Numerical Investigation on the Neutral Plane in a Negative Skin Friction Pile

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ABSTRACT
This paper presents a parametric study on the location of the neutral plane along a negative skin friction pile using finite element method. The neutral plane, where the pile and soil settle the same, is one of the most important factors in accurately predicting the negative skin friction or dragload in the pile. The negative skin friction is a common problem for a pile when it is designed in a highly compressible soil. Dragload can cause severe damages or even structure failure of the pile. Finite element program, ABAQUS, is employed in this study to investigate the variation of the neutral plane with different parameters, including the consolidation time, the properties of the soil-pile interface, the intensity of surcharge, and the stiffness of bearing layer. First, a brief review on various design codes and guidelines is provided. Second, a numerical model is established and verified with a known case history. Third, a parametric study is performed under various conditions. Fourth, the most important influence factors are identified in this research.

RÉSUMÉ
Ce document présente une étude paramétrique sur l'endroit de l'avion neutre le long d'une pile négative de frottement superficiel suivre la méthode d'élément fini. L'avion neutre est l'endroit où la pile et le sol arrangent la même chose, qui est l'un des facteurs les plus importants en prévoyant exactement le frottement superficiel ou le dragload négatif dans la pile. Le frottement superficiel négatif est un problème commun pour une pile quand il est conçu dans a fortement - sol compressible. Dragload peut causer des dommages ou même l'échec graves de structure de la pile. Le programme fini d'élément, ABAQUS, est utilisé dans cette étude pour étudier la variation de l'avion neutre avec différents paramètres, y compris la période de consolidation, les propriétés de l'interface de sol-pile, l'intensité de la surtaxe, et la couche de roulement. D'abord, une brève revue sur de divers codes de conception et des directives est fournie. En second lieu, un modèle numérique est établi et vérifié avec des antécédents connus. Troisièmement, une étude paramétrique est réalisée dans de diverses conditions. Quatrièmement, les facteurs d'influence les plus importants sont identifiés dans cette recherche.

1 INTRODUCTION

Piles are normally designed to achieve axial loading capacity through the development of positive shaft skin resistance and end-bearing resistance. The positive shaft skin resistance will be developed under the condition that the pile settles more than adjacent soil. However, in areas of deep compressible soil, the soil adjacent to a pile is likely to settle more than the pile, and the relative settlement between the pile and surrounding soil will change the direction of skin friction on the pile, i.e. negative skin friction occurs. Depending on the magnitude of the negative skin friction, it would induce additional vertical loading and cause significant pile settlement, and in worse conditions even lead to structure failure (Fellenius 1984; Hanna & Sharif 2006). In the design of a pile foundation in a highly compressive soil, this dragload must be added to the structural load to evaluate the pile capacity and ensure the safety of the structure. The design, therefore, should accommodate on the potential negative friction that a pile may experience (Matyas & Santamarina 1994).

Many methods, including analytical method, numerical modeling, field testing, and centrifuge modeling, have been proposed to investigate the magnitude and distribution of negative skin friction (Poulos & Mattes 1969; Indraratna et al. 1992; Wong & Teh 1995; Leung et al. 2004; Comodromos & Bareka 2005; Fellenius 2006). Most of these researches focused on the distribution or magnitude of negative friction or dragload. No systematical study has been performed on the location of the neutral plane.

In this paper, the changes of the neutral plane are studied under various influence factors, including the consolidation time, the soil-pile interface properties, the intensity of surcharge, and the stiffness of the bearing layer. The first part of this paper will provide a brief review on various design codes and guidelines. Second, a numerical model is established and verified with a known case history. Third, parametric study is performed under various conditions. Fourth, the most important influence factors are identified in this research.

2 DESIGN GUIDELINES AND METHODS

2.1 Estimation of Unit Skin Friction

There are mainly two methods: α (total stress) and β (effective stress) methods in calculating unit skin friction (f_s) for driven piles in clay (Meyerhof 1976). The same methods have been applied to calculate the negative skin friction.

$$f_s = \alpha S_u \quad [1]$$

$$f_s = \beta \sigma'_v \quad [2]$$

Where S_u is the average undrained shear strength of clay along the length of the pile;

α is an empirical adhesion factor;

σ'_v is the average vertical effective stress in the soil along the pile before driving;

β is an empirical factor;

$\beta = (1-sin\phi')tan\phi'$ for normally consolidated clay;

$\beta = (1-sin\phi')OCR^{0.5}tan\phi'$ for overconsolidated clay;

ϕ' is effective internal friction angle of soil.

Most research focused on establishing α and β values to get a more accurate skin friction. For instance, CGS (2007) suggests the α value is in the range of 0.5 to 1.0 and the undrained shear strength S_u is specified as the strength after consolidation under the new load.

The β method is more popular since it is based on effective stress theory. CGS (2006) suggests the application of β method in the range of 0.2 to 0.3. Based on full-scale load tests, NAVFAC (1986) mainly recommends the β method for the unit skin friction and β value in the range of 0.2 to 0.25 for clay, 0.25 to 0.35 for silt, and 0.35 to 0.50 for sand.

2.2 Location of Neutral Plane

The location of the neutral plane, where the pile settles the same amount as the surrounding soil, is an important parameter in designing pile foundations in highly compressible soil. Once the location of the neutral plane is determined, the available equations could be used to evaluate the dragload. NAVFAC (1986) suggests a ratio between the depth of the neutral plane and the length of the pile, L_{NP}/L, to be taken approximately as 0.75 in case of no test data available. This approximation may lead to uneconomical or unsafe design. It also suggests calculating the depth by trial and error procedure which compares the settlement of soil to that of the pile. This paper studies the location of the neutral plane with several influence factors using the finite element method (FEM), including the consolidation time, the friction coefficient of the soil-pile interface, the intensity of surface surcharge, and the modulus ratio of the bearing layer to the consolidating layer.

3 MODEL VALIDATION WITH A KNOWN CASE

A numerical model developed with ABAQUS is verified based on a known case, which was conducted by Indraratna et al (1992). The pile with a length of 25 m and a diameter of 0.4 m was driven in the layered soil in five stages. A 2 m high embankment was placed around the piles over an area of 14 m × 24 m. The pile was monitored for 9 months. Ground water table was located at the ground surface. The material properties employed in the FEM are shown in Table 1 and Table 2. The limiting displacement of 5 mm and a friction coefficient of 0.15 are used in this model. This type of interface is well capable of describing the frictional interaction between the pile and soil.

The skin friction along the pile after consolidation for 265 days of present numerical model is compared with the field data and FEM results from Indraratna et al. (1992), as shown in Fig. 1. There is a good agreement between the present FEM analysis and the field data. This model and this type of interface are capable of predicting the distribution of the skin friction and the location of neutral plane.

4 PARAMETRIC ANALYSES ON NEUTRAL PLANE

The variations of the neutral plane with several influence factors are addressed in this paper with a simplified model where only two soil layers are employed: the consolidating layer and the bearing layer, as shown in Fig. 2. A pile with a diameter of 0.5 m is used with a length of 20 m fully embedded in the consolidating layer. The bearing layer and the consolidating layer are divided at the pile tip level. The water table is located on the ground surface. The element types assigned to the soil and the pile are CAX4RP and CAX8R, respectively. The general parameters used are the consolidation time of 560 days, the friction coefficient of 0.3, the surcharge of 50 kPa at the ground surface, and the modulus ratio, E_b/E_c, of 1, where E_b is the Young's modulus of the bearing layer and E_c is the modulus of the consolidating layer A loading time of 5 days is used to simulate the construction of surcharge. Typical material properties used in the analyses are summarized in Table 3.

The ranges of the parameters, as shown in Table 4, are for the consolidation time, the friction coefficient of soil-pile interface, the intensity of the surcharge, and the modulus ratio E_b/E_c. During the parametric study, all the parameters are kept the same except the one under investigation.

4.1 Consolidation Time

The consolidation times of 10, 30, 60, 200, 560 days are used to investigate the neutral place change with time. The effective stress in the soil increases with time due to the dissipation of excess pore water pressure. This eventually leads to a full mobilization of shearing resistance at the soil-pile interface. The increasing relative movement between the pile and soil results in an appreciable movement in the location of the neutral plane. The depth of the neutral plan is 5 m below the surface on the 10^{th} day after the surcharge and increases to 12.5 m on the 560^{th} day, as shown in Fig. 3. The unit skin friction also increases due to the increase of the effective stress in the soil. The change of the neutral plane with time is consistent with most of the field measurements (Indraratna et al. 1992; Fellenius 2006).

Table 1. Modified Cam-clay parameters used in ABAQUS

Depth (m)	Density (t/m^3)	κ	ν	λ	M	e	k(x10^{-5} m/day)
0-4	0.17	0.053	0.33	0.182	1.05	2	67.6
4-10	0.17	0.063	0.33	0.323	0.97	3	5.5
10-20	0.17	0.063	0.33	0.323	0.98	4	2.63
20-24	0.17	0.027	0.33	0.116	0.9	1.2	3.72

Table 2. Material properties of pile and end bearing

Material type	Depth (m)	Density (t/m^3)	E (t/m^2)	ν	e	k(x10^{-5} m/day)
End bearing	24-40	0.17	2800	0.33	1.2	3.72
Pile	0-25	0.17	3000000	0.33	-	-

Table 3. Material properties used in the analysis

Material	E (kPa)	ν	c (kPa)	φ	ψ	k(x10^{-8} m/s)	γ(kN/m^3)
Concrete pile	2.8×10^7	0.17	-	-	-	-	18
Consolidating layer	5×10^3	0.35	3	20	0.1	1	18
Bearing layer	5×10^3	0.3	0.1	35	10	1	18

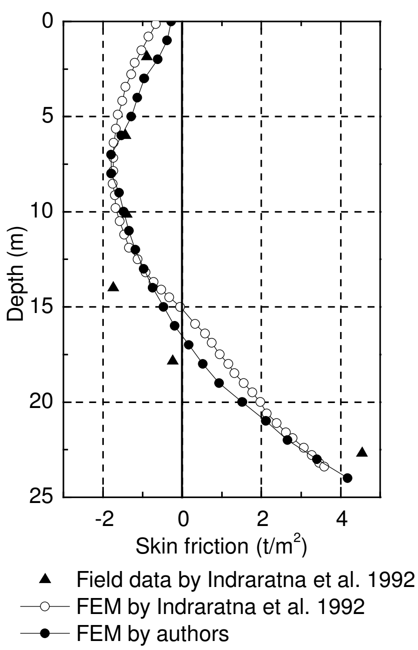

Fig. 1. Distribution of unit skin friction along the pile

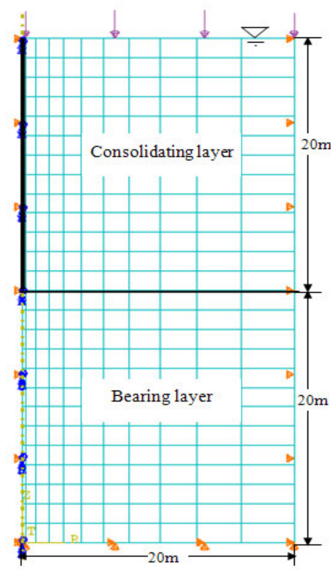

Fig. 2. FEM model and mesh used in parametric study

4.2 Friction Coefficient of Soil-Pile Interface

The interface properties between the pile and soil play an important role in calculating the dragload. The friction angle of the interface, δ, was proposed to be in the range of 9° to 21° by Potyondy (1961). Based on these values, the friction coefficient, $\beta=\tan\delta$, varying from 0.15 to 0.4 is used in this study. In addition, the friction coefficient of 0.1, indicated by Indraratna et al. (1992), is used herein to simulate coated pile.

Table 4. Range of parameters tested in present study

Parameters	Range of testing
Consolidation time (day)	10, 30, 60, 200, 560
Friction coefficient of pile/soil	0.1, 0.15, 0.2, 0.3,0.4
Intensity of surcharge (kPa)	25, 50, 100, 200
Modulus ratio (E_b/E_c)	1, 10, 100, 1000

The neutral plane moves slightly up from 14 m to 12 m below the ground surface as the friction coefficient increases from 0.1 to 0.4, as shown in Fig. 4. As expected, both the negative and the positive skin frictions increase with the increase of the friction coefficient. The figure also shows that the reduction of friction coefficient such as coating with bitumen can effectively reduce the negative skin friction.

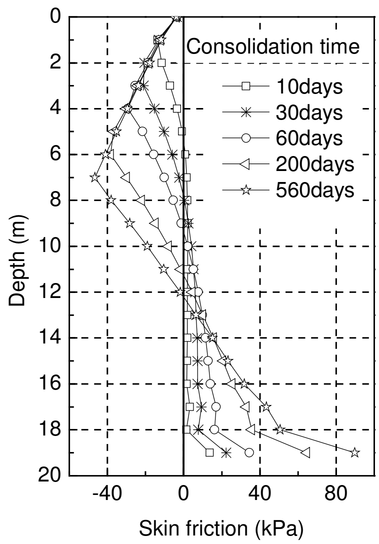

Fig. 3. Neutral plane change with consolidation time

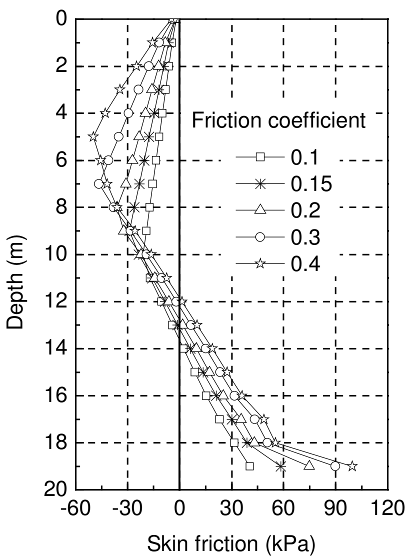

Fig. 4. Neutral plane change with friction coefficient

4.3 Intensity of Surcharge

The depth of the neutral plane moves slightly down with the increasing surcharge load, as shown in Fig. 5, which is consistent with that investigated by Comodromos & Bareka (2005). Compared to a range of 0.83 to 0.95 in their study, the L_{NP}/L ratio changes from 0.55 to 0.65 in this study under the same surcharge increment from 25 to 100 kPa. This can be attributed to the fact that the pile was founded on a much stiffer bearing layer in previous study. It is worthy to note that the skin friction at all elevations increase with the increasing surcharge load.

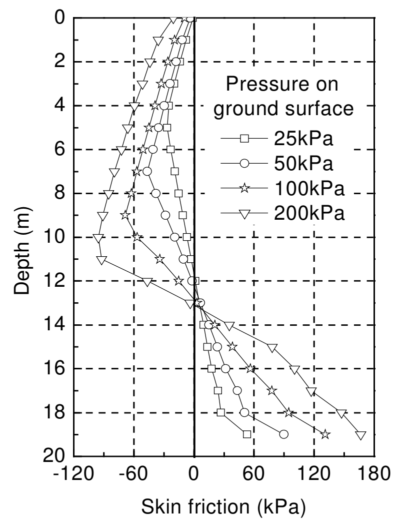

Fig. 5. Neutral plane change with surcharge

4.4 Stiffness of Bearing Layer

The Young's modulus is used to study the effect of the stiffness of the bearing layer on the neutral plane. In order to cover a wide range of soil stratum conditions, the Young's modulus of the bearing layer ranging from 5 MPa to 5000MPa and a constant modulus of 5 MPa in the consolidating layer are used in this research, which corresponds to an E_b/E_c ratio varying from 1 to 1000. The same modulus ratio was used by Lee et al. (2002). The location of the neutral plane is influenced remarkably by the stiffness of the bearing layer, as shown in Fig. 6. The influence of the bearing layer is mostly located at the bottom half of the pile length. The stiffer the bearing layer, the deeper the neutral plane.

For the end-bearing pile corresponding to the E_b/E_c of 1000, the neutral plane locates at the pile tip as expected. In this case, the negative skin friction is generated along the full length of the pile. This finding is consistent with that reported by Lee et al. (2002). The L_{NP}/L ratio increases approximately linearly from 0.6 to 1.0 with the Eb/Ec ratio from 1 to 1000, as shown in Fig.7 with known case histories.

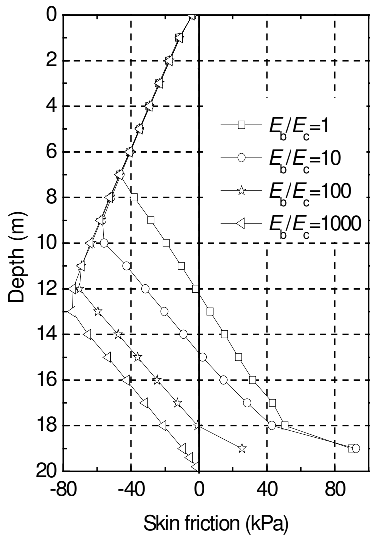

Fig. 6. Neutral plane change with modulus ratio

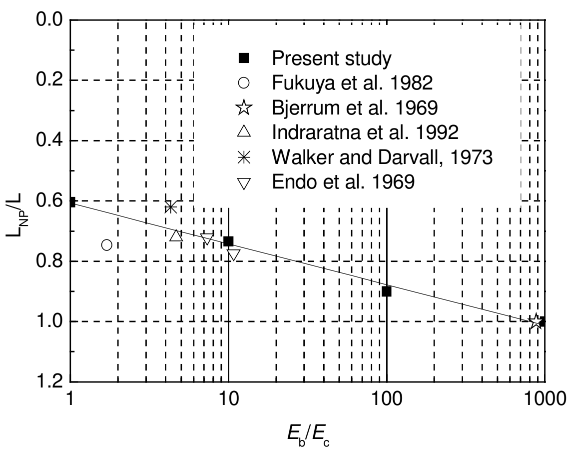

Fig. 7. The relationship between L_{NP}/L and the modulus ratio E_b/E_c

5 CONCLUSIONS

This paper employed numerical modelling with ABAQUS to study the change of the neutral plane. Among the four parameters investigated, the stiffness of the bearing layer and the consolidation time are the most critical ones in changing the depth of the neutral plane. The depth of the neutral plane increases gradually with consolidation time due to the increasing soil settlement. The stiffer the bearing layer, the lower the neutral plane. A linear relationship is established between the depth of the neutral plan and the modulus ratio of the bearing layer to the consolidating layer. This agrees well with the field measurements from a few known case histories.

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