To account for the soil reaction on the pile annulus formed at 3m depth, where the pile diameter changes from 3m to 1.5m, an additional axial spring was considered at this depth, whose stiffness was also determined with the "end bearing" equation (2).

Figure 7 shows that the agreement between measured and predicted pile settlements was extremely good for any value of the applied load. It also shows that the effect of enlarged pile top diameter on axial pile response was significant. The ultimate bearing capacity of the pile was increased by about 30% while the reduction in pile settlement was even greater. Pile top enlargement reduced the settlement, which corresponds to half the axial bearing capacity, by about 40%. It should be noted that predictions made using other spring stiffness relationships (API 1993, DIN4014 1990) were not so accurate, overestimating the actual pile settlements.

A comparison between measured and predicted diagrams of axial force versus depth is presented in Figure 8 for three values of applied axial load, P= 4.1, 10.3 and 15 MN (the latter corresponds to the ultimate bearing capacity). This figure illustrates that the agreement between measured and predicted axial forces was remarkably good. It also shows that, due to the end bearing reaction provided by the silty sand at 3.0m depth, the enlarged-top pile can support about 30% higher axial load.

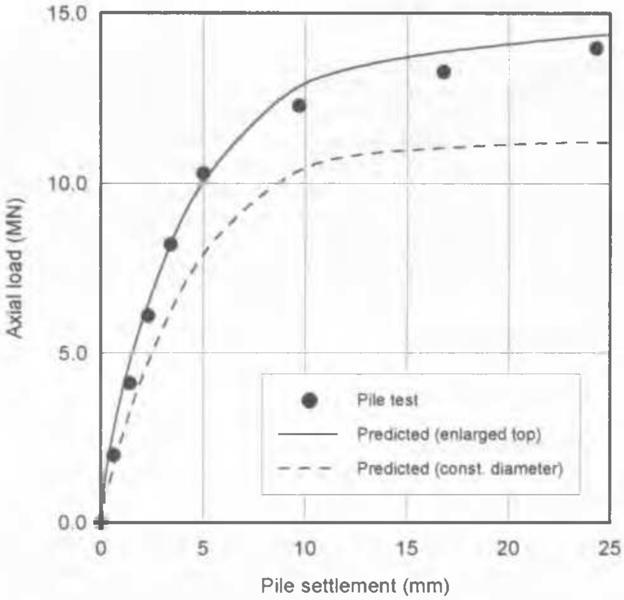

Figure 7. Axial load versus pile settlement relationships

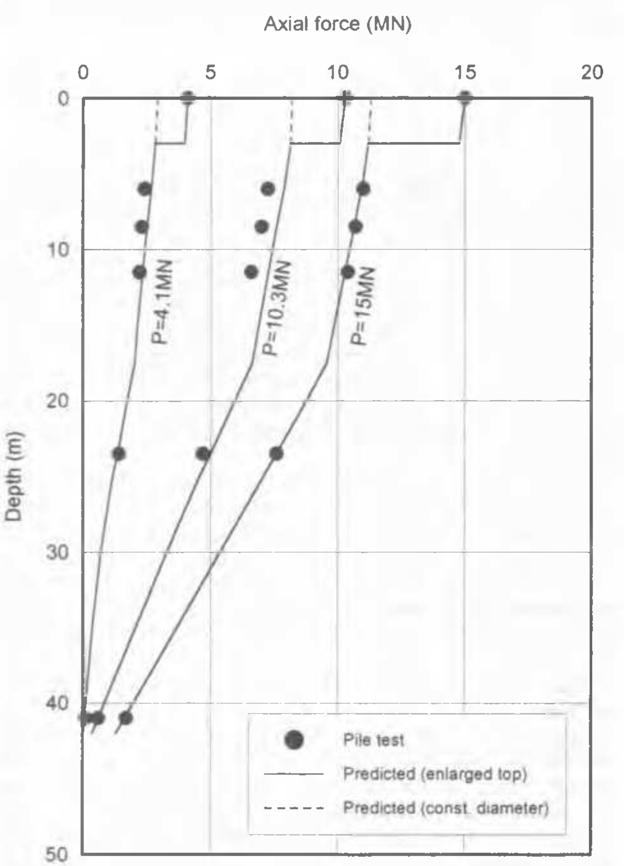

Figure 8. Variation of axial force with depth

5 CONCLUSIONS

A full scale pile test was performed on an instrumented 42m long and 1.5m diameter bored pile, having an enlarged to 3.0m diameter in the upper 3.0m long section. The pile was subjected to axial and lateral loading and the results were compared to numerical predictions of the response of enlarged-top and constant diameter piles.

These comparisons demonstrated that enlargement of pile top diameter over a relatively short section reduces significantly lateral and axial displacements and bending moments. Lateral pile top displacements and rotations were reduced as much as 65% while the maximum bending moment was reduced by 23%. The ultimate axial pile capacity was increased by about 30% while settlement was reduced by 40% for an axial load equal to half the ultimate pile capacity.

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