

Numerical Study of Pipe Pile Behaviour in Clays Considering Inner and Outer Shaft Frictions

Kicheol Lee, Byunghyun Choi, Jongho Park, Dongwook Kim

Incheon National University

119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea

wlq4619@inu.ac.kr; qudqus555@inu.ac.kr; rdvagabond@gmail.com; wooldong2@gmail.com

Abstract – Axial resistance of open-ended steel pipe pile is influenced by the external frictional resistance generated between the outer pile surface and its surrounding soils and the internal frictional resistance generated between the pile inner surface and plugged soils. For the assessment of axial pile resistance including its ultimate load, characteristics of both external and internal shaft frictional resistances should be examined. However, limited previous research was available. In this study, the effects of frictional resistance characteristics on the long-term ultimate loads were analysed through numerical analysis. As results, the long-term pile ultimate loads were numerically quantified. It was found that the effect of the outside friction coefficient on pile resistance was more significant compared with inside friction coefficient's contribution on pile resistance.

Keywords: Open-Ended Steel Pipe Pile, Ultimate Load, Surface Interface Friction Coefficient, Numerical Analysis.

1. Introduction

In the case of open-ended steel pipe piles (OESPP), frictional forces are acting on both outer pile shaft surface and inner pile shaft surface. The external frictional resistance on outer pile surface is mobilized between pile surface and the pile's surrounding ground, while the internal frictional resistance on inner pile surface is exerted between pile surface and plugged soils resulted from pile installation process[1]. Examination of these external and internal frictional resistance characteristics is important to evaluate their separate effects on pile ultimate load and behaviour. Limited literature on the quantification of these effects is available; therefore, in the study, the changes of long-term ultimate load of OESPP in clays for different combinations of external and internal frictional resistance characteristics were analysed based on numerical analysis results. Numerical program of ABAQUS/CAE [2] was used for the numerical analysis. The important frictional characteristic of interface friction coefficients of inner and outer frictions were varied in combinations from 0.2 to 1.0 (in increments of 0.2), respectively. For different combinations of friction coefficients (c_{in} and c_{out}), long-term ultimate pile loads were analysed in details.

2. Numerical Analysis

2.1. Modelling

Long-term pile ultimate loads for different combinations of internal and external friction resistance characteristics of OESPP were analyzed using ABAQUS/CAE [2], which is three-dimensional finite element program. The material properties of the clay foundation and the OESPP used in numerical analysis are summarized in Table 1. For numerical modelling of clay foundation, the outer boundary of clay foundation is assumed to be a large cylindrical shape with a diameter of 25 m and a height of 30 m. The embedment depth, total length, diameter, and thickness of OESPP are assumed to be 25 m, 30 m, 0.5 m, and 0.012 m, respectively (Fig. 1). To ensure that the outer boundary of clay foundation is sufficient not to have boundary issue in analyses, sufficient ratio (50) of clay foundation outer boundary diameter (25 m) to pile diameter (0.5 m) is assumed.

2.2. Frictional Interaction Characteristics of Inner and Outer Pile Surfaces

The frictional interaction characteristics of clay-steel surface interface are summarized in Table 2. In ABAQUS / CAE, the master surface and the slave surface must be set when setting the interface frictional surfaces. The interface between

clay and steel surface on clay foundation is set as the master surface because typically the master surface is set for larger model (clay foundation model is far larger than pile model); thus, the interface on pile is set as slave surface.

Table 1: Material properties used in the analysis.

Property	Open-ended Steel pipe pile (OESPP)	Soft clay
Model	Elastic	Mohr-Coulomb
Young's modulus, E (MPa)	200,600	5
Cohesion, c (kPa)	-	3
Poisson's ratio, ν	0.3	0.3
Friction angle, ϕ ($^{\circ}$)	-	20
Unit weight, γ (kN/m ³)	76.82	18
Lateral coefficient of earth pressure at rest, K_0	1	0.65

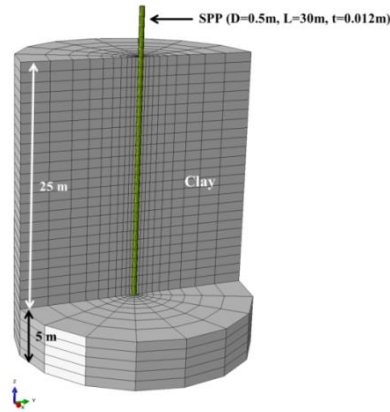


Fig. 1: OESPP and clay foundation modelling used in the analysis.

The frictional interaction condition was assumed to be combination of “hard contact” and “tangential behaviour.” The “hard contact” covers typical condition of interface between two different materials and the “tangential behaviour” specifies frictional properties such as friction coefficient of interface surfaces. Typical friction coefficient between soil and steel pile shaft ranges from 0.2 to 1.0 depending on roughness of pile surface and particle size distribution. The analysis was carried out by changing the coefficients of friction of inner and outer pile shaft surface (interface frictional coefficient between soft clay and OESPP). The friction force is applied when the friction surface between the contact bodies is set. When the magnitude of the shear stress reaches the threshold, the body slips, otherwise it does not move. This friction has a disadvantage that it is difficult to obtain a solution because the nonlinear effect is very large. However, in ABAQUS/CAE, the analysis equation of friction value is made as unsymmetrical, and when the friction coefficient is larger than 0.2, the ‘unsymmetrical solver’ works.

Table 2: Interaction characteristics used in numerical analysis.

Master surface	Slave surface	Normal behaviour	Tangential behaviour
Soft clay surface on inner pile shaft	Inner shaft surface of pile	Hard contact	Penalty-friction coefficient = 0.2 ~ 1.0
Soft clay surface on outer pile shaft	Outer shaft surface of pile	Hard contact	Penalty-friction coefficient = 0.2 ~ 1.0
Soft clay surface in contact with pile bottom's cross section	Pile bottom's cross section	Hard contact	-

2.3. Analysis of Load-Settlement Curves and Ultimate Loads of OESPP

In order to analyze the ultimate load of the OESPP, the maximum pile head displacement (settlement) of 0.1 m was controlled and the reaction force was analyzed for each increment of settlement. The analysis is repeated by varying combination of friction coefficients of the inner and outer interface surfaces, and the corresponding load-settlement curves were derived. From each load-settlement relationship, pile ultimate load was determined through Davisson's Criterion ([3] and [4]).

3. Results of Numerical Analysis

3.1. Load-Settlement Curves of OESPP

Figure 2(a) shows the pile load-settlement curves varying outer friction coefficient c_{out} from 0.2 to 1.0 for given inner friction coefficient c_{in} of 0.2. As a result of the analysis, the c_{in} was found to have little effect on axial behaviour of OESPP. Significant change of axial OESPP behaviour was found for c_{out} increase from 0.2 to 0.6; however, little change was observed for c_{out} exceeding 0.6. Figure 2(b) shows the pile load-settlement curves varying c_{in} from 0.2 to 1.0 under fixed c_{out} of 0.2. Overall, insignificant change of pile load-settlement curve was shown under pile settlement less than 50 mm (corresponding to 10% of pile diameter, which is a significant settlement). From the comparison of Figure 2(a) and Figure 2(b), the effect of outer friction coefficient on axial pile behaviour was much significant than that of inner friction coefficient.

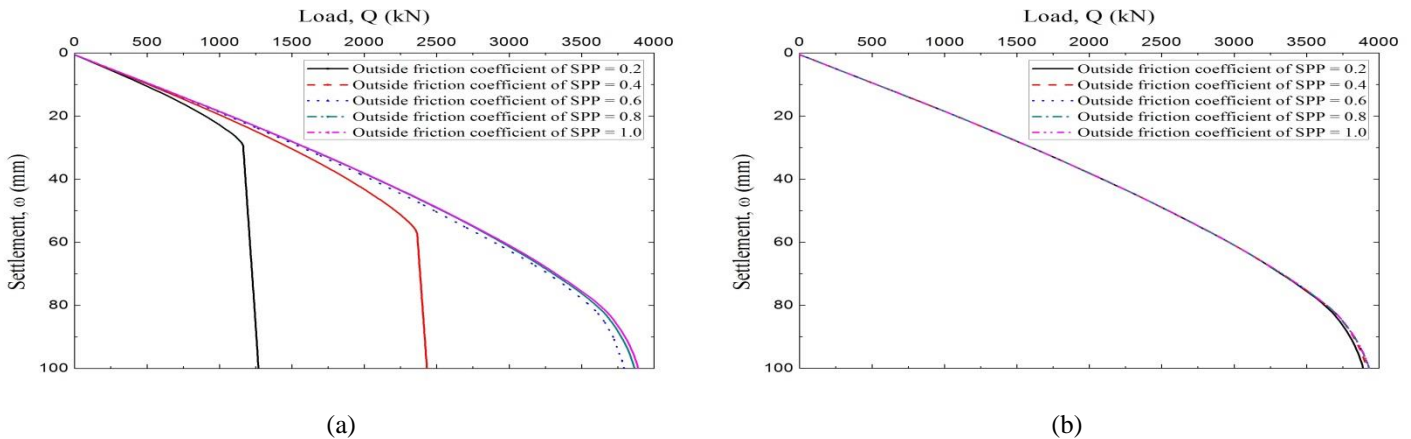


Fig. 2: Pile load-settlement curves; (a) outer friction coefficient varied from 0.2 to 1.0 for the given inner friction coefficient of 0.2; (b) inner friction coefficients varied from 0.2 to 1.0 for the given outer friction coefficient of 0.2.

The determined pile ultimate loads using Davisson's criterion from Figure 2 for different combinations of inner and outer friction coefficients are summarized Table 3. The minimum pile ultimate load (1,197 kN) is achieved when both inner and outer friction coefficients (c_{in} and c_{out}) are the minimum (0.2). The maximum pile ultimate load (3,179 kN) was obtained when outside and c_{out} was 1.0 and c_{in} exceeds 0.4. The ratio of the maximum-to-minimum calculated ultimate load is about 2.65, which is a large value. However, it is noteworthy to know that pile ultimate loads (underlined values in Table 3) somewhat converge to a certain values for c_{out} exceeding 0.6 regardless of c_{in} value. The results in Table 3 are alternatively shown in Figure 3.

Table 3: Ultimate loads with inside and outside friction coefficient using Davisson's criterion.

Ultimate load (kN)	Outer friction coefficient (c_{out})	Inner friction coefficient (c_{in})				
		0.2	0.4	0.6	0.7	1.0
	0.2	1,197	1,225	1,251	1,254	1,254
	0.4	2,370	2,398	2,422	2,424	2,425
	0.6	3,096	3,117	3,125	3,122	3,126
	0.8	3,153	3,165	3,165	3,167	3,168
	1.0	3,177	3,179	3,179	3,179	3,179

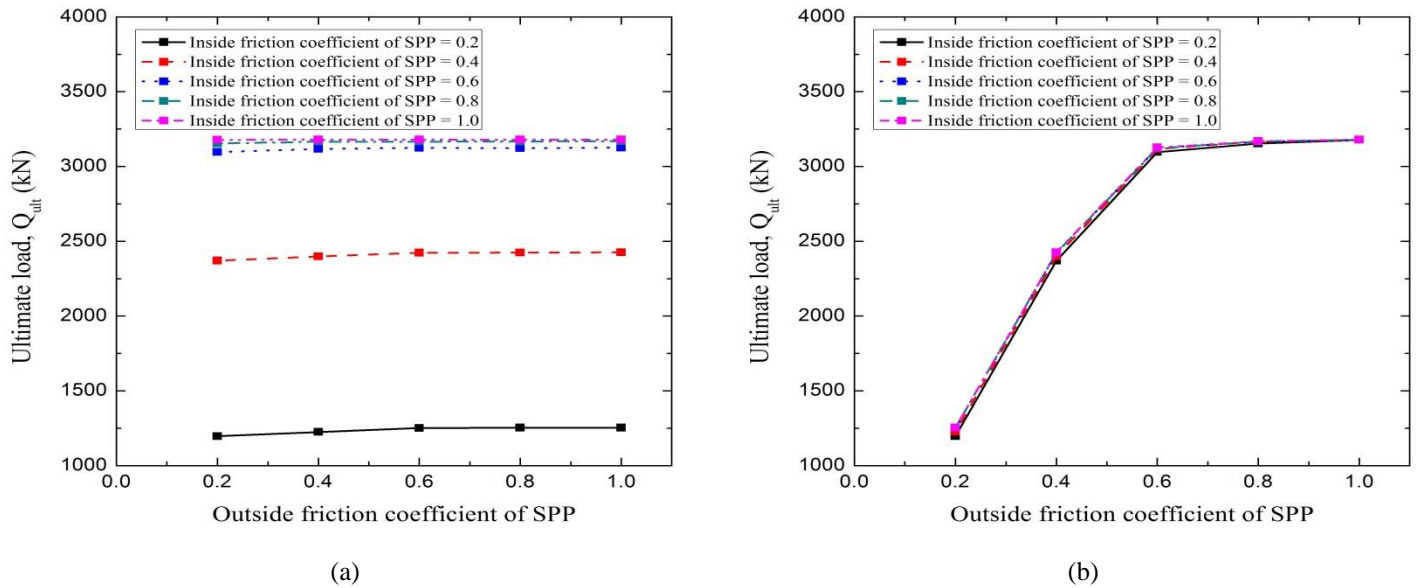


Fig. 3: Ultimate load based on the Davisson's criterion: (a) effect of inner friction coefficient on ultimate load and (b) effect of outer friction coefficient on ultimate load.

4. Conclusion

The purpose of this study is to investigate the ultimate load changes varying combination of internal and external friction resistance characteristics (inner and outer friction coefficients) of the steel pipe pile. The ABAQUS / CAE, a general-purpose program, was used for the numerical analysis program, and the friction coefficients of interface surfaces between the steel pipe pile and the clay foundation were varied within a range of 0.2 through 1.0. As a result, the inner friction coefficient (c_{in}) did not have a significant effect on the load-settlement curve of pile; however, the outer friction coefficient (c_{out}) significantly influences axial pile behaviour. It was interesting that the significant effect of outer friction coefficient on pile behaviour diminishes for outside friction coefficient (c_{out}) exceeding 0.6. In order to improve the reliability of the analysis results, it is necessary to perform a comparative analysis from laboratory and field tests.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2015R1C1A1A02037490).

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