The negative skin friction of piles produced by subsidence in Murcia

Le frottement négatif des pieux produit par l'affaisement du terrain à Murcia

J.L.Justo, N.J.Vázquez & E.Justo – *Department of Continuum Mechanics, University of Seville, Sevilla, Spain*

ABSTRACT: Recently the town of Murcia has suffered the first case of subsidence ever produced in Spain due to water extraction from irrigation wells during a drought period. Differential settlements up to 10 cm have been measured in the street pavement with respect to buildings on piles embedded in gravel, but the total calculated settlements reach up to 25 cm. An original elasto-plastic method to estimate downdrag forces in end bearing and floating piles has been developed by the authors for a heterogeneous subsident soil. The pile settlement and stresses produced by negative skin friction in several parts of the town have been calculated. The head settlements range from 1 to 20 cm, and the final safety factor falls to non allowable values in extreme cases.

RÉSUMÉ: Rècemment la ville de Murcia a enduré le premier cas de subsidence produit en Espagne par l'extraction de l'eau dans des puits d'arrosage pendent une période de sécheresse. Des tassements différentials jusqu á 10 cm ont été messurés dans le pavé de la rue par rapport aux bâtiments fondés sur des pieux encastrés dans le gravier, mais les tassements calculés ont attaint 25 cm. Les auteurs ont dévelopé une méthode elasto-plastique originelle, pour estimer le frottement négatif dans des pieux portant en pointe ou flottants dans un sol stratifiée subsidant. Les tassements et les contraintes produites aux pieux par le frottement négatif dans plusieurs zones de la ville on été calculés. Le tassement dans la tête du pieux varie entre 1 et 20 cm, et le coefficient de sécurité finale tombe, dans des cas extremes jusqu a des valeurs non admissibles.

1 INTRODUCTION

1.1 *Subsidence in Murcia (Spain)*

Figure 1 shows the soil profile in boring S'25 in Murcia, where the head drop (Fig. 2) which ocurred during the last drought, in the lower aquifer, produced settlements in the subsoil. These have been the cause of the first case of subsidence observed in Spain (Justo & Vázquez 1999).

Differential settlements up to 10 cm have been measured between street pavements and buildings on piles embedded in gravel, and calculated total settlements reach up to 25 cm. This has produced widespread damage in facings supported on the ground, urbanizations, equipment and public works. Tilt of buildings on friction piles has been observed in expansion joints, and law-suits against the architects have been filed (Jaramillo 1996, Jaramillo & Ballesteros 1997).

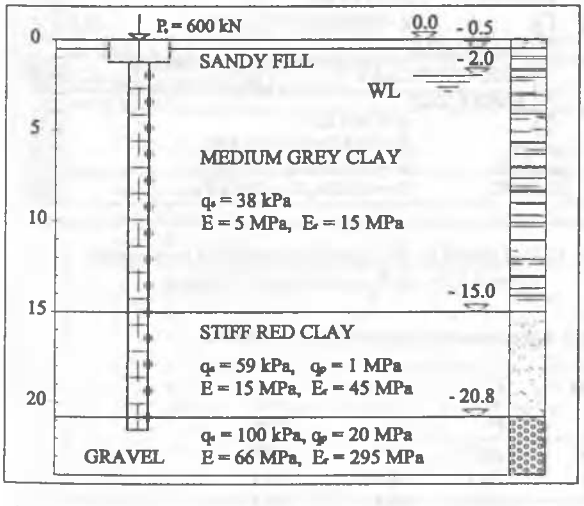

Figure 1. Soil profile in S'25. Pile embedded in the gravel. ν= 1/3
E = modulus for loading
E_r = modulus for unloading & reloading
q_s = skin friction; q_p = unit point resistance

1.2 *Negative skin friction on piles*

The consolidation of the soil surrounding piles is one of the causes of negative skin friction. The downward movement of the soil relative to the pile induces increasing negative shear stresses and downward forces upon it. When at some node of the soil-pile contact the shear strength at the shaft or the strength of the soil at the pile tip is reached, the stress remains steady and pile-soil slips may appear. If the evolution of the subsidence is known, the shear stresses at the shaft, the normal stresses at the tip and the settlement of the pile head may be calculated for specific times.

Walker & Darvall (1973) describe a case record of end bearing piles embedded in medium to stiff clay. A settlement of up to 33 mm in the ground surface produced large downdrag forces but the soil-pile shear strength was not completely mobilized. Indraratna et al. (1992) measured the negative skin friction on piles in soft Bangkok clay; the pile movements approached stable levels for surface settlements of 150 mm.

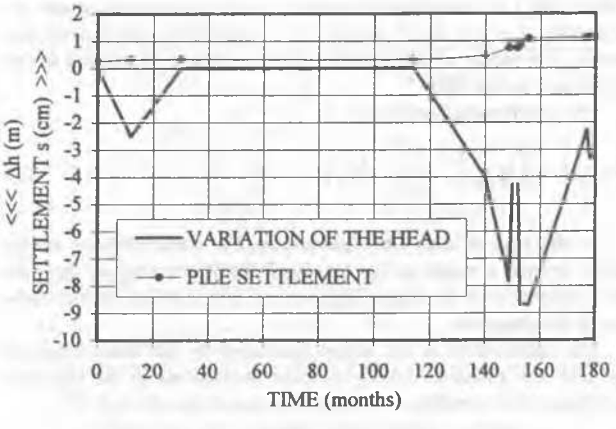

Figure 2. Variation of the head (Δh) with time at the clay-gravel boundary and settlement of the top of the pile. S'25

2 CALCULATION METHOD

Summaries of the calculation methods for negative skin friction have been presented by Poulos and Davis (1980) and Alonso et al. (1984). Salas and Belzunce (1965) first used the theory of elasticity to estimate downdrag forces. They also initiated boundary element methods based upon Mindlin equations. Included in this group is Poulos and Davis's analysis (1980) for piles embedded in homogeneous soil and resting on a rigid stratum; this method takes pile-soil slip into account. Although not stated by the authors, this analysis for piles in swelling and shrinking soils may be used for floating piles in subsident soils; for heterogeneous soil they suggest an approximate method. Non elastic finite element methods have been presented by Walker & Darvall (1973) and Indraratna et al. (1992), in which good agreement with measurements is claimed.

Finite element methods are more cumbersome than boundary element methods. The elasto-plastic boundary analysis quoted by Justo et al. (1994) for a pile subject to a load on its head has been adapted here for heterogeneous subsident soil. It is assumed that the presence of the pile does not influence the consolidation of the soil far from the pile. The pile shaft is divided into *n* partitions and the tip into *N* rings of equal area connected by the central circumference (herein called node) to the soil until plastification occurs (Fig 1). The hypotheses upon which the analysis is based have been listed by Justo et al. (1994). The following hypotheses are specific for the subsident soil:

1. The measured variation of the water head with time in the lower boundary of the clay stratum (Figs 1, 2) has been followed to calculate subsidence by a finite difference method, taking into account the loading and unloading phases (Justo & Vázquez 1999).
2. The stresses produced by driving and building loads are calculated and introduced as initial stresses.
3. An incremental procedure is followed to solve the problem between two time increments. Each increment ends when a new node is plastified.
4. Before each time increment it is verified whether the soil is in a process of consolidation or swelling, and the soil modulus for loading or unloading is introduced accordingly.

The calculation has been programmed by Justo (2000) and a detailed explanation will be published soon. At every increment, the unknown quantities are the shear stress increments at the shaft and normal stress increments at the tip of non-plastified nodes. The displacement compatibility between soil and pile at the non-plastified nodes, and the equation of equilibrium will provide the same number of linear equations and unknown quantities that may be put in matrix form.

For a pile subject to a load increment ΔP_0 at the head:

$$[M_{uv}]\{\Delta\tau_v\} = \frac{\Delta P_o}{SE_p}\{z_u\} \qquad (1)$$

where $[M_{uv}]$ = compatibility matriz, $\{\Delta\tau_v\}$ = vector of stress increments, S = pile shaft section, E_p = elasticity modulus of pile and $\{z_u\}$ = vector of depth of the active nodes with respect to the lower non active node.

The solution of Equation 1 is:

$$\{\Delta\tau_v\} = [M_{uv}]^{-1}\frac{\Delta P_o}{SE_p}\{z_u\} \qquad (2)$$

At the end of each time increment, the shear stresses at the shaft, normal stresses at the tip, load distribution along the pile and settlement at the top of the pile are obtained as normal output of the program.

The settlements at the nodes produced by the subsidence of the free soil (without piles) are now introduced in the calculation, also by increments. The equation equivalent to 2 is:

$$\{\Delta\tau_v\} = -[M_{uv}]^{-1}\{\Delta s_{ti} - \Delta s_{tif}\} \qquad (3)$$

where $\{\Delta s_{ti} - \Delta s_{tif}\}$ = vector of settlement increments produced by subsidence between nodes i and i_f (last non plastified node).

3 RESULTS

3.1 *Soil profiles*

The soil profiles chosen for calculation correspond to boring S'25 where the clay depth is greater, boring S'46 where the clay is softer and to S1 where the head drop is at a maximum. The soil parameters for S'25 and S1 are indicated in Figures 1 and 3 respectively.

3.2 *Settlement calculations*

The variation of the head in the lower aquifer for S'25 is shown in Figure 2 as a function of time. In many zones of the city the initial water level is inside the clay stratum and the upper part of the clay is partly saturated (Fig. 1). The settlements produced by subsidence in a saturated-unsaturated soil have been calculated using the predictor-corrector method (Justo & Vázquez 2000) and the maximum values are included in Table 1.

As indicated in Section 2 these settlements are the basis for the calculation of negative skin friction.

3.3 *Negative skin friction*

To study the effect of subsidence, 450 mm in shaft diameter cast-in place displacement piles have been selected. The point diameter is 900 mm, the characteristic concrete strength 17.5 MPa and the initial load 600 kN.

Two hundred millimeter in diameter reinforced concrete, micro piles with a concrete strength of 25 MPa have also been considered as a possible underpinning solution.

Piles and micro piles have been calculated either embedded in gravel (Figs 1, 3) or as floating piles. The initial load of the micro piles is 300 kN for piles embedded in gravel and 150 kN for floating piles.

A summary of the results is presented in Table 2.

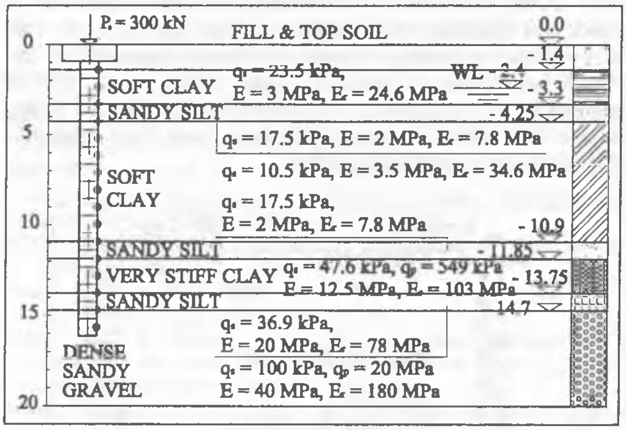

Figure 3. Soil profile in S1. Micro pile embedded in the gravel. Legend for ν, E, E_r, q_s and q_p as in Figure 1

Table 1. Subsidence in singular places of Murcia.

Boring	H	$-\Delta h_{max}$	s_{max}
	m	m	mm
S'25	20.3	8.7	60
S'46	10.5	9.4	255
S1	13.77	10.8	112

H = thickness of clay stratum.
$-\Delta h_{max}$ = maximum head drop.
s_{max} = maximum settlement

Table 2. Effect of building load and negative friction on piles in Murcia.

Boring	Pile Type	Depth	Max. settlement s	Time	Max. load P	Time	Factor of safety Structural	Soil
		m	mm	months	kN	months		
S'25	EBP	21.52	11.3	180	930	180	2.99	8.96
S'25	FP	18.63	17.2	180	737	180	3.78	1.90
S'46	EBP	12.30	200.0	150	763	150	3.65	11.52
S1	EBP	16.13	65.6	180	830	152	3.35	11.15
S1	FP	13.28	124.3	180	600	--	4.64	1.10
S1	EBM	16.13	78.9	180	397	152	1.98	1.88
S1	FM	14.23	89.4	180	164	152	4.79	1.01

EBP = End bearing pile
FP = Floating pile
EBM = End bearing micro pile
FM = Floating micro pile

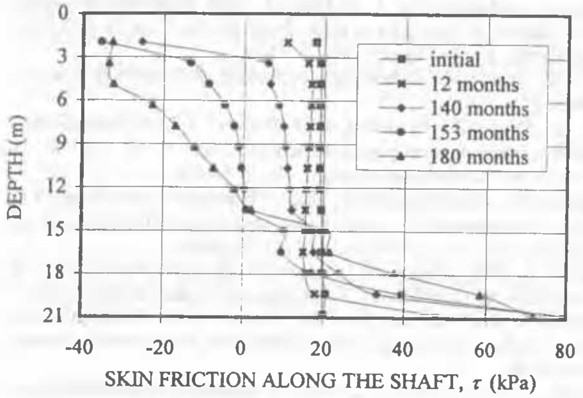

Figure 4. Skin friction along the shaft in an end bearing pile in S'25.

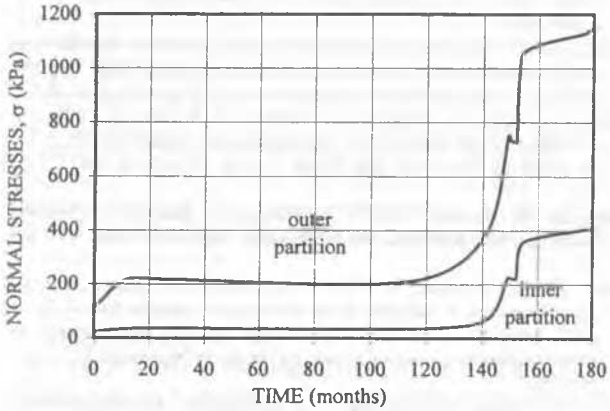

Figure 5. Normal stresses in the two partitions in the point of an end bearing pile in S'25.

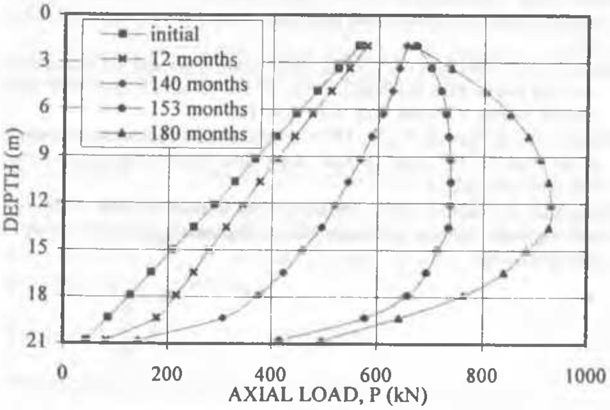

Figure 6. Axial load along an end bearing pile in S'25.

Figure 4 shows the mobilization of skin friction with time for an end bearing pile in S'25. Figure 5 shows the normal stresses in the two partitions of the point, and figure 6 the axial load along the pile.

The initial shear stresses are positive and nearly constant, the initial normal stresses small and settlement 2.5 mm. The times in Table 2 and the figures refer to the initial head measurement (January 1983).

As the head drop increases, the skin friction decreases along the pile, except near the tip where it increases. The tip's normal stresses and the axial load also increase. For a head drop of 4 m (t = 140 months) the skin friction becomes negative near the pile head and the lower shaft element becomes plastified. When the maximum head drop is attained (8.7 m at 153 months) the neutral point (where the maximum axial load is reached) is at around 13 m in depth but, notwithstanding the subsequent head recovery in the gravel (Fig. 2), both negative skin friction above the neutral point and positive skin friction below continue to increase in absolute value, because a consolidation process is under way. The maximum head settlement (Table 2), tip stress (Fig. 5) and axial load (Fig. 6) are reached at 180 months. The existence of a neutral point at a similar depth in point bearing piles is confirmed by the measurements and calculations carried out by Indraratna et al. (1992) and Walker and Darvall (1973). This also appears in the measurements made by Bjerrum et al. (1969), Endo et al. (1969) and Wong et al. (1995). The calculations of Poulos and Davis (1980) lead to a maximum axial load at the tip, probably because they assume a rigid bearing stratum (Poulos 1989). This situation may be produced in some steel piles driven to rock (Johannessen & Bjerrum 1965). The maximum total settlement is 11.3 mm (Table 2).

In floating piles, final settlement and the structural factor of safety are greater, and maximum axial load and the soil factor of safety smaller. The axial load on both piles exceed the structural limit indicated by the Spanish Instruction for piles (NTE 1984), 546 kN, although they are below the limit indicated by the Spanish Instruction for Structural Concrete (EHE 1999). The soil safety factor of the floating pile is well below the value recommended by the Spanish Instruction for piles (3).

The next calculation has been carried out at pile S'46, where the pile crosses 7 m of very soft clay and is embedded in 3.5 m of very dense sand and gravel. As the depth of the dense granular soils is small, only end bearing piles have been considered. The calculated subsidence of the soil reaches 255 mm (Tab. 1), and in this case there is recovery of axial loads and settlements when the head in the granular aquifer increases. Owing to this, maximum settlement (200 mm) and axial load (763 kN) coincide in time with the maximum head drop in the granular aquifer (9.4 m).

At the location of boring S1 (Fig. 3) the pile embedded in the gravel reaches its maximum settlement (65.6 mm) at 180 months (Tab. 2). Therefore, there is no recovery of displacements when the head rises (Fig. 2). On the other hand, the maximum axial

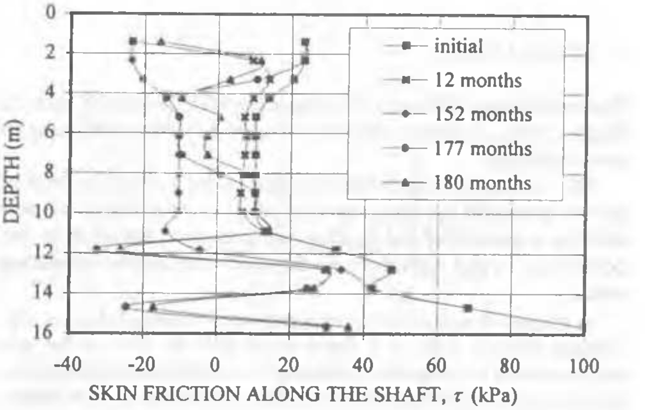

Figure 7. Skin friction along the shaft in an end bearing micro pile in S1.

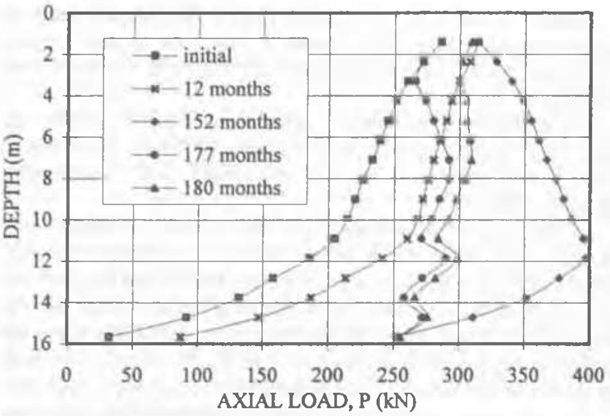

Figure 8. Axial load along an end bearing micro pile in S1.

load (830 kN) is attained when the maximum head drop (10.8 m) in the granular aquifer is produced (152 months), and there is recovery when the head increases in the granular aquifer.

The floating pile at the location of S1 has been selected to study the effect of subsidence on a pile whose soil safety factor is near 1. The maximum axial load stays at the head, and the settlement increases up to 124.3 mm, nearly twice the value of the end bearing pile.

The same location has been selected to study the effect of subsidence on a micro pile (Fig. 3).

Figure 7 shows the mobilization of skin friction with time for an end bearing micro pile, and Figure 8 the axial load along the pile. Under the initial load (300 kN) all the shaft nodes are plastified, but the tip is far from plastification and the axial load is at a maximum at the head where settlement reaches 6.5 mm.

As the head drop increases, the normal stresses at the tip and the axial load increase. The skin friction decreases except in the lower part of the shaft, where the pile is embedded in very dense sandy silt and gravel. When the maximum head drop is produced (at 150 months) the shaft is plastified but with negative skin friction until reaching the bottom of the soft clay layer. The maximum axial load (397 kN) appears at a depth of 12 m and the settlement reaches 59 mm.

At 177 months there is a head recovery in the gravel of 7.6 m. Figure 7 shows the complex change of skin friction due to the complex process of consolidation in the clay strata under the increase of the head in the gravel. Figure 8 shows that there is a strong decrease in the axial loads along the pile except for the base, but the pile head settlement slighty increases (72.4 mm). Finally, at 180 months there is a new head drop (0.5 m), and the axial loads and the pile settlement increase (78.9 mm).

In the point bearing micro pile, both the safety factor in the soil and the structural one reach unacceptable levels according to Spanish standards.

The final settlement of the floating pile is greater (89.4 mm).

4 CONCLUSIONS

The settlements induced by the negative skin friction on piles in Murcia (Tab. 2) during the last drought has produced harm in some buildings.

The process of consolidation of clay under a changing head in the lower aquifer has been reproduced. The settlement of the soil induces a transfer of the bearing capacity from the shaft to the point (Fig. 5) and sometimes to the shaft embedment in bearing strata.

In general a neutral point appears when the head drop is significant (Figs 4, 6-8), at a depth from 60% to 75% of the pile depth in point bearing piles, and near the middle in floating piles. Similar results are obtained in the axial load along the pile measured by other authors.

The reductions experienced by the structural and soil safety factors are, in some cases, unacceptable by Spanish standards.

5 ACKNOWLEDGEMENTSS

This research has been carried out thanks to help provided by the Dirección General de Enseñanza Superior e Investigación Científica of Spain, Grant TRA99-0528.

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