Analysis of skin friction in prebored and precast piles

Sangseom Jeong i), Gyoungja Jung ii), Dohyun Kim iii) and Jongjeon Park iv)

i) Professor, Department of Civil Engineering, Yonsei University, 50 Yonsei-ro, Seoul, Republic of Korea
ii) Senior researcher, Korea Expressway Corporation, 922 Dongbudae-ro, Hwasung, Republic of Korea
iii) Ph.D Student, Department of Civil Engineering, Yonsei University, 50 Yonsei-ro, Seoul, Republic of Korea
iv) Msc Student, Department of Civil Engineering, Yonsei University, 50 Yonsei-ro, Seoul, Republic of Korea

ABSTRACT

Skin friction may be one of the most critical factors in designing the prebored and precast pile. Special attention was given to the interface behavior of pile-cement milk-surrounding soil during the installation of prebored and precast pile. The case of single pile was analyzed through a three-dimensional finite approach. It is shown that the settlement of the pile is increased as the friction coefficient between the cement milk and soil is decreased. A parametric study on the effect of thickness of the cement milk and water-cement ratio of the cement milk filling the prebored hole, on pile settlement was also conducted. Based on this, it is found that, as the thickness of the cement milk and the water-cement ratio decreased, the settlement of the pile is decreased. It is also found that the reduction in settlement is much less favorable for a skin friction pile than for an end bearing pile.

Keywords: prebored and precast pile, interface, water-cement ratio, friction coefficient, pile settlement, 3D FE analysis

1 INTRODUCTION

The nuisance caused by construction, such as noise, dust and vibration, has become a big social issue. For this reason, pile installment near existing structures or in urban areas has become severely difficult. To deal with this situations, the use of prebored and precast piles are rapidly increasing. After the prebored and precast piles are set in place, cement milk is poured in to the borehole. For this reason, interface shear stresses are mobilized between the pile-cement milk interface. Numerous studies have been conducted on the effect of friction between the pile-soil, pile-cement milk interface. Numerous studies have been carried out to investigate the effect of friction between sand-steel and sand-cement milk, and found that the major factor of the tangential displacement of the pile under monotonic and repeated loading, and suggested the maximum coefficient of friction between dry sand and steel is dependent on the surface roughness and the mean particle diameter of the sand (Uesugi and Kishida, 1986; Uesugi et al., 1989; Uesugi et al., 1990). Lim et al. (2002) found in his study that the density of the sand was a major influence factor of the skin friction of prebored and precast piles. Park (2004) suggested that after the casted concrete milk was hardened, the ultimate unit friction coefficient of the prebored and precast piles increased 700%, and the ratio of the skin friction capacity on the total bearing capacity increased over 400%. Hong et al. (2008) studied the behaviour of the prebored and precast piles skin friction. It was found that, the N-value, type of soil and the water-cement ratio is the major influence factor on the skin friction, and among the factors, the water-cement ratio of the cement milk filling the borehole was dominant.

The overall objective of present study was to investigate the behaviour of interface of prebored and precast piles by using the 3D finite element (FE) numerical analysis, ABAQUS. Through numerical analysis, the effect of borehole diameter, water-cement ratio, friction coefficient and the effect of end bearing condition was investigated. Based on this, the behaviour of the cement milk-soil interface will be thoroughly to suggest a formula which can predict and estimate the bearing capacity of prebored and precast piles. The properties and geometry of the pile and site was based on the actual construction site of a residence complex in Gwangju, Korea.

2 FINITE ELEMENT MODELING PROCEDURES

2.1 FE mesh and boundary conditions

A commercial finite element package, ABAQUS was used in this study. Table 1 summarizes the pile conditions and geometries, and Fig 1 and 2 show the actual 3D finite element mesh and the representative 2D FE mesh used in the analysis. Due to symmetry,
only a quarter of a whole mesh was used in the 3D analyses to save memory space. The pile and soil is modeled based on the 27-noded second-order brick elements, and a relatively fine mesh was generated near the pile-cement milk-soil interface to enhance the accuracy of the analysis, while a coarser mesh was used further from the pile. In this study, the pile was taken to be 10.5m in length (L) and 0.457m in diameter (D). It was assumed that the pile was installed through relatively soft soil with the pile tip located on a 10-m thick weathered rock bearing layer.

Table 1. Pile geometry and analysis cases.

|                  | Length (m) | Diameter (m) | Thickness (m) |
|------------------|------------|--------------|---------------|
| Pile             | 10.5       | 0.457        | 0.012         |
| Cement milk      |            |              |               |
| Thickness (mm)   | 25 / 50 / 75 / 100 / 150 |
| Water-cement Ratio |           |              |               |
| Young’s modulus (MPa) | 1,000 / 2,000 / 3,000 / 4,000 / 5,000 |
| $\mu$            | 0.1 / 0.3 / 0.4 / 0.7 / 1.0 / 1.5 |

Fig. 1. 3D finite element mesh.

Fig. 2. 2D representative mesh.

Fig. 3. Pile and cement milk thickness.

Table 2. Material parameters used in the analysis.

| Model               | $E$ (MPa) | $\nu$ | $c$ (kPa) | $\phi$ (°) | $\gamma$ (kN/m$^3$) |
|---------------------|-----------|-------|-----------|-------------|---------------------|
| Pile L.E            | 200,000   | 0.2   | -         | -           | 75                  |
| Cement Milk L.E     | 5,000     | 0.25  | -         | -           | 20                  |
| Fill M.C            | 10        | 0.30  | 0         | 25          | 17                  |
| Sedimentary Layer (SM) M.C | 20     | 0.30  | 19        | 32          | 19                  |
| Sedimentary Layer (GP) M.C | 100   | 0.30  | 0         | 33          | 20                  |
| Weathered Soil M.C  | 80        | 0.32  | 26        | 33          | 20                  |
| Weathered Rock M.C  | 250       | 0.29  | 30        | 34          | 21                  |
Interface surface, between cement milk-sand, were specified in the interface analysis. After the initial equilibrium, initial surface loading of 500kPa was applied on the top of the pile to induce pile settlement. The loading was increased by 500kPa each step till it reached the ultimate bearing capacity. The pile installed on the soil was modeled without a free head length, and the ground water table was not considered in the analysis.

2.2 Constitutive model and material parameters

Table 2 summarizes the material parameters used in the analyses. The properties of materials and the geometry of the ground condition used in this analysis is based on the construction site in Gwangju, Korea. An isotropic elastic model was used for the pile and a non-associated Mohr-Coulomb model was used for the sand and end-bearing rock bed. Dilation angles of 0.1° for the clay and for the bearing layer was used. In this study, the pile was analyzed by increasing the axial load at different cement milk thickness, water-cement ratio and interface friction coefficient. Fig 3 shows the concept of the modeled borehole, pile diameter and the thickness of the cement milk casted between the pile and soil.

2.3 Analysis process and interface modeling

Surface loading was simulated by the application of a uniform vertical surface load on the top of the pile head after the initial equilibrium stage. The interface elements were modeled, and the interface elements of zero thickness can only transfer shear forced across their surfaces when a compressive normal pressure ($p'$) acts on them (Fig 4). When contact occurs, 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 $\mu = tan(\delta)$. A limiting displacement of 5mm was assumed for full mobilization of skin friction (Jeong et al., 2004)

In the effective stress method, the unit friction ($f$) at the pile-soil interface is taken proportional to the effective overburden stress $\sigma'_v$.

$$ f = \beta \sigma'_v $$  \hspace{1cm} (1)

where, $\sigma'_v$ is the vertical effective overburden stress at the depth considered and $\beta$-values for various soil and rock conditions considered in the numerical analysis. By considering the typical earth pressure coefficient at rest ($K_0$) of 0.5, the typical $\beta$-values used in the numerical analysis were between 0.15 and 0.75, based on the soil types, density and end bearing conditions. The interface friction coefficient $\mu$ would be in the range of 0.1 to 1.5 based on the following equation:

$$ \mu = tan(\delta) = \beta/K_0 $$  \hspace{1cm} (2)

3 COMPUTED RESULTS

3.1 Effects of cement milk thickness

Numerous studies found that the density and the confinement pressure surrounding prebored and precast pile is critical to the pile settlement and the bearing capacity (Uesugi and Kishida, 1986; Uesugi et al., 1989; Lim et al., 2002, Park, 2004; Hong et al., 2008). As the prebored and precast pile is being installed, it is the cement milk which surrounds and confines the pile. It is found through numerous tests that, the cement milk has denser and stronger confinement compared to regular soils. Hence, as the thickness of the cement milk gets bigger, the denser the environment around the pile forms, providing a higher confinement on the pile. Thus, the resistance of the pile skin friction increases, leading to lesser settlement. This result can be observed through the load-settlement curve in Fig 5. As the cement milk thickness around the pile increase from 50mm to 150mm, the settlement of the pile head decrease to about 44%, and the ultimate bearing capacity increased over 500%.

Fig. 5. The effect of cement milk thickness.
3.2 Effects of water-cement ratio

Through direct shear test, the properties of the cement milk specimen obtained from the actual construction site was investigated. As the water-cement ratio increases from 60% to 70, 80 and 90%, it was found that the Young’s modulus of the specimen tends to decrease from 4,000MPa to 3,000, 2,700 and 2,500MPa respectively. Based on the Young’s modulus from the direct shear test, numerical analysis on the effect of the water-cement of the cement milk was carried out. The results showed that, as the water-cement ratio increases, the settlement of the pile head also tends to increase (Fig 6). This tendency was shown more significantly, based on the numerical analysis results with different Young’s modulus of the cement milk. As the Young’s modulus of the cement milk increase 1,000MPa to 5,000MPa, the settlement of the pile head decreases about 31% (Fig 7). These results from the numerical analysis agrees with the predated studies which also concluded that higher water-cement ratio yields more pile settlements.

3.3 Effects of friction coefficient

The effect of friction coefficient between the cement milk and the soil on the pile settlement was also investigated. The coefficient of friction was designated as an interface value between the cement milk and soil. By analyzing the numerical results, it was shown that the friction coefficient has a reverse-proportional relationship with the pile settlement (Fig 8). As the friction coefficient increases and was fully mobilized, the pile settlement decreased up to 44%. This results agrees with results based on numerous experimental results obtained from numerous literatures (Uesugi et al., 1990; Park, 2004).
3.4 Effects of end-bearing condition

The settlement and bearing capacity of the pile are changed significantly due to different end bearing conditions. Through numerical analysis, the effect of end-bearing condition were investigated (Fig 9). By comparing the results shown in Fig 10, it was shown that the friction pile condition with no end-bearing condition yielded greater pile settlement compared to the weathered rock end-bearing condition. It was also shown through numerical analysis that, under the friction pile condition, the effect of friction coefficient on the pile settlement was dominant compared to the rock socketed condition. As the friction coefficient changes from 0.1 to 1.5, there was a 44% decrease in the pile settlement for the rock socketed condition, whereas for the fiction pile the settlement decreased up to 67%.

4 CONCLUSIONS

A series of 3D finite element analyses were conducted to investigate the effect of cement milk thickness, water-cement ratio, friction coefficient and the end-bearing condition on the prebored and precast pile. From the numerical results, following conclusion can be made:

(1) As the cement milk thickness increases, the density and the confinement acting on the pile also increases, which leads to smaller pile settlement. As the cement milk thickness increase from 50mm to 150mm, the pile settlement decreased by 56%, and the bearing capacity increased by over 500%.

(2) Water-cement ratio of the cement milk casted in the borehole is related to the Young’s modulus of the cement milk. As the water-cement ratio increases, the cement milk’s Young’s modulus decreases, yielding more pile settlement and lower bearing capacity. This results shows similar tendencies obtained from numerous field tests, which suggested that the higher N-value of the surrounding ground leads to less settlement of the prebored and precast piles.

(3) Higher friction coefficient between the cement milk and soil, restrains the settlement of prebored and precast piles. As the friction coefficient increases from 0.1 to 1.5, the settlement of the prebored and precast pile has decreased by about 44%. Although the skin friction of the prebored and precast pile is a critical parameter of the pile settlement, the end-bearing condition can also affect the pile settlement. The pile with a rock socketed end-bearing condition shows less settlement compared to the friction pile condition. Also, the effect of the friction coefficient was shown greater in case of friction pile condition for both pile settlement and the bearing capacity.

ACKNOWLEDGEMENTS

This work was supported by both the National Research Foundation of Korea (NRF) grant founded by the Korean government (MSIP) (No. 2011-0030040), and the Korea Expressway Corporation.

REFERENCES

1) Hong, W., Lee, J. and Chai, S. (2008): Bearing capacity of SDA augered piles in various grounds depending on water-cement ratio of cement milk, Journal of Korean Geotechnical Society, 24(5), 37-54.
2) Jeong, S., Lee, J. and Lee, C. (2004): Slip effect of the pile-soil interface on dragload, Computers and Geotechnics, 31, 115-126.
3) Lim, H., Park, Y. and Park, J. (2002): Investigation of characteristics and suggestion of evaluation formulae for skin resistance of SIP, Journal of the Korean Geoenvironmental Society, 3(2), 15-21.
4) Park, J. (2004): Strength and friction behavior of cement paste poured in the bored pile, Journal of the Korean Geoenvironmental Society, 5(3), 31-39.
5) Reddy, K. and Saxena, S. (1993): Effects of cementation on stress-strain and strength characteristics of sands, Soils and Foundations, 33(4), 121-134.
6) Uesugi, M. and Kishida, H. (1986): Influential factors of friction between steel and dry sands, Soils and Foundations, 26(2), 33-46.
7) Uesugi, M., Kishida, H. and Tsubakihara, Y (1989): Friction between sand and steel under repeated loading, Soils and Foundations, 29(3), 127-137.
8) Uesugi, M., Kishida, H. and Uchikawa, Y (1990): Friction between dry sand and concrete under monotonic and repeated loading, Soils and Foundations, 30(1), 115-128.