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5th International Conference on **Deep Foundation Practice** incorporating Piletalk : 4 - 6 April 2001, Singapore

Recent findings on negative skin friction in piles and pile groups in consolidating ground

C J Lee, Cambridge University, United Kingdom
M D Bolton, Cambridge University, United Kingdom
A Al-Tabbaa, Cambridge University, United Kingdom

Abstract

This paper presents recent findings of pile behaviour subjected to Negative Skin Friction (NSF) through a series of Finite Element Analyses (FEA). Consideration of the slip at pile-soil interface is found to be the most crucial factor in understanding pile behaviour in consolidating ground.

Keywords: Negative Skin Friction, Dragload, Downdrag, Group effect, Finite Element Analysis

1. Introduction

Negative skin friction (NSF) is the most common problem in the design and construction of pile foundations in soft ground when the soil next to a pile moves down more than the pile. Various causes have been reported [1-3], which are mainly related to the increase of effective vertical stress. The development of additional compressive force (dragload) and excessive pile settlement (downdrag) will increase cost and cause difficulty in construction and maintenance. Failure of the pile foundation from the viewpoint of serviceability due to downdrag is not uncommon even with the presence of a geotechnical engineer [4]. However, to date most of the current design approaches are based on simplified methods and are not satisfactory. Predictions presented by distinguished engineers in the Wroth Memorial Symposium failed to estimate dragload within a range of 98~515% of the observed value [5].

It has been known that less dragload is developed for piles in a group due to pile-soil-pile interaction. A relatively large group effect (large reduction of dragload) is predicted from current design approaches [6-8], especially for the central pile. However, for most situations relatively small group effects have been reported [2, 9-11] from various previous observations. Contrary to ordinary pile foundation design, where elastic analysis could present a reasonable estimation of the pile behaviour, soil yielding is to be developed at the interface due to large soil movement and hence large shear strain. Phamvan [1] and Nishi [12] pointed out the significance of including slip at the interface for a single pile. Kuwabara [13] and Chow [14] reported that the effect of the slip at the pile-soil interface is a key factor governing the group effect. However, to date the effect of soil slip for piles in a group is not well known. In this work, 2D and full 3D analyses, including soil yielding are presented. For the purpose of validating the soundness of the current approach, elastic solutions will be compared. Then various parametric studies will be presented considering the major factors for the group effect. Finally field observations will be compared with the Finite Element Analyses (FEA).

2. FE modelling

In this work numerical analysis for a single pile and piles in a group is carried out in 2D axi-symmetric and full 3D conditions respectively. Although a simplified 2D-approach can sometimes be useful in full 3D situations, it has been found unrealistic in this research where the effect of the relative position of a pile within the group cannot be included. Traditionally full 3D analysis is considered very expensive and time consuming. However, with the advances in computer capacity for calculation and powerful graphical tools, 3D analysis is no longer difficult or time-consuming work. The program PATRAN was used for mesh generation. A FEM package ABAQUS was used for the calculation and for Post-processing.

Figure 1 presents a typical FE mesh used in this analysis. A Fine mesh is used near the pile soil interface and increases in thickness radially outwards. For 3D problems, various sensitivity studies have been carried out. Considering calculation time and accuracy, compromises are necessary. Therefore the following simplifications have been made. Firstly, possible stress changes after pile installation are not considered. Indraratna [15] reported that residual load after pile installation is not significant. Therefore, before initiating analysis the pile is free of residual stress. Secondly, soil settlement and hence NSF is developed by the application of surface loading on the soil surface. Table 1 summarises the material properties used in this analysis. An Elastic model is used for the pile and a non-associated Mohr-Coulomb model is used for the clay and sand. For clay the critical state angle (ϕ_c) is used with a very small dilation angle (ψ) since excessive shear deformation is developed at the interface. The peak friction angle ($\phi_c + \psi$) is assumed for sand because of small soil movement. Deformation of the soil after the yielding will be governed by the dilation angle.

Table 1 Material properties used in the analysis

Material	Model	E (kN/m^2)	C(kN/m^2)	ν	ϕ_c(°)	ψ(°)	Ko	γ(kN/m^3)
Pile	Isotropic Elastic	2000000	.	0.3	.	.	1.0	25
Clay	Mohr Coulomb	5000	3	0.3	20	0.1	0.65	18
Sand		50000	0.1	0.3	35	10	0.5	20

* water table on the top of clay layer

In this study pile groups of 3×3 and 5×5 with typical minimum and maximum pile spacing, surface loading and interface friction angle are considered. The piles are taken to be 0.5m in diameter and 20m in length. 8 noded 2nd order elements and 20 noded 2nd order brick elements are used for the 2D and 3D analysis respectively.

The ABAQUS interface modelling technique based on the contact surface is used in simulating the slippage behaviour at the soil-pile interface. Duplicated nodes are used at interface forming zero thickness interfaces. ABAQUS uses the Coulomb frictional law where frictional behaviour is specified by a coefficient of friction μ. The normal effective stress (p) between two contacting surfaces is multiplied by μ and this gives a limiting frictional shear stress (μp). If the applied shear stress to the surfaces is less than μp the surfaces will stick. The nodes at the soil element next to the pile can slide along the pile when soil yielding is developing.

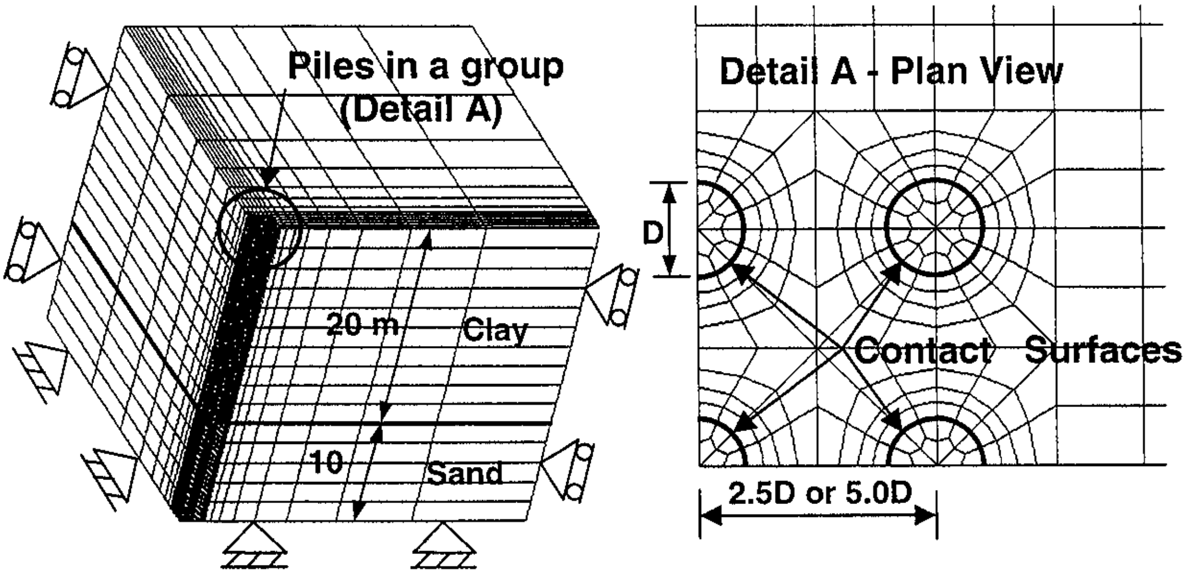

Fig.1. A typical 3D mesh used in FEA

3. Discussion for a Single Pile

3.1 Elastic solution

Figure 2 presents the elastic solution from Poulos [16] and FEA results based both on an elastic model and an elastoplastic soil model including slip. The no-slip elastic FEA simulations agree closely with the elastic model of Poulos [16]. However, because of large interfacial shear stresses, a very large dragload is observed. However, when including soil slip, quite different distributions of the dragload are observed. Relatively small dragload is developed, especially when relatively stiff soil is considered (K=50). Figure 2 also presents dragload predicted from the β method, which cannot consider the effect of the change of relative pile stiffness ($K = E_{pile}/E_{clay}$). Larger dragload is observed than predicted by the slip approach since the effective vertical stress is reduced due to transfer of soil weight to the pile [8] and partial mobilisation of skin friction near the pile toe.

3.2 Dragload and downdrag

Figure 3 shows the different mechanisms of shear stress and dragload for a floating pile and an end-bearing pile. In this analysis different $E_{bearing\ layer}/E_{clay}$ values are used in order to specify a floating pile or bearing pile as shown in Figure 1. In Figure 1 the sand layer is replaced by the bearing layer in this analysis. The ratio of 1 and 1000 is used in this analysis, respectively. For a floating pile NSF is developed from the top of the pile to the neutral point (NP) which is around 70% of the pile length. For a bearing pile, NSF is developed for almost the entire length of pile. This observation is well-explained based on simple vertical force equilibrium (ΣNSF = ΣPSF + bearing resistance). Since small bearing resistance is available for a floating pile, PSF should be large enough to resist NSF. Hence NSF will be reduced with the neutral point (NP) well above the pile tip. However for a bearing pile where end-bearing resistance is quite large, PSF is not required, thereby more NSF is developed. It could also be explained based on relative settlement between the soil and the pile. When pile moves more in the case of the floating pile, PSF will be developed near the pile tip. Pile movement will be very small for the end-bearing pile, therefore NSF is developed for the entire length of the pile. Partial mobilisation of negative and positive skin friction is developed near the NP, where the shear stress is less than the limiting shear stress (μp) since the soil is in an elastic stress condition.

In this analysis more dragload and less downdrag (1.5mm) is developed for a bearing pile and less dragload and more downdrag (79.0mm) is developed for a floating pile. It has been shown that for most cases, dragload is not significant when piles of less than 30m length are used [17]. However, there are many cases where failure of structures is reported [4, 18] due to excessive (differential) settlement of piles. Excessive pile settlement is very likely for friction piles. Therefore, piles should be installed as deep as possible. Of course the structural safety of the pile material and driveability of the pile and piling system should be thoroughly investigated.

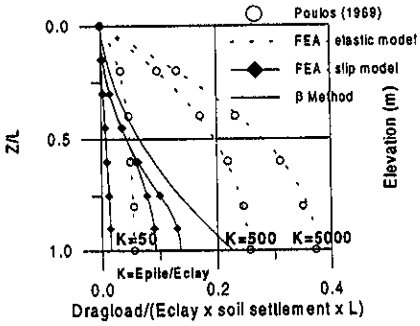

Fig. 2. The comparison for the elastic solution

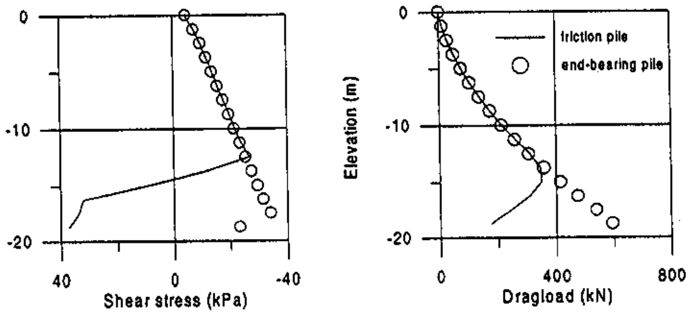

Fig. 3. The development of dragload for a friction pile and end-bearing pile
(E=5000kPa, surface loading = 50kPa, interface friction = 0.3)

3.3 Effect of soil yielding

The development of the negative shear stress is heavily dependent on the friction coefficient and surface loading as shown in Figure 4. When the friction coefficient is small (μ=0.2) the slip length is increased and vice-versa. The distribution of shear stress is linear as the simple effective model (β method) predicts. Partial mobilisation of skin friction near the NP is observed as discussed in Section 3.2. From a continuum approach (μ=∞), where the compatibility relation is valid even with the very large shear strain, large shear stresses occur, which are larger than the shear stresses predicted by the β method (β = 0.2 and 0.3). The shear stress predicted by the β method will be over-estimated since maximum shear stress is assumed for the entire length of the pile and partial mobilisation of skin friction near the NP cannot be included. Hence larger dragload will be developed based on the continuum approach and β method. The effect of surface loading is also shown in Figure 4. When surface loading is small (10kPa), the slip length is less, developing less dragload. Under the application of large surface loading (100kPa), slip is developed for the almost entire pile length. Overall more slip will be developed when μ is small and surface loading is larger and vice versa. Therefore, it could be said that the development of the negative shear stress is heavily dependent on the slip, which is mainly governed by the interface friction angle and the surface loading.

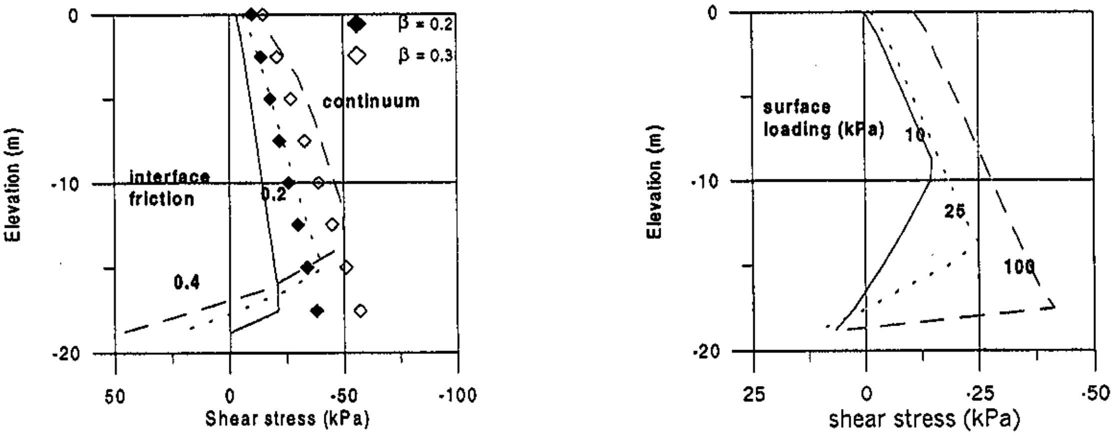

Fig. 4. The development of NSF depending on slip. (E=5000kPa)

4. Discussion for Piles in a Group

4.1 Elastic solution

Figure 5 presents the development of dragload in pile groups of 5x5 piles with spacing of 5D from FEA based on an elastic model together with an elastic solution presented by Kuwabara [13] (refer to 1,2,3 in Figure 6). The trends of the distributions of dragload are very similar although the solutions from Kuwabara [13] present smaller dragloads, particularly at the pile toes a discrepancy also observed by Chow [14]. However this small dragload, which is only 10 ~ 50% of that of the single pile, is not supported by previous observations with similar pile configurations [9, 19]. Normally small group effects have been reported with the pile spacing of 5.0D by Jeong [8]. Figure 5 also presents the elastoplastic analysis including slip. Relatively small reductions of the dragload (40 ~ 70% of the single pile) for piles in a group are observed.

4.2 Development of group effect

Figure 6 shows the distributions of shear stress and dragload for piles in a group. When slip is developed similar shear stress is developed for the upper part of the pile. But as soil slip is not developed for the middle and lower part of the pile due to the pile-soil-pile interaction, less shear stress is developed as discussed in Section 3.2 and hence less dragload will be obtained. This phenomenon is more noticeable for the central part of the pile in which the slip length is only 35% of that of a single isolated pile. Therefore the dragload for the central pile is only 25% that of the single pile; thereby a group effect of 75% is obtained. In this work the group effect is defined as the ratio of ($\text{dragload}_{\text{single pile}}$ - $\text{dragload}_{\text{piles in a group}}$) over $\text{dragload}_{\text{single pile}}$. Also similar observations are shown for the side and corner piles with the increase of slip length and little group effect. Therefore, the group effect is mainly dependent on the slip length.

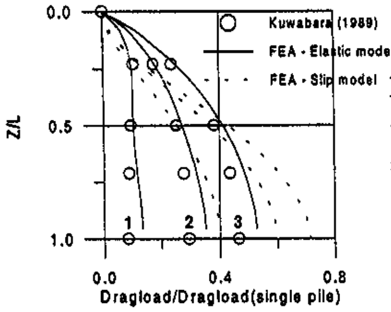

Fig. 5. The comparison of dragload (Spacing = 5.0D, E=20000kPa)

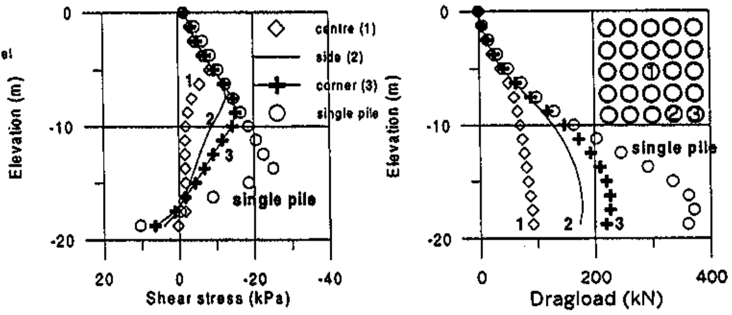

Fig. 6. The development of the group effect (Spacing = 2.5D, E=5000kPa, interface friction = 0.3, surface loading = 25kPa))

4.3 Consideration of various factors (3x3 and 5x5 pile group)

Figures 7 and 8 show the change of group effect considering interface friction angle (μ), configuration of pile groups, relative position of piles in a group, pile spacing and surface loading respectively. Group effects are gradually reduced when surface loading is increased because the slip length is increased (Figure 7). Larger group effect is observed with the increase of the interface friction angle because slip is prevented (Figure 8). Also, more group effects are observed for 25 piles in 5x5 than 9 piles in 3x3. The maximum group effect is observed for central piles, whereas minimum group effect is developed for corner piles. Relatively small group effects are observed when wide spacing (5.0D) is considered. In ordinary situations, where μ is 0.3 ~ 0.4 and surface loading is 50 ~ 100kPa, the maximum group effects of 10 ~ 40 % and 30 ~70 % will be observed for piles in 3x3 and 5x5 piles in 2.5D spacing respectively. Smaller group effects will be obtained when larger pile spacing is considered. Table 2 summarises various factors influencing the group effect.

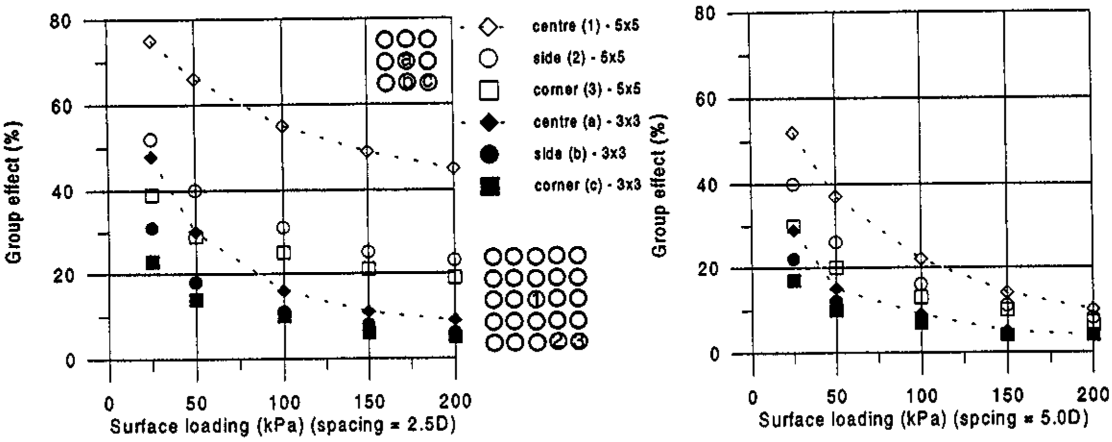

Fig. 7. The development of group effect (E=5000kPa, interface friction=0.3)

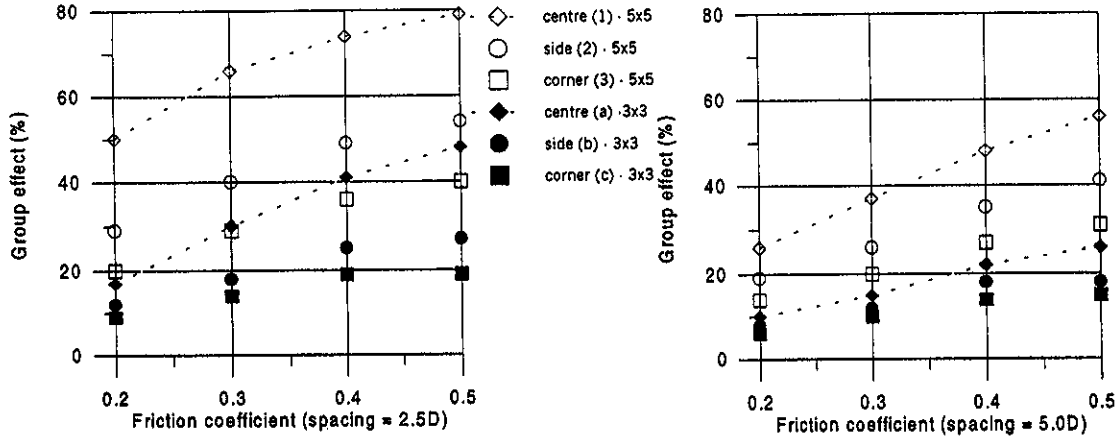

Fig. 8. The development of group effect (E=5000kPa, surface loading = 50kPa)

Table 2 Change of group effect due to various factors

	Pile spacing		Pile number		Interface friction				Surface loading	
					Pile type		Installation method			
	close	wide	more	less	concrete	steel	driven pile	bored pile	small	large
Group effect	more	less	more	less	more	less	more	less	more	less

5. Comparisons from Previous Observation

A comparison is made between predicted and observed dragload for single piles and group effects for piles in a group. Since detailed information regarding soil properties, stress history and interface friction angle is not provided for some cases, assumptions have been made considering typical soil properties.

5.1 Phamvan [1]

Phamvam [1] reported the development of dragload due to embankment loading. A single isolated pile is considered in this study. After construction of a 2m embankment, a pile is driven into soft and stiff clay. No residual stress is observed along the pile after driving [15]. Detailed soil properties, stress history and interface friction angle are provided based on critical state soil mechanics. Therefore, in this analysis the Modified Cam Clay model is used for clay. Figure 9 shows the distribution of dragload from observation and numerical analyses. As mentioned in Section 3.3, over-estimation of dragload is observed from the continuum analysis and the β method taking average of $\beta = 0.2$ which is measured from the field. For the β method better prediction might be obtained if partial mobilisation of NSF and PSF near the NP is considered. Good agreement is obtained when soil slip is included although position of the NP is slightly above the measured NP.

5.2 Lee [3]

Lee [3] presents measurements of dragload in a model pile from a centrifuge test. Soil properties and stress history of the soil are presented. The mechanism for the development of dragload is composed of two parts. Firstly, little amount of dragload is developed due to increase of self-weight of the test package from the change of gravity from 1*g* to 50*g*. Then after some time for consolidation, effective vertical stress is increased roughly by 65kPa due to de-watering. In the FE simulation the vertical effective stress is increased to 65kPa. Overall reasonable prediction of dragload is obtained from the slip model in Figure 10. Although the pile was intended to have a fixed base, a pile movement of 1.5mm was observed in the centrifuge test. Therefore, maximum dragload was developed at 85% of the pile length. Little positive skin friction was observed near the pile tip. In numerical analysis the model pile is assumed to be end bearing resting on a rigid base. Therefore, if some amount of pile movement is permitted assuming a fictitious soil layer below the pile tip, a better prediction of the distribution of dragload would be expected as shown in Figure 10 by the dotted line.

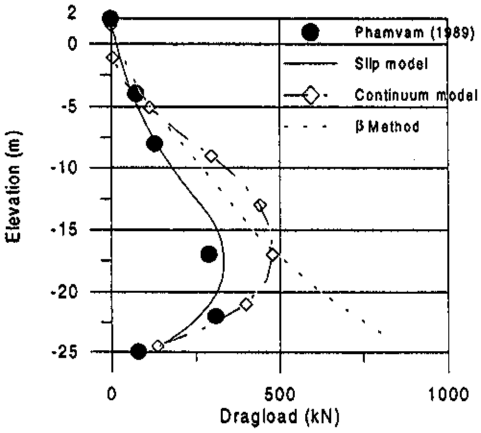

Fig. 9. The comparison of the development of dragload

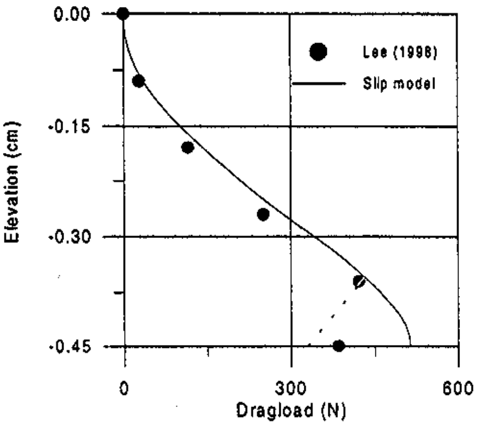

Fig. 10. The comparison of the development of dragload

5.3 Little [2]

Little [2] presented the development of dragload for two groups of nine piles (3x3) with spacing of 4.0D. The friction piles and the end-bearing piles are considered respectively. An embankment loading of 40kPa was applied after driving the piles. A soil modulus of E=3500kPa is assumed which gives similar ground settlement and $\mu = 0.35$ is used, which is a typical interface friction value for a driven pile. Table 3 presents normalised group effects ($\text{dragload}_{\text{central pile}}/\text{dragload}_{\text{corner pile}}$) between a central pile and a corner pile since dragload for a single pile is not given. Group effects are interpolated from the results of the FEA as discussed in sec 4.3. In order to predict dragload for a central pile based on Jeong's and Shibata's methods, observed dragload for a single pile is assumed as 250~300kN and 300~350kN for a friction pile and a bearing pile respectively. Large group effect and hence small dragload for the central piles are predicted from a continuum approach interpolated from Jeong [8]. Also the predictions from Briaud [7] and Shibata [11] under-estimate dragload for a central pile. A small group effect is obtained from a slip approach, which is reasonably matched with the observations. However slightly larger dragload is estimated for the central piles. The group effects predicted by Broms [6] were found to be unrealistic and therefore are not included.

Table 3 Predictions of the group effects

	Observed [2]	Predictions by various methods			
		Jeóng [8]	Briaud [7]	Shibata [11]	Current work
Dragload for central pile (kN)	friction - 187 bearing - 202	friction - 90~108 bearing - 108~126	106	Friction -130~156 bearing - 135~158	friction - 223 bearing - 311
Normalised Group effect(%)	friction - 86 bearing - 82	49	friction-57~71 bearing-40~47	friction - 76 bearing - 74	85

5.4 Shibata [11]

Shibata [11] carried out laboratory tests for piles in a group. In his tests the pile group consisted of 3x3 piles with spacing of 2.5D. A surface loading of 20kPa was applied. The piles are assumed to be end-bearing piles. An E of 150kPa is assumed from the consideration of soil settlement. A group effect of 13-28% is obtained from the tests. Table 4 summarises the group effects and dragload from the various methods. Larger group effects and hence very small dragload for the central pile are obtained based on the continuum approach by Jeong [8] and the method by Briaud [7]. Analyses from current work and Shibata [11] provide better prediction of the group effects and dragload for the central pile.

Table 4 Predictions of the group effects

	Observed [11]	Predictions by various methods			
		Jeong [8]	Briaud [7]	Shibata [11]	Current work
Dragload for central pile (N)	294	62	45	242	297
Group effect (%) (centre, side, corner) refer to a,b,c in Figure 7	28,15,13	85,60,50	89,50,25	41,33,26	15,10,7

6. Conclusion

1. When the possibility of NSF is considered for piles in soft ground, dragload (compressive force) is normally not a major problem. Downdrag (pile settlement) will present some difficulties from the viewpoint of serviceability of the pile foundation. Therefore, piles should be installed as deep as possible to a stiff layer in order to reduce downdrag, considering driveability and dragload. In this sense, floating (friction) piles should be used with great care.

2. The development of dragload and group effects is heavily dependent on soil yielding and slipping at the interface, which is governed by surface loading, pile spacing and interface friction. Therefore, various factors such as the relative position of piles within the group, the amount of soil settlement, the number of piles and the pile type should be included.

3. Estimation of dragload and group effects based on current design practice is neither satisfactory nor realistic. Dragload is normally over-estimated from empirical methods and elastic and continuum analyses. Also, over-estimation of group effects for piles in a group is observed. In reality, however, less dragload and less reduction of the dragload for piles in pile groups have been reported from the field observations. Current analyses are compared to elastic solutions and previous observations from the field. Reasonable agreement was obtained. Normally reduction of dragload due to group effect is found to be 10~40% and 30~70% for typical situation for 3x3 and 5x5 group respectively from the current analyses. These amounts of group effect are significantly smaller than current design guidelines. Hence, it is necessary to re-consider current design approach.

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