Shaft resistance characteristics of steel pipe prebored and precast piles based on field loading tests

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ABSTRACT

Prebored and precast piles (here and after, PPP) are being frequently used for various structures to reduce nuisance caused by vibration and noise, substituting driven piles. In PPP design, skin friction is the most critical factor affecting bearing capacity and settlement behavior. Main focus of this paper is set to establish an analysis model considering the interface behavior at the pile-cement milk-surrounding soil interface during the installation and in-use of PPP. A case of single pile was analyzed through a three-dimensional finite element approach and field load tests. In the analysis, t-z curve allowing a slip along the interfaces were proposed, designed with a certain length of slip for each soil layers. A series of numerical analysis on the interface of pile-cement milk-soil was conducted based on a proposed t-z curve. It is shown that the complex elements around the pile increases the skin friction to some extent and reduces the pile settlement.

Keywords: Prebored and precast piles, interface modelling, load-settlement curves, load-transfer curves, field loading test, 3D FE analysis

1 INTRODUCTION

The vibration and noise induced during pile installation have become a significant consideration in modern construction projects. For this reason, various construction projects, such as urban construction and highway construction, are using PPP over conventional driven piles.

A PPP is installed by boring a hole in the ground and placing the precast PHC (Pretensioned Spun High Strength Concrete) or steel pile in the borehole and finished by casting cement around the pile. The preboring process induces significantly less noise and vibration during construction compared to driven piles and is more cost effective compared to drilled shafts. However, compared to driven piles and drilled shafts, very few studies, let alone full scale experiments, on PPP have been performed. Studies and experiments on PPP have been limited to only standard penetration test-based empirical methods which roughly estimates the bearing capacity. Deformation based studies, such as analyzing the load-settlement curve and predicting the settlement of PPP, have not been conducted.

The bearing capacity and settlement of PPP are affected not only by the end bearing capacity, but also by the skin friction between the pile and the cement milk poured in the borehole. However, as mentioned above, to date, most of the measurements and experiments were based on driven piles or drilled shafts. Among the major factors, the water-cement ratio of the cement milk was found to have the biggest influence on the skin friction (Hong et al., 2008; Jung et al., 2017; Jeong and Kim, 2018; Kim, 2018; Kim et al., 2018).

To enhance the accuracy of the numerical analysis, various elements observed in the field test were included in this study, such as cement milk inside and around the steel pile. The cement milk layer that infiltrated into the surrounding soil was considered in the numerical modeling process. The interface between the elements was analyzed based on the proposed multi-interface model. The proposed multi-interface model simulates the behavior of the prebored and precast pile by considering not only the interface between the pile and the cement milk but also those of the inner cement milk-pile, cement milk-cement milk infiltrated in to the surrounding soil and cement milk infiltrated in to the surrounding soil-soil. The multi-interface model considers the relative movement of the pile-soil based on the modified t-z curve, which considers the shear stress of various interfaces and relative settlement.

2 FIELD LOADING TEST

In this study, the actual behavior of PPP was observed by real-scale field load tests

2.1 Full-scale field load test

Field load test on an actual pile was conducted in the southern region of the Korea. After a series of field investigations and laboratory tests, the ground condition was shown to reflect the typical soil conditions of the Korean peninsula.

The diameter of the steel pile used in the loading test was 0.508m, and the thickness was 0.012m. The strain gauges indicating the settlement and the load-transfer curve of the test pile were installed at the surface of the test pile. The spacing of the gauges was regular with 1m at the upper part of the pile, and the spacing was reduced to 0.5m around the foot of the pile. The gauges were placed on two sides of the pile for each depth to prevent the loss of records due to gauge failure, with exceptions on the boundary of layers, where the spacing differs to 0.5m. The base of the pile was installed under N-value of 50/20 (Case #1) and 50/10 (Case #2) conditions.

A standard static loading test was carried out after the ground investigation. Based on the ground investigation, the base of the pile was installed under various N-value conditions. The procedure of the standard static loading test was based on the ASTMD1143-81(1994). The period of the loading was based on four steps by loading 25%, 50% and 75%, sustaining the load until the settlement of the head was less than 0.25mm per hour (maximum of two hours). After the completion of the loading, the unloading process was carried out by unloading 50% over 20 minutes. The yielding load was assumed to be reached when a sudden settlement occurred during the loading process, and the test had come to an end.

2.2 Test results and discussions

A load-settlement curve based on the full-scale pile loading test was obtained and the results are shown in Fig. 1. The load-settlement curve of TP-1 shows a stiff shaft resistance only in the initial loading stages, and acts similar to conventional driven piles. However, the load-settlement curve of TP-2 acts stiff not only in the beginning but until the later section (3,000kN/m^2) of the loading process due to the high shaft resistance caused by the cement milk layer around the steel pile. After the yielding of the shaft resistance, the load-settlement curve acts similarly to the driven pile.

The load-transfer (t-z) curve shows two distinctive types of load-transfer curves. Load-transfer curve of TP-1 shows a bilinear configuration in most measurements. The shear stress acting on the skin of the pile gradually increases as the depth increases, and converges to a maximum value. TP-2, on the other hand, shows a steep rise in shaft resistance in the early loading stages and reaches its peak. After, the shaft resistance drops showing a brittle like behavior.

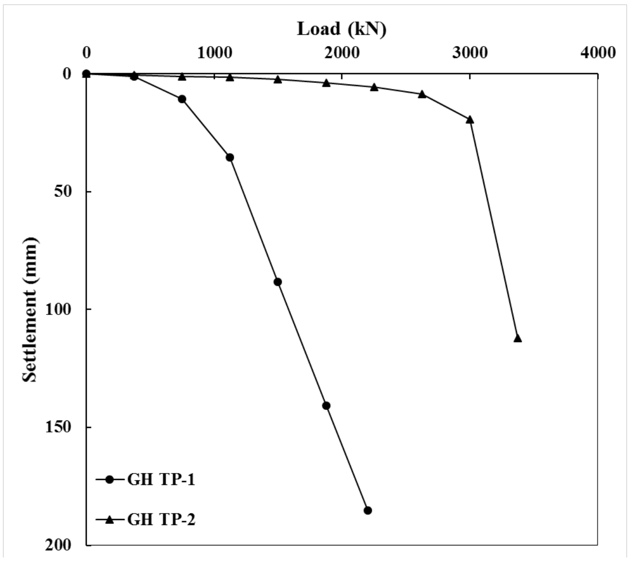


Fig. 1. Load-settlement curve from the full-scale pile loading test

3 FE ANALYSIS MODEL

In this study rigorous numerical modeling was conducted to establish an analytical method for steel pipe PPP.

3.1 FE mesh and boundary conditions

A commercial finite-element package, ABAQUS CAE 6.13 (2013), was used in this study for modeling and analyzing of a single PPP load test. Based on symmetry, only a quarter of a whole mesh was used in the three-dimensional analyses to save calculation time and memory space. For the three-dimensional finite element analysis (FEA), the pile and the soil were modeled by 27-noded second-order brick elements.

3.2 Interface modelling

In this study, the analysis of PPP was performed using three-dimensional finite element numerical analyses. To reflect the actual condition of the loading test site, the steel pipe PPP, cement milk around and inside the pile and cement milk infiltrating into the soil were modelled. Interface modeling was executed based on the suggested modified t-z curve that considers the relative settlement between each of the elements. By using the ABAQUS user-subroutine option "FRIC", the relative settlement and the maximum shear stress were modelled for each interface.

Pile – Cement Milk

Due to the cement milk cast in the borehole, the skin friction of a PPP is much greater than the skin friction of a driven pile. Additionally, the shear stress acting between the pile and the soil is relatively higher than the shear stress acting between the elements. This condition was confirmed through the small-scale model pile test carried out in this study. Based on the test results, we found that the failure surface appeared between the cement milk and the soil. To simulate the actual behavior of the interface between the pile and the cement milk, we assumed a 'hard contact', 184 which has infinite shear stress and failure does not occur. The left part of figure 7 shows the modeling of the interface between the pile and the soil, where no relative settlement (sliding) is allowed.

Cement Milk – Infiltrated Cement Milk – Soil

The roughness of the surface of the drilled-shaft socketed in rock relies on the equipment used for boring and the type of soil or rock. Similar to PPP, the main source of the skin friction of a drilled-shaft is also the cement milk poured into the borehole. During the hardening process of the cement milk, the cement milk infiltrates into the surrounding soil, and excess adhesive strength forms between the cement milk and the soil (Reddy et al 1993). Through this process, higher shear stress acts along the interface, in some cases showing brittle failure behavior when socketed in rocks (O'Neill et al. 1994). Also, the maximum shear stress is mobilized after a certain relative settlement occurs between the elements. Thorough numerical and field studies show that considering the relative settlement between the elements more accurately predicts the behavior of the pile under axial load.

In this study, the interface was modelled based on the two different types of load-transfer curve, which can consider high shear stress between the elements due to the hardening of cement milk and the relative settlement in to account. The length of the relative settlement differs according to the types of soil in which the pile is socketed (Broms 1979, Briaud et al. 1991). The interface between the cement milk and the cement milk infiltrated in to the soil is assumed to be an intermediate stage, where the load-transfer curve has a lower shear stress compared to the drilled-shaft, but higher than the result of the direct shear stress between the hardened cement milk and soil. This assumption reflects the failure mechanism observed from the small-scale field test. Through the small-scale field test, it was observed that the cement milk has infiltrated in to the surrounding soils and induced an excessive shaft resistance along the interface.

Maximum shear stress (τ_{max}) after the elastic slip section is estimated based on the earth pressure (ρ') and the friction coefficient (μ). Equation (1) shows the estimation of τ_{max} and the friction coefficient is estimated based on equations (2) and (3).

$$\tau_{max} = \mu \times \rho' \tag{1}$$

$$\mu = tan\delta \tag{2}$$

$$\delta = tan^{-1}((sin\varphi \times cos\varphi)/(1+sin^2\varphi)) \tag{3}$$

where, δ is the interface friction angle and φ is the friction angle of the soil layer. However, additional adhesive strength was considered in the analysis between the cement milk layer and the infiltrated cement milk layer.

Table 1 shows the relative displacement between the pile and the soil based on soil and rock layer (Broms, 1979; Kim, 2018). Table 2 states the material properties used in the analysis.

Table 1. Relative displacement of each soil and rock layer

Soil / rock layer	Relative displacement (mm)
Fill	7 – 9
Sedimentary layer	5 – 7
Weathered soil	4 – 5
Weathered rock	2 – 4
Soil-cement	1.5 – 2

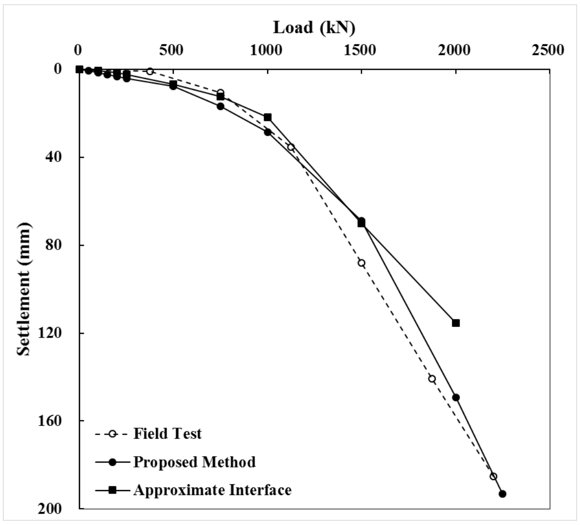
Table 2. Material properties used in analysis

Physical properties	Model	γ (kN/m^3)	E (MPa)	ν	c (kPa)	φ (°)	μ
Pile	Linear elastic	75	200,000	0.2	-	-	-
Cement milk	Linear elastic	20	5,000	0.25	-	-	-
Fill	Mohr Coulomb	17	10	0.30	0	29	0.343
Sedimentary layer (SM)	Mohr Coulomb	19	20	0.30	3	28	0.340
Sedimentary layer (GP)	Mohr Coulomb	20	40	0.30	5	29	0.343
Weathered soil	Mohr Coulomb	20	12.724	0.30	22	39	0.343
Weathered rock	Mohr Coulomb	21.5	185.18	0.30	35	32	0.351

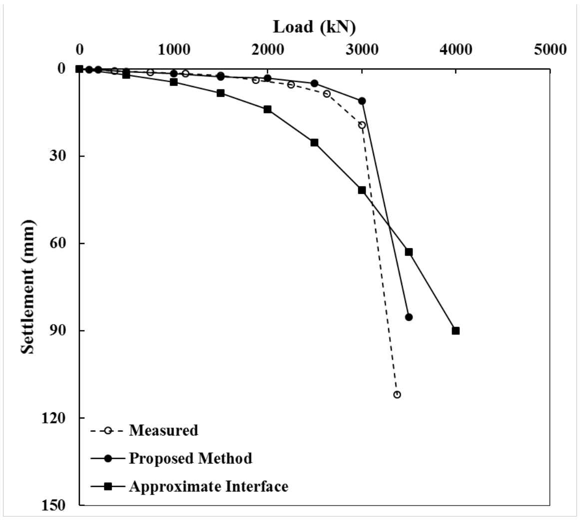
3.2 Validation of numerical model

Validation of the numerical model was carried out by comparing the results of the numerical analysis and the field loading tests. To emphasize the accuracy of the proposed analytical model additional analysis using a commercial code PLAXIS 3D (2013) was conducted.

In the case of TP-1, where the cement milk infiltration has not occurred and the load-transfer mechanism was similar to the conventional bilinear behavior, both numerical model was capable of simulating the load-settlement behavior (Fig. 9 (a)). However, based on the comparison, the accuracy of the proposed model (method) considering the relative displacement and the cement milk infiltration along the shaft of the pile was found to be significantly higher than the conventional numerical results in TP-2 (Fig. 9 (b)). From this, it can be concluded that the load-transfer behavior of the steel pipe PPP can only be simulated by



(a) TP-1



(b) TP-2

Fig. 9 Validation of the proposed numerical model

applying two different characteristics along with the loading stages.

4 CONCLUSION

In this study, the behavior of the PPP was investigated based on the field load test and multi-interface analysis model. The multi-interface analysis model uses two type of suggested load-transfer curves, considering relative settlement and cement milk infiltration into the surrounding soil. Based on the preceding studies and the studies conducted in this paper, the behavior of prebored and precast piles distinctively differs from the behavior of driven piles and drilled shafts.

In the simulation of the complex behavior of interfaces in prebored and precast piles, modeling of various elements – cement milk, cement milk infiltration in to surrounding soil and the cement milk inside the pile – is necessary. Based on the field tests and the series of numerical analyses, the analytical method which considers the relative settlement and cement milk infiltration into surrounding soil was established. The suggested model is verified by comparing the load-settlement of two example analyses and two experimental measurements. The results of the numerical analysis carried out based on the proposed multi-interface model and the t-z curve significantly enhanced the accuracy of the prediction and are in good agreement with the field test data.

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