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Slip Effect at the Pile-soil Interface on Dragload

하향력을 받는 말뚝-지반 접촉면의 슬립 효과

Jeong, Sang-Seom*1 정 상 섬
Lee, Cheol-Ju*2 이 철 주

요 지

본 연구에서는 말뚝이 근입된 연약지반의 탄소성 해석을 수행하여 말뚝에 작용하는 하향력을 산정하였다. 이때 단독말뚝과 군말뚝(3×3, 5×5)을 대상으로 각각 2차원과 3차원 유한요소해석을, 말뚝주면에서 slip의 유무에 따라 수행하여 그 영향정도를 파악하였다. 하향력의 발생정도는 말뚝주면에서의 마찰계수, 지표면과 말뚝두부에 작용하는 상재하중에 큰 영향을 받는다. 이와 같은 영향인자를 토대로 수치해석 결과, 하향력은 no-slip의 경우가 slip의 경우에 비해서 상당히 과대하게 산정되었으며, 또한 말뚝두부에 하중이 증가함에 따라 하향력은 감소하는 것을 알 수 있었다. 한편 그룹효과가 있는 군말뚝의 하향력은 단독말뚝의 하향력에 비해서 크게 감소 하는 것으로 나타났으며, 수치 및 사례분석을 통해 slip 해석의 적절함을 확인하였다.

Abstract

The dragload on pile groups in consolidating ground was investigated based on a numerical analysis. The case of a single pile and subsequently the response of groups were analyzed by 2D and 3D finite element studies. Conventional continuum elements and special slip elements were used in the analyses for comparison. Based on a limited parametric study, it is shown that dragload for a single pile and group effect are normally overestimated by continuum analyses, compared with the predictions by the slip analyses. The group effect was examined from the slip analysis by considering various factors such as pile configurations, surface loading, interface friction coefficient, and axial loading on piles. An examplary analysis and one previous experimental observation of dragload and group effects were back-analysed. The case histories demonstrated that the slip analysis might predict a better estimate of dragload and group effect compared to the no-slip continuum analysis.

Keywords : Continuum analysis, Dragload, Group effect, Numerical analysis, Pile groups, Slip analysis, Slip effect

1. Introduction

During the settlement of the consolidating soil layer, the shear stresses close to the pile shaft are mobilized when the relative movement between the soil and the pile is generally large. Therefore, some of the weight of the surrounding soil causes additional compressive load (dragload) on the pile shaft and excessive pile settlement (downdrag). In this situation, the developed shear stresses along the pile-soil interface act generally downward and are called the negative skin friction (NSF).

*1 Member, Associate Prof., Dept. of Civil Engrg., Yonsei Univ. (soj9081@yonsei.ac.kr)
*2 Member, Postdoctor, The Hong Kong Univ. of Science and Technology. (cjl0725@hotmail.com)

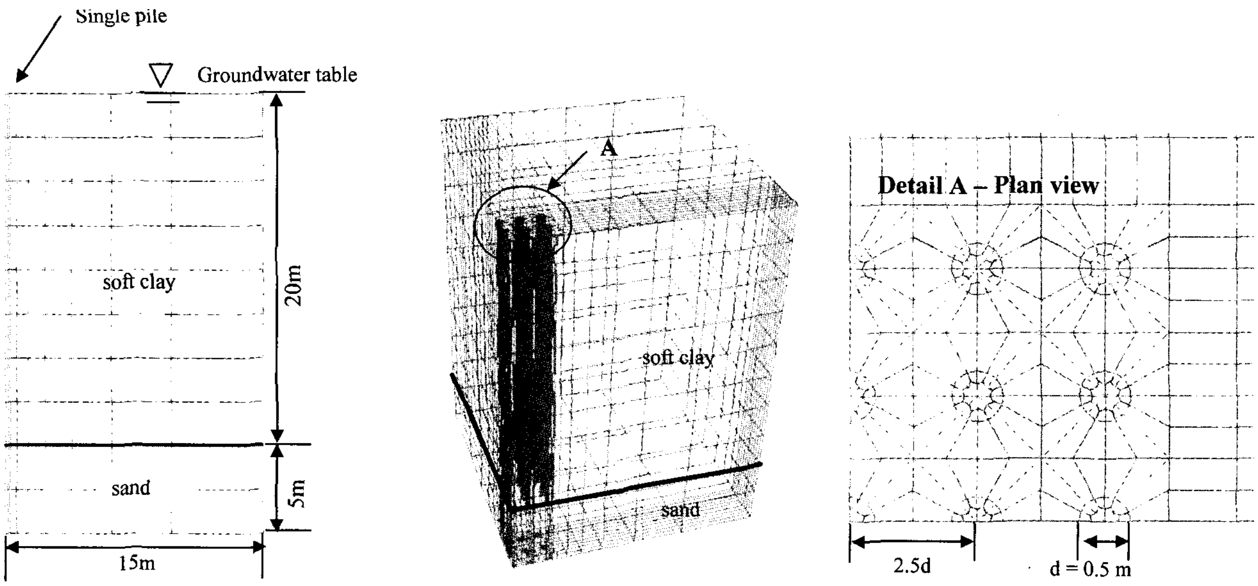
Much work has been done on the behaviour of piles in consolidating ground for the last few decades. However, to date, most of the design approaches applicable to NSF problems are still based on simplified empirical methods (Fellenius, 1998). Dragload predictions by many researchers at the Wroth Memorial Symposium varied within a range of 98-515% of the measured value(Little et al., 1993). Over-prediction (225-515%) was also reported based on the effective stress β-method, which is commonly used in engineering practice. In addition, current design approaches predict a relatively large reduction in dragload on piles in a group due to overestimation of the pile-soil interaction(Lee et al., 2002). However, this has not been supported by experimental observations, which showed relatively small reductions in dragloads for piles in groups(Denman et al., 1978; Shibata et al., 1982; Little et al., 1994; Thomas, 1998).

Since the 1970's, pile behavior in consolidating ground has been studied using a finite element method(Walker et al., 1973; Desai et al., 1978; Nishi et al., 1982; Phamvan et al., 1989; Wong et al., 1991; Jeong et al., 1997; Maugeri et al., 1997), leading to overestimation of dragload. Several researchers have included interface soil slip in the analyses since the difference in stiffness of the soil and the pile was very large and large shear strain developed at the pile-soil interface(Lee et al., 2001; Lupini et al., 1981; Francescon, 1983). However, some researchers did not permit the idea of soil sliding at the pile-soil interface (Walker et al., 1973; Jeong et al., 1997; Maugeri et al., 1997). Moreover, there are limited finite element analyses of the pile behavior in groups. Jeong(1997) proposed a very large reduction in dragload of 50 to 85% for piles in groups at 2.5D pile spacing from the 3D finite element analyses, excluding soil slip at the pile-soil interface. However, this was not proven by the aforementioned experimental observations and theoretical analyses.

In this study conventional no-slip continuum and slip analysis were performed to examine the effects of soil yielding at the pile-soil interface by using two-dimensional (2D) and three-dimensional(3D) finite element analyses. The effect of axial loading on dragload reductions was investigated. Furthermore, an examplary case analysis and one experimental observation were back-analyzed based on the numerical analyses.

2. Finite Element Model

Figs. 1(a) and 1(b) show typical 2D and 3D FE meshes used in slip analyses. Due to symmetry, only a quarter



(a) 2D mesh for a single pile (b) 3D mesh for pile groups (5×5, 2.5d)

Fig. 1. 2D mesh for a single pile and 3D mesh for pile groups

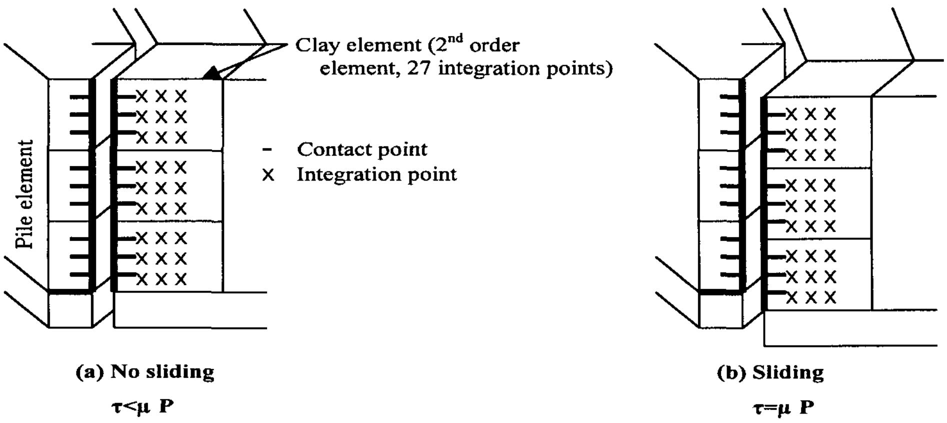


Fig. 2. Soil behavior at the interface before and after yielding

of a whole mesh was used in the 3D analyses. Lee(2001) showed that the influence zone was affected by pile in case of the slip analysis is about 5-10D, where D is the pile diameter. However, larger boundary of about 60D is allowed for the continuum analysis. A relatively fine mesh was used near the pile-soil interface and became coarser further from the pile. In this study piles were taken to be 20m in length L and 0.5m in diameter D. The piles were assumed to have been installed through soft clay with the pile tip located on a bearing layer of medium sand. The base of the mesh was assumed as bedrock overlain by 5m layer of sand. In this study the case of a single pile and subsequently the response of groups with 3×3 and 5×5 group sizes were analyzed for different pile spacings, surface loading, interface friction coefficient, and axial loadings.

The piles and the soil were modelled by eight noded 2^{nd} order quadrilateral elements for the 2D analysis and 27 noded 2^{nd} order brick elements for the 3D finite element analysis(FEA). The interface elements were composed of 2D quadratic 18-node elements, each element with two ninenode surfaces compatible with the adjacent solid elements: the two surfaces coincide initially. This model was selected in the element library of ABAQUS(1998), the commercial finite-element package used for this work. As shown in Fig. 2, the interface elements of zero thickness can transfer only shear forces across their surfaces when a compressive normal pressure (p) acts on them. When contact exists, the relationship between shear force and normal pressure is governed by a modified Coulomb's friction theory. Thus, these elements are completely defined by their geometry, a friction coefficient, μ, an elastic stiffness and a limiting displacement, γ_{crit} used to provide convergence. A critical displacement of 5 mm was assumed to mobilize maximum skin friction, typical of field measurements reported by Broms(1979). Table 1 summarizes the material parameters used in the analyses. An isotropic elastic model was used for the pile and a non-associated Mohr-Coulomb model was used for the clay and sand. Same value of Poisson's ratio(0.3) was used for the pile and clay, though material property of pile is different from surrounding clay. For clay the internal angle of friction ϕ' was set at 20°, typical of a critical state angle

Table 1. Typical material parameters used in the analyses

material	model	E (MPa)	c (kPa)	ν	ϕ_c(°)	Ψ(°)	K_o	γ_t (kN/m^3)
pile	isotropic elastic	12500	.	0.3	.	.	0.01	25
clay	Mohr-Coulomb	5	3	0.3	20	0.1	0.65	18
bearing Sand		50	0.1	0.3	35	10	0.5	20

Notes: 1. Ground water table is located on the top of the soft clay layer.
2. Hydrostatic water pressure distribution is assumed

ϕ_c' with the very small dilation angle Ψ since large shear deformation developed at the interface. For the bearing sand layer the peak internal angle of friction was set at 45° with a dilation angle Ψ of 10° consistent with the critical state angle ϕ_c' being about 35°.

For continuum analysis, where the nodal compatibility condition is always satisfied, soil elements of 100-250 mm thickness were used next to the pile depending on convergence performance, which is similar to what Jeong(1997) used in his continuum analysis. Two sets of interface surface(i.e. pile side and pile toe) have been specified at the pile-soil interface for the slip analysis. It was reported that typical β-values for soft clay are in the range of 0.15 ~ 0.25(Lee et al., 2001). By considering a typical earth pressure coefficient at rest (K_o of normally consolidated clay: 0.5 ~ 0.7), the interface friction coefficient, μ, (μ = tan(δ)), would be in the range of 0. 2 ~ 0.5 based on Eqs. (1).

$$\mu = \tan(\delta) = \beta / K_o \tag{1}$$

In addition, interface friction angle δ can be estimated using Eqs (2) based on Randolph and Wroth (1981).

$$\delta = \tan^{-1}(\sin\phi' \times \cos\phi' / (1 + \sin^2\phi')) \tag{2}$$

For a soil friction angle ϕ' of 15°-30°, the interface friction angle δ would be 13.2° ~ 19.1°. Therefore, interface friction coefficients μ of 0.235 ~ 0.346 are obtained from Eq. (1). Thus, in this study interface friction coefficients μ of 0.2~0.4 were adopted. Shear displacement of 5 mm between pile-soil interface was assumed for full mobilization of the skin friction.

Since modeling of the entire pile installation process is rather complicated(Baguelin et al., 1982), the pile is assumed to be in a stress-free state at the start of the analysis, and hence the stress change in the soil during pile installation is not included. A surface loading was simulated by the application of a uniform vertical load on the top of the clay surface after initial equilibrium stage. The increased vertical stress leads to soil settlement and hence the NSF.

On completion of the analysis, the normal stress and shear stress components at the interface element (slip analysis) and soil elements next to the pile(continuum elements) were considered in the post-analysis. In the estimation of dragload, the shear stress at the contact points was considered in the slip analyses, whereas in the continuum analysis it was considered at the integration points inside the soil element next to pile, as shown in Fig. 2. To check the validity of these analyses, the dragload was calculated from the summation of the shear stress along the pile-soil interface and the summation of the vertical stress in the pile element (Eqs. 3).

$$Dragload = \pi r^2 \sigma_v \tag{3}$$

where, r = pile radius, σ_v = vertical stress in the pile element.

Generally, very close results were obtained from both equations in the slip analyses. So, in this study, the dragload was calculated from Eqs. (3). A smaller dragload was calculated based on the continuum analyses since shear stress was at the integration points inside the element, not at interface.

3. Single Pile Behavior

3.1 Effect of Soil Slip at the Interface

Figs. 3(a) and 3(b) show changes of shear stress and dragload based on the different analysis conditions. Predictions from the β-method are also included. The development of the shear stress is heavily dependent on the interface friction coefficient. When the interface friction coefficient is small (μ=0.2), the slip length increases and vice-versa. The slip length is defined as the distance from the pile head to the point where partial mobilization of the shear strength begins. The distribution of shear stress is nearly linear as the β-method predicts. However, partial mobilization of the shear stress near the neutral plane is observed due to small relative displacement between the pile-soil.

The shear stress predicted by the β-method was also overestimated since maximum shear stress was assumed for the entire length of the pile, partial mobilization of

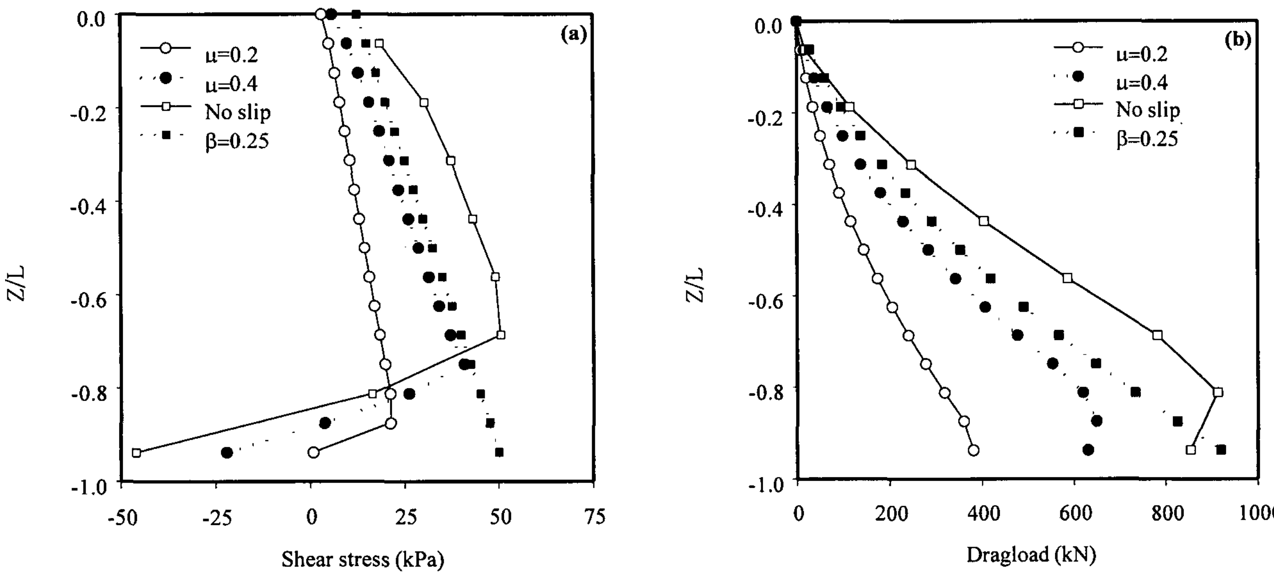


Fig. 3. Effects of interface friction coefficient on (a) shear stress, (b) dragload

skin friction near the neutral plane and reduction of the vertical stress at the pile-soil interface cannot be included (Lee et al., 2001). Hence larger dragload was predicted based on the no-slip analysis and β-method.

3.2 Continuum and Slip Analysis

In order to clarify the difference between slip analysis and continuum analysis for piles in consolidating ground, a simple example case reported by Jeong(1992) is discussed here. Geometry, soil parameters and boundary conditions of a single isolated end-bearing pile are shown in Fig. 4. The pile with a rectangular shape of 0.6×0.6m is 30m in length and a surface loading Δp of 250kPa is applied to the surface of soft clay layer. A rigid boundary condition is assumed for the bearing layer. In the original FEA, a friction angle of 25° and a cohesion of 3 kPa were used based on the Drucker-Prager soil model.

However, in this analysis a circular pile with same sectional area has been adopted in 2D axisymmetrical condition and a non-associated Mohr-Coulomb model was used for the clay. Since the interface friction coefficient μ was not considered by Jeong(1992), it was estimated as a value less than the soil friction angle (i.e. μ = tan (25°) = 0.466). Therefore, in these analyses lower interface friction coefficients of 0.3 and 0.4 were used.

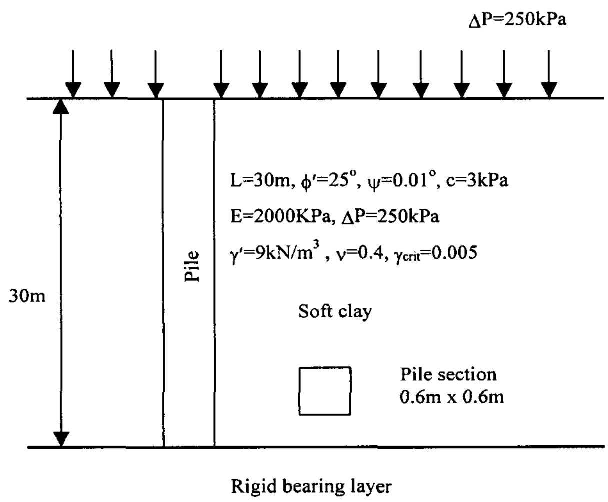


Fig. 4. Configuration of an example by Jeong(1992)

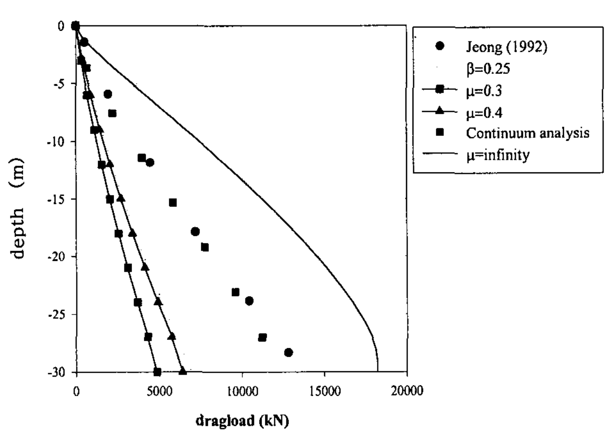


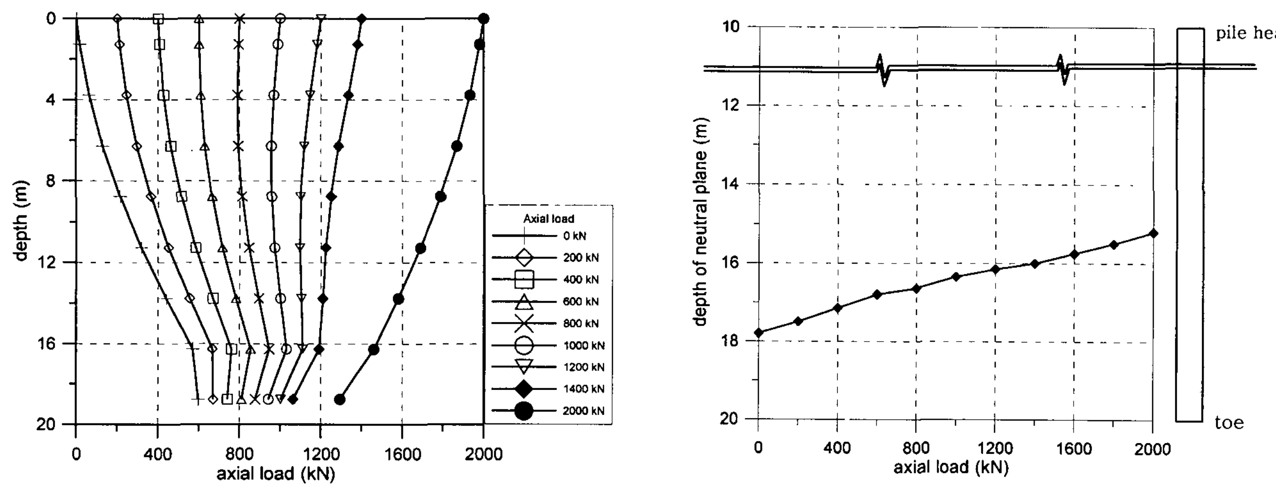
Fig. 5. Dragload distribution computed by various methods

Fig. 5 demonstrates dragload distributions predicted by the various approaches. In this study, the slip model (μ = 0.3, 0.4) and the β-method (β = 0.25) were used together with continuum analysis and compared to previous predictions by Jeong(1992). Based on the continuum analysis(Jeong et al., 1992), a very large dragload of about 12821kN was obtained. From the slip analysis dragloads of 4857 and 6412kN were obtained with μ=0.3 and 0.4. This figure also shows the prediction from the current continuum analysis taking account of the central integration points of soil elements next to the pile. A very close correlation was observed (11748kN) since Jeong(1992) also considered only central integration points (12821kN). From the calculation based on the β-method a dragload of 6930kN was obtained, which is slightly larger than the slip analysis. Compared to the calculation based on the β-method, the continuum analyses over-predict NSF by about 200%. Since the surface loading was very large (250kPa) and the soil was very soft (E = 2000kPa), soil slip is likely to develop over the entire pile length. Therefore, it is not surprising that the result from the continuum analysis was not appropriate for such a large strain problem. In the absence of soil slip, excessive dragload was computed to have occurred and hence it was found that the increase in horizontal stress due to surface loading was excessively large, thereby leading to a very large shear stress. Furthermore, the results from the continuum analysis depended on the position of integration point considered and thickness of soil element next to the pile.

3.3 Effects of Axial Loading on Dragload

When axial loading was applied on the pile head, several researchers reported the reduction in dragload based on the field measurement(Fellenius, 1998) and a numerical analysis(Indraratma et al., 1992). To clarify the effect of axial loading on dragload, the axial loading was applied on the pile top after full development of dragload. Fig. 6(a) shows the load-transfer characteristics of a pile and demonstrates the reductions in dragload with gradual increase of axial loads. Assuming maximum pile capacity is 3000kN using β = 0.25, beyond the working load level (about 1000 kN) only positive skin friction is mobilized along the pile. This is because the dragload and the axial load combined increase the pile settlement relative to the soil and consequently, change the location of the neutral plane.

It is to be noted in the Fig. 6(b) that the position of neutral plane is changing toward the pile head with increasing the same axial loads, as shown in Fig. 6(a). Therefore, to determine the location of the neutral plane, an analysis of the load distribution in the pile must first be performed. From this analysis illustrated in Figs. 6(a)



(a) Effect of axial load on dragloads

(b) Effect of axial loading on neutral plane

Fig. 6. Effect of axial load on dragload and neutral plane (E=5MPa, △p=50 kPa, μ=0.35)

and 6(b), a reduction of the dragload on the pile results in a lowering of the location of the neutral plane but has a proportionally smaller effect on the magnitude of the maximum load in the pile.

4. Behavior of Pile Groups

4.1 Development of Group Effect

Major parameters influencing the group effect are the pile spacing, pile group configuration, relative position of piles in a group, surface loading, interface friction coefficient, and axial loading on a pile(Lee et al., 2002). In this study, group effects are defined as the ratio of (maximum $\text{dragload}_{\text{single pile}}$ - maximum $\text{dragload}_{\text{piles in a group}}$) over maximum $\text{dragload}_{\text{single pile}}$.

Group effects gradually reduce as surface loading increases, because of an increase in slip length. Larger group effects were observed with an increase in the interface friction coefficient μ that reduces soil slip. The maximum group effect was observed on central piles, whereas the minimum group effect developed on corner piles. Relatively small group effects were observed for groups with a wider spacing (5.0D). These group effects by the slip analysis are substantially smaller than that proposed by Jeong et al.(1997), which is governed only by pile spacing and pile position and the slip analysis leads to unsafe dragload estimation for piles. Therefore, it is shown that once soil slip develops, extremely small soil settlement is computed inside the pile group, leading to small dragload(Lee et al., 2002).

4.2 Effects of Axial Loading on Dragload

Of all parameters influencing the group effect, less is known about the effect of axial loading on the dragload changes in piles in a group. For simplicity, in this study, same magnitude of the axial loading was applied on each pile head like a single pile. The capacity of the individual piles was assumed to be the same as that of the single pile.

The positions of the piles with spacings of 2.5D and 5.0D are shown in Fig. 7. The piles are modeled as free-headed piles in a group, which can be considered as similar to piles in a flexible pile cap. It is assumed that piles are not connected to each other, so that each pile can respond separately in response to dragload and axial load and in accordance with its magnitude.

As shown in Fig. 8, the magnitude of dragload is clearly related to the applied axial load and thus represents a significant reduction in dragload with increasing axial load, although the distributions in each pile show generally similar shapes in all cases. This figure also shows the effect of pile spacing and pile location within the group on the dragload profiles. For a center spacing-to-diameter ratio of 2.5 there is a group effect. For a ratio of 5.0, there is little difference in dragload between the corner pile, the side and center pile subjected to axial loading.

Table 2 presents the influence of axial load on the group effect for group configuration, relative position of piles in a group, and pile spacing. There is a group effect

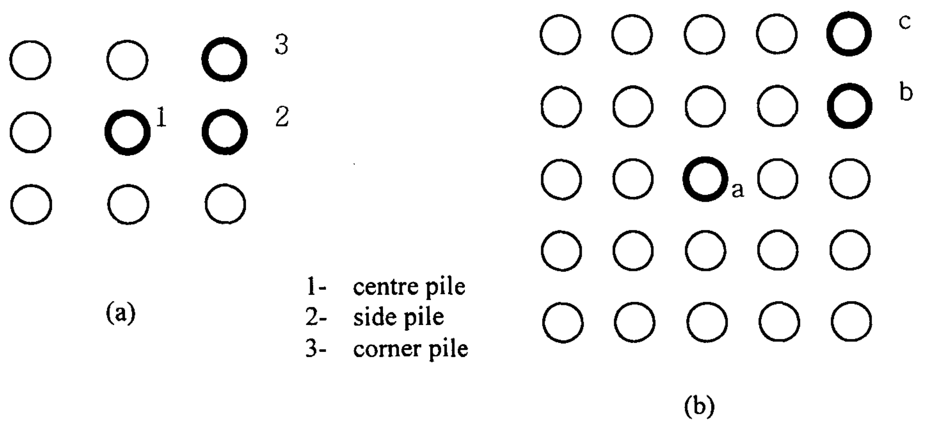
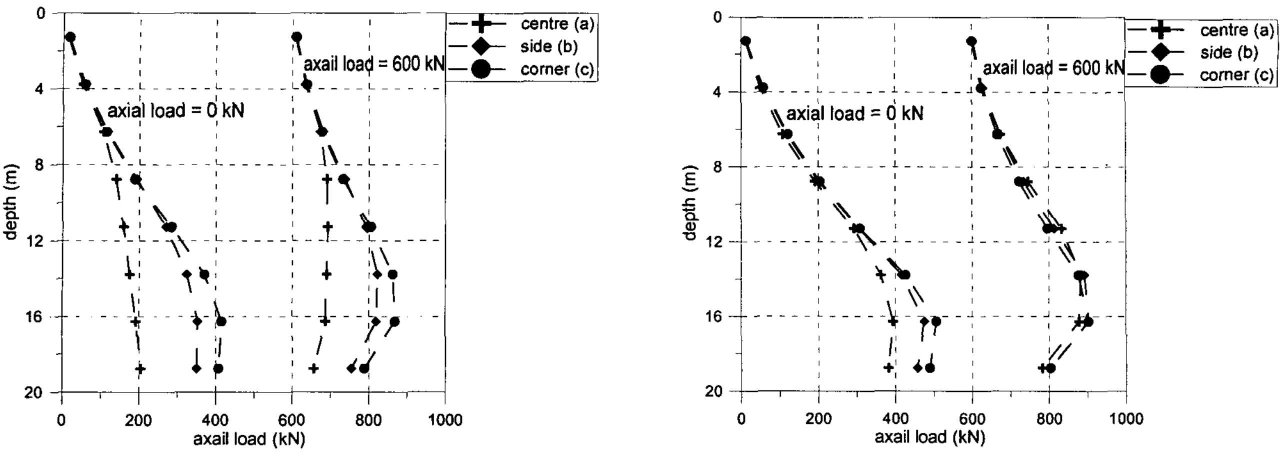


Fig. 7. The position of piles in a group: (a) 3×3 piles; (b) 5×5 piles



(a) s = 2.5D (b) s = 5.0D

Fig. 8. Effect of axial loading on pile groups (5×5)
(E=5MPa, △p=50 kPa, μ=0.35)

Table 2. Change of group effect due to axial loads

group effect: %, △p=50 kPa, μ=0.35							
axial loading	pile spacing	3×3			5×5		
		position of piles*					
		1	2	3	a	b	c
0 kN	2.5D	37.2	25.5	18.7	64.3	38.3	27.3
200 kN		25.4	16.7	11.0	46.6	24.2	15.5
400 kN		15.9	8.7	4.0	31.1	12.8	5.4
600 kN		7.7	2.8	-	19.1	3.8	-
800 kN		0.5	-	-	7.8	-	-
0 kN	5.0D	14.5	9.9	7.5	31.1	16.8	11.3
200 kN		7.1	3.8	2.6	17.7	7.5	4.3
400 kN		0.1	-	-	6.0	-	-

Note: * see Fig. 7 for position of the piles.
- no more group effect was identified.

and therefore a reduction in dragloads for the two spacings studied and for a group size up to 5×5. Group effect is more significant for the 5×5 group than the 3×3 group. The maximum group effect was observed on central piles, whereas the minimum group effect developed on corner piles. Relatively small group effects were observed for groups with a wider spacing (5.0D). The reason for reduction in dragload is that as the axial loading on piles increases, the average shear stress and slip length along the pile shaft tend to increase. The settlement of the pile group also increases. In a situation where the axial loading increases from zero to 600 kN, group effects of 30~19 % and 45~27% decreased for the 3×3 and 5×5 pile groups respectively, each with an internal spacing of 2.5D.

5. Comparison With Previous Observation

Comparison is performed between computed and observed dragloads for single piles and group effects for piles in a group from the experimental tests. Since appropriate material parameters are not available, best assumptions were made. A Mohr Coulomb model has been used for soil and an elastic model is used for pile.

Shibata et al.(1982) carried out laboratory tests for a single pile and piles in a group. The instrumented model piles had a diameter D of 0.06m and a length L of 0.7m. The pile group consisted of 3×3 piles at a spacing S

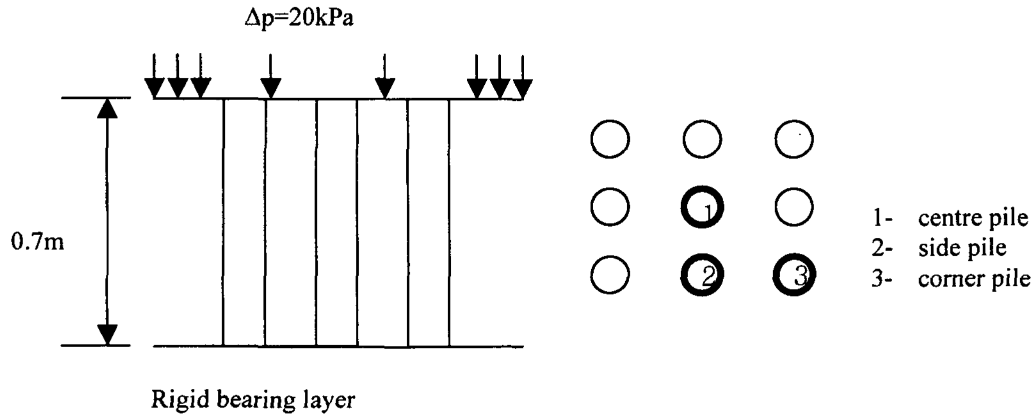


Fig. 9. Configuration of a pile group reported by shibata et al.(1982)

Table 3. Comparison of the dragloads and group effects [5]

	measured	predictions by various methods			
		Jeong(1992)	Briaud et al.(1991)	Shibata et al.(1982)	Present study
dragload for the central pile (N)	294	62	45	242	297
group effect (%) (center, side, corner)	28, 15, 13	85, 60, 50	89, 50, 25	41, 33, 26	15, 10, 7

of 2.5D as shown in Fig. 9. The piles were assumed to be end-bearing. The model clay was formed from a kaolin slurry under self-weight consolidation. A surface loading of 20kPa was applied on the top of the clay surface to produce soil settlement after completion of the self-weight consolidation. In this research, a soil modulus E of 150kPa was assumed from the consideration of measured soil settlement (65mm). An average interface friction value β of 0.18 was provided by Shibata et al.(1982). Assuming a K_o value of 0.5～0.7 for normally consolidated clay, a rough estimate of interface friction coefficient μ of 0.26～0.36 was obtained based on Eqs. (1), and hence an interface friction coefficient of 0.3 was used in the analysis. Due to convergence problem, which was associated with a very large shear strain level, continuum analysis could not be carried out and hence only slip analyses were performed for a single pile and pile group.

Table 3 summarizes dragload for the central pile and the group effects found from the slip analysis and other methods. Shibata et al. (1982) reported group effects of 13～28% for piles in a group, depending on the position of the piles. From the slip analysis, a group effect of 7～15% was computed, which is slightly smaller than measured. However, very large group effects of 50~85% were obtained from the continuum analysis reported by Jeong et al.(1997). In addition, large group effects of 25～89% are predicted by Briaud et al.(1991). The current FEA and Shibata et al.(1982) offer a reasonable prediction of the group effect. It is clearly shown that group effects are not as large as predicted by continuum analysis.

6. Discussions and Concusions

A series of 2D and 3D finite element analyses (FEA) were performed to investigate the effect of soil yielding at the pile-soil interface on pile groups in consolidating ground. The main characteristic of these analyses was to consider soil slip at the pile-soil interface using a special type of interface element. The significance of including soil slip at the pile-soil interface was shown from the study of a single pile. A much larger dragload was predicted by continuum analyses, where slip was not included. It has been shown that continuum analysis could not present reasonable estimation of the skin friction at the pile-soil interface due to large shear strain level. In addition, its result depends on thickness of the soil element next to the pile and position of integration points under consideration. In an examplary case history, it has been demonstrated that the simple β-method may predict better estimate compared to the continuum analysis.

The effect of axial load demonstrates the reductions in dragload with gradual increase of axial load which was applied on the pile head after full development of dragload. The combined dragload and the axial load increase the pile settlement relative to the soil and, consequently, change the location of the neutral plane. Therefore, to determine the location of the neutral plane, an analysis of the load distribution in the pile must first be performed. From this analysis, a reduction of the dragload on the pile results in a lowering of the location of the neutral plane but has a proportionally smaller effect on the magnitude of the maximum load in the pile.

Piles in a group were also simulated in 3D FEA taking into account various variables such as interface friction angle, surface loading, soil modulus and pile configuration. Relatively small group effects, which were smaller than those predicted from continuum analysis, were obtained. The computed group effects described here are significantly smaller than that from the continuum analysis. Numerical back-analysis of previous experimental observations agreed well with the slip analysis. Experimental observations confirm that more realistic interface and yielding behavior must be introduced if analyses are to be accurate.

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