Friction piles in consolidating soils

Pieux flottants dans des sols en cours de consolidation

G.Auvinet & J.F.Rodríguez – *Institute of Engineering, National University of Mexico, Mexico*

ABSTRACT: This paper presents a quantitative analysis of the interaction between soil, structure and friction piles located in a consolidating clayey soil using the Finite Element Method (FEM). The consolidation process due to the weight of the structure and to a pumping–induced decrease in pore water pressure is simulated. The evolution of stresses developed within the soil and at the interface between pile and soil is evaluated. Progressive increase of soil strength due to consolidation is taken into account. The analysis performed provides valuable insight into the complex interaction phenomenon between soil, piles and structure and suggests some important new elements to be taken into account in the design of friction piles for this condition.

RÉSUMÉ: Cette communication présente une analyse quantitative de l'interaction entre le sol, la structure et les pieux flottants fichés dans des sols en cours de consolidation. On a recours à la méthode des éléments finis. On simule le processus de consolidation du sol dû au poids de la structure et aux abattements de pression interstitielle induits par pompage. L'évolution des contraintes développées dans le sol et à l'interface sol-pieu est évaluée. On tient compte de l'augmentation progressive de la résistance du sol durant le processus de consolidation. Les analyses presentées permettent de mieux comprendre les complexes phénomènes d'interaction mis en jeu et fournissent des éléments importants à prendre en compte dans la conception de ce type de fondation.

1 INTRODUCTION

Foundations on friction piles in the Mexico City lacustrine clays are seldom used since the 1985 earthquakes. The unsatisfactory behaviour of several structures with this type of foundation contributed to generalize the idea that this system is unreliable. It can be shown, however, that friction piles are still attractive and secure when properly designed. It is especially important that the interaction between soil, piles and structure due to both structural loading and pumping-induced regional subsidence affecting the lacustrine area of the city be properly accounted for. Some useful insight into this problem can be obtained by simulating the working conditions of friction piles in these complex conditions using the Finite Element Method (FEM).

2 FOUNDATIONS ON FRICTION PILES

Friction piles transfer most of their load to the soil through skin friction. In Mexico City's soft soil, they have been mainly used as a complement to box-type partially compensated foundations aimed at reducing settlement (design in terms of deformations). Not so frequently, they have been used to carry the total weight of the structure and ensure the overall stability of the foundation (design in terms of bearing capacity).

In both cases, a complex interaction develops between the soil, the piles and the structure. This is due to the fact that the soil is submitted to a double process of consolidation: the first one due to the load of the structure and the second due to variations in the pore pressure conditions in the soil associated to the intense pumping of water from the subsoil in the urban area.

In such conditions, if not properly designed, friction pile foundations can present excessive settlements but also, in some cases, they can protrude from the subsiding surrounding soil.

Design of foundations on friction piles must then be based on a detailed evaluation of the stresses developed near the tip and along the shaft of the piles and of the resulting strains and displacements. Those stresses are a function of the geometrical characteristics of the foundation, the stiffness and separation of the piles, the mechanical properties of the soil, the magnitude of structural loading and the evolution of pore water pressure.

It is commonly admitted that negative skin friction develops on the upper part of the shaft of the pile and positive friction on the lower part and that a *neutral point* can be defined where no relative displacement between pile and soil occurs (Figure 1, Reséndiz and Auvinet 1973).

A simple way to estimate the position of the neutral point is to admit that limit conditions develop both at the tip and at the shaft of the pile (Figure 2). The position of the neutral point can then be found by trial and error until the following equation is satisfied (Reséndiz and Auvinet 1973):

$$Q - C_P = \left|C_F^+\right|_{Z_0}^{Z_P} - \left|C_F^-\right|_{D_F}^{Z_0} \qquad (1)$$

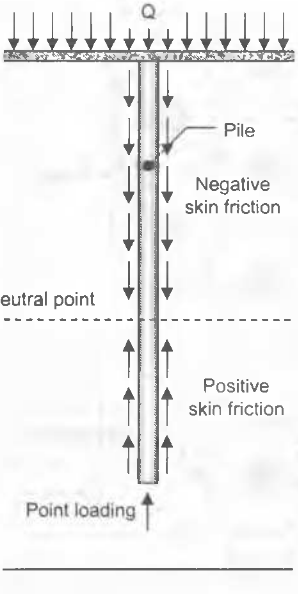

Figure 1. Shear stresses on the shaft of friction piles

where Q is the load transmitted to pile; c_P is the point bearing capacity of pile; Z_O is the depth of neutral point; Z_P is the depth of pile tip; D_F is the depth of foundation raft; $\left|c_F^+\right|_{Z_o}^{Z_P}$ is the limit adhesion along the pile shaft between Z_O and Z_P and $\left|c_F^-\right|_{D_F}^{Z_o}$ is the limit adhesion along the pile shaft between D_F and Z_O

Taking into account that the hypotheses implicit in equation (1) can be clearly unrealistic in certain conditions, it was considered necessary to evaluate its validity for different geometric and loading conditions, using the FEM.

3 NUMERICAL MODEL

A group of friction piles connected to a rigid slab and arranged according to a regular pattern is considered (Figure 2). The tributary area or *influence cell* (Schlosser et al., 1984) of each pile is hexagonal but it can be considered as practically circular. The radius R of this area is approximately equal to half the separation S between piles ($S \approx 2R$).

A simple finite element model can be used to represent this axisymmetric problem. This numerical model was adapted to perform the following operations

a) Step by step simulation of the consolidation process induced by external loading and pore water pressure changes.

b) Adjustment of the soil shear strength due to effective stress increments according to the soil behaviour observed in CU (Consolidated-Undrained) tests.

c) Step by step simulation of the stress redistribution along the shaft of the pile when shear stresses exceed the undrained shear strength of the soil.

d) Simulation of the separation between foundation slab and soil when tension stresses occur at this boundary.

Detail of the procedure and of the software that was developed can be found elsewhere (Rodríguez 2001).

Parametric studies were performed for a foundation with reinforced concrete 25m long friction piles with a diameter of 0.4m, driven in typical Mexico City lacustrine soil. Table 1 presents the properties of the materials considered in the analysis, including deformation modulus and Poisson's ratio in drained conditions, initial undrained shear strength and apparent friction angle in CU tests.

Table 1. Properties of materials

Material	E'	ν'	S_U	ϕ_a
Soil	1300kPa	0.33	19kPa	17^0
Pile and slab	18×10^6kPa	0.35	-----	-----

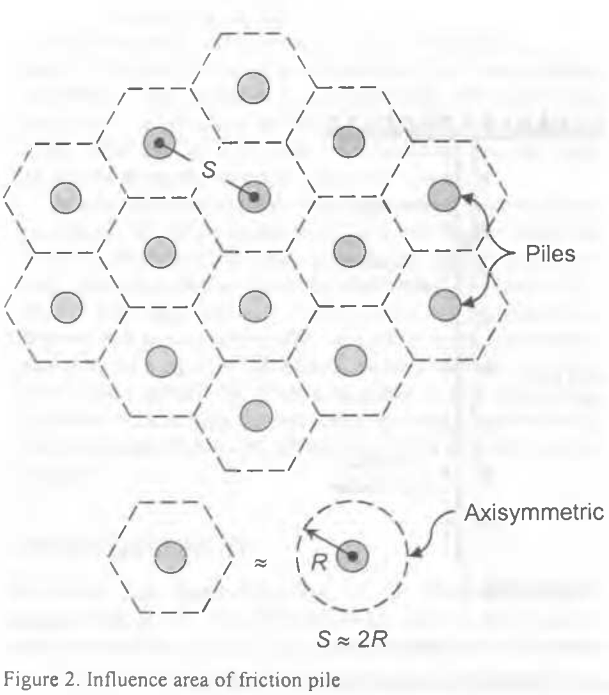

Figure 2. Influence area of friction pile

The analysis was developed in two stages; first, ten 5kPa increments were applied on the slab simulating structural loads; then a decrease of 100kPa of pore water pressure was introduced at the depth (30m) of the pervious and hard layer (Figure 3).

Figure 3 presents the contours of vertical stress increments developed in the soil around the pile at the end of the consolidation process, for pile separations of 3 and 10m respectively.

It can be observed that, for a 3m separation, the largest vertical stress increments are located near the tip of the pile and practically no stress increment is induced around the shaft from 0 to 15m. On the other hand, for a 10m separation, stress increments develop along the whole length of the shaft. In the very first loading steps, limit conditions are reached at the interface between soil and pile, while a contact pressure develops between the slab and the soil.

The first case (3m separation) is typical of the condition prevailing when the piles have a high factor of safety (design in terms of bearing capacity). The second case (10m separation) is, on the contrary, representative of what can be expected when frictions piles are used for settlement reduction purposes only (design in terms of deformation).

Figures 4 and 5 show the maximum shear stress values (τ_{MAX}) reached at the soil-pile interface, at the end of the first and second stage respectively, as a fraction of undrained shear strength, for different separations.

In the first stage (Figure 4), positive skin friction develops along the whole length of the shaft and a limit condition ($\tau_{MAX} / S_U = 1$) is attained for a small separation between piles. In the second stage (Figure 5), negative skin friction develops in the upper part of the pile and positive friction develops in the lower part. The neutral point position move upwards progressively as the consolidation process advances. On the other hand, its position is found at a higher elevation for larger pile separations. It can be observed that the negative skin friction developed is only a small fraction of the limit shear strength. As a matter of fact, for large separations between piles ($S > 5$m), no negative skin friction develops at all.

When using expression (1), negative skin friction is thus generally largely overestimated. This also is the case, but in a much smaller degree, for positive skin friction.

These results show that equation (1) should be modified applying reduction factors to both positive and negative skin friction:

$$Q - c_P = f_R^+ \cdot \left|c_F^+\right|_{Z_o}^{Z_P} - f_R^- \cdot \left|c_F^-\right|_{D_F}^{Z_o} \tag{2}$$

These factors can be determined computing the relation between the area under the curve describing the shear stress variation with depth and the area of the curve giving the variation of strength with depth. The calculated factors for the conditions prevailing in the analysis are presented in Figure 6.

For different loading and subsidence conditions, these coefficients should be re-evaluated but the values presented in Figure 6 can be considered as typical. Equation (2) should lead to a more realistic position of the neutral point. Moreover, the reduced values of positive and negative skin friction can be introduced in analytical models that have been developed for computing settlement of friction pile foundations, (Auvinet and Rodríguez 2000). The Finite Element model developed is however simple enough to be used directly for design.

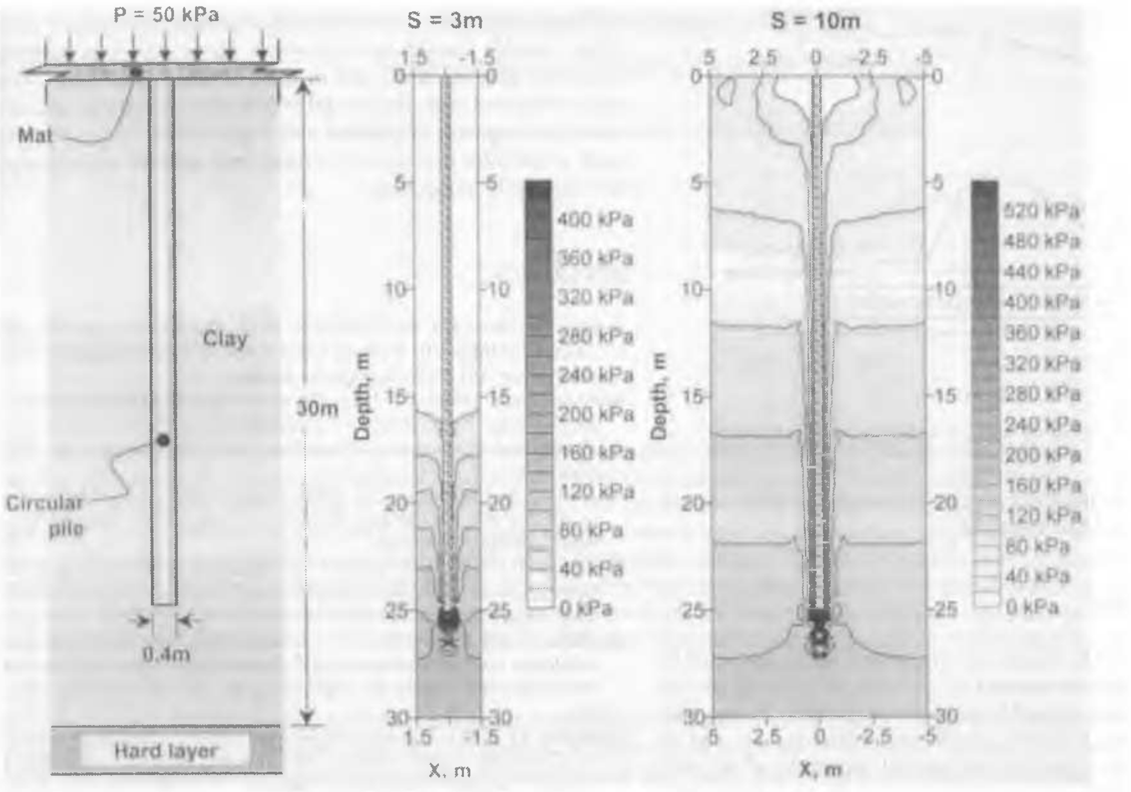

Figure 3. Vertical stress increments developed in the soil around the pile

In Figure 7, the relation ($\delta_{YCON}/\delta_{YSIN}$) is presented for different pile separations, where δ_{YCON} is the vertical displacement of the foundation with respect to the surrounding surface, i.e. (Figure 8):

$$\delta_{YCON} = \delta_{YREG} - \delta_{YTOT} \qquad (3)$$

where δ_{YREG} is the regional subsidence, calculated with the same model but without any pile; δ_{YTOT} is the total vertical displacement in presence of piles and δ_{YSIN} is the settlement induced by the structural load when no piles are used.

For a separation of 1m, $\delta_{YCON}/\delta_{YSIN} = 0.5$, and the foundation protrudes from the surrounding soil an amount equal to 50% of the settlement induced by the structural load without any pile (δ_{YSIN}). For a separation of 10m, $\delta_{YCON}/\delta_{YSIN} = -0.9$, meaning a settlement equal to 90% of δ_{YSIN}.

According to Figure 7, in this special case, the ideal separation between piles should be about 3.2m, corresponding to

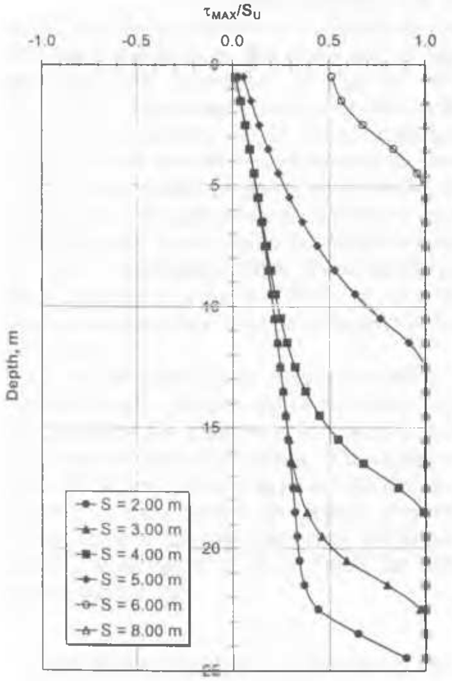

Figure 4. Fraction of shear strength developed along the shaft at the end of the first stage

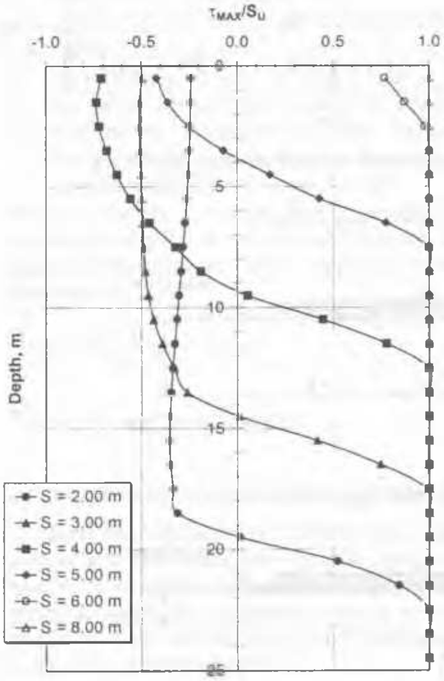

Figure 5. Fraction of shear strength developed along the shaft at the end of the second stage

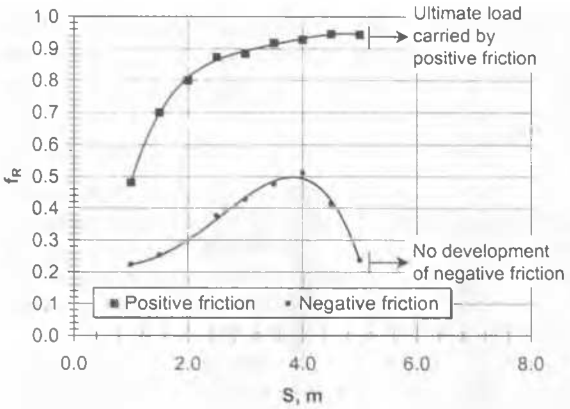

Figure 6. Reduction factors for positive and negative skin friction

$\delta_{YCON}/\delta_{YSIN} = 0$. In this condition, no settlement nor protrusion of the foundation would be expected.

4 CONCLUSIONS

Design of friction pile foundations in consolidating soils must be based on a detailed assessment of the complex interaction between soil, slab and piles. This interaction depends on the geometrical conditions, including the distance between piles, and on the stiffness of the piles, the mechanical properties of the soil, the magnitude of the structural loading and the pore water pressure evolution.

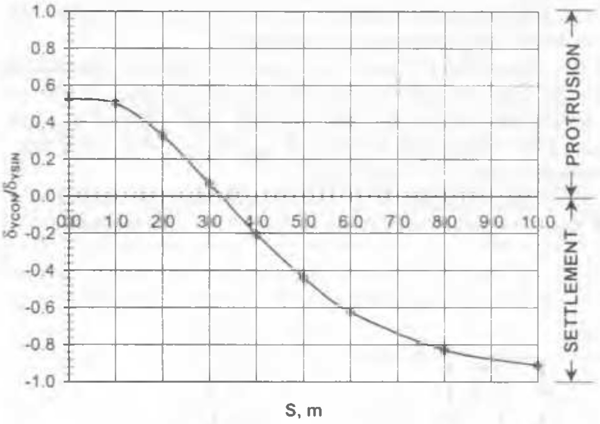

Figure 7. Vertical displacements for different piles separations

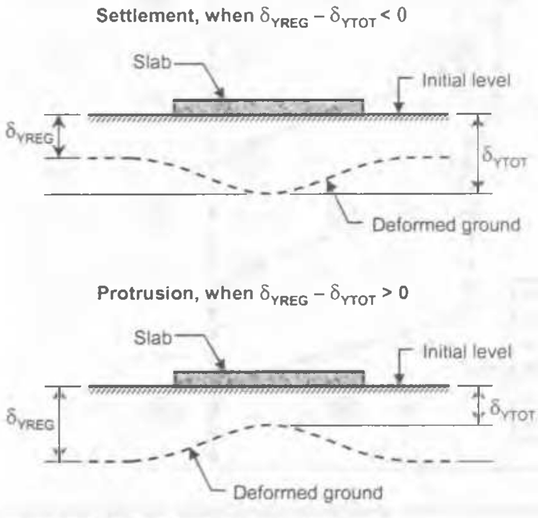

Figure 8. Types of displacements

The simple Finite Element model presented in this paper provides valuable insight into the stress, strain and displacement fields that develop in the soil in these complex conditions. The results obtained with this model clarify some important aspects of the development of positive and negative skin friction on the shaft of the piles that should be taken into account in the design of friction pile foundations.

REFERENCES

Auvinet G., Hanel J. J. and Murillo R. 1976. *Research on negative skin friction*. SMMS. VIII National Conference on Soils Mechanics. Volume III. pp. 101-105. Guanajuato. Mexico

Auvinet, G. and Hanel, J. J. 1981. *Negative skin friction on piles in Mexico City clay*. Proceedings. Xth International Conference on Soil Mechanics and Foundation Engineering. Stockholm. Sweden. pp. 599-604

Auvinet, G. and Rodríguez J.F. 2000. *Program MICRA2000 for design of friction pile foundations*. Institute of Engineering. National University of Mexico. Mexico

Reséndiz, D. 1964. *Field research on reinforced concrete piles*. Engineering Journal (Revista Ingeniería). National University of Mexico. Engineering Faculty. January. Mexico

Reséndiz D. and Auvinet G. 1973. *Analysis of pile foundations in consolidating soil*. Proceedings. VIIIth International Conference on Soil Mechanics and Foundation Engineering. pp. 211-218. Moscow. Russia

Rodríguez J.F. 2001. *Use of inclusions for control of settlement in soft soils*. Master Degree Thesis. Postgraduate Division. Engineering Faculty. National University of Mexico.

Schlosser F., Jacobsen H. M. and Juran I. 1984. *Le renforcement des sols (1)*. Revue Française de Géotechnique. No 29. pp. 7-32, France