3D FEM Analysis on Load Distribution Behavior for Pile Foundation during Vertical Extension of Apartment Building

Analyse 3D FEM du comportement du processus de répartition des charges pour la fondation des pieux lors de l'extension verticale d'un immeuble

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ABSTRACT: Reinforcement of foundations is of great importance to bear the additional load acting on existing foundations caused by the vertical extension. This study mainly investigated the load distribution behavior of the existing pile and the reinforcing pile during loading, unloading and reloading phase in vertical extension using 3D FEM analysis. In order to evaluate the effect of pile's stiffness on load distribution behavior, three cases of reinforcing piles with different stiffness were conducted in this study. In each case, to model the remodeling process of buildings, reinforcing stage was based on the unloading of existing load at 40%. Numerical results showed that the stiffness of piles had an influence on load distribution behavior. Load distribution ratio of reinforcing piles increased with an increase of stiffness. In addition, in the case of remodeling process of apartment buildings, load distribution ratio of reinforcing piles should be increased to avoid allowable bearing capacity of existing piles from being exceeded.

RESUME : Le renforcement des fondations est d'une importance capitale, afin de supporter la charge supplémentaire agissant sur les fondations existantes en raison de l'extension verticale. Cette étude a principalement porté sur le comportement de répartition des charges du pieux existant ainsi que celles du pieux de renforcement lors des phases de chargement, de déchargement et de rechargement en extension verticale à l'aide de l'analyse FEM 3D. Afin d'évaluer l'effet de la raideur du pieux sur le comportement de répartition de la charge, trois cas de pieux de renforcement ayant une rigidité différente ont été réalisés dans cette étude. Dans chaque cas, pour modéliser le processus de remodelage des bâtiments, l'étape de renforcement s'est appuyée sur le déchargement de la charge existante à 40%. Les résultats numériques ont montré que la rigidité des pieux avait une influence sur le comportement de répartition de la charge. Le rapport de répartition de la charge des pieux de renforcement a augmenté avec une augmentation de la rigidité. En outre, dans le cas du processus de remodelage des immeubles d'habitation, le taux de répartition de la charge des pieux de renforcement devrait être augmenté afin d'éviter que la capacité portante admissible des pieux existants ne soit dépassée.

KEYWORDS: Vertical extension, Reinforcement, Existing pile, Micropile, Stiffness, Load distribution

1 INTRODUCTION

In recent years, with the rapid development of population and decrement of land resources, vertical extension of buildings is considered as one of the ways to broaden and enhance the utilization of existing buildings. The Ministry of land, Infrastructure and Transport in Korea stated that existing buildings over 15 years can be retrofitted with vertical extension up to 2-3 floors (Ministry of land, Infrastructure and Transport, 2013). In order to avoid the allowable bearing capacity of the existing pile from being exceeded during vertical extension, installation of reinforcing piles play a very important role in bearing the additional load.

A building includes the superstructure (i.e., Frame Load (FL), Finishing Material Load (FML), Live Load (LL)), and substructure (i.e., pile foundation). Frame loads occupy 56-58–% of apartment buildings (KICT, 2013). The stages of vertical extension construction are shown in Fig. 1: 1) Removing FML of existing building; 2) Installing reinforcing piles; 3) Extending stories and recovering FML.

Piles can be divided into three major categories, depending on their lengths and mechanisms of load transfer onto the soil: a) point bearing piles, b) friction piles, and c) compaction piles (Das, 2007). In Korea, since the rock layer can be generally found within 30 m of the surface (Yoon and Kim, 2006), conventional buildings generally use point bearing piles (i.e., PC pile or PHC pile) in the foundation. However, in the reinforcing foundation construction, due to the lack of space and construction methods, micropiles are widely used. Micropiles are regarded as frictional piles ignoring end-bearing resistances, which are piles that are drilled and grouted with a small diameter (less than 300 mm) (FHWA, 2005). Many researches have been conducted on vertical or lateral behavior of micropiles and demonstrated the applications of micropiles on reinforcing existing foundations by field experiments, numerical analysis, and centrifuge tests (Alnuaim et al., 2014; Han and Ye, 2006(a)). Han and Ye (2006(b)) experimentally investigated micropile's behaviors on underpinning a soil foundation. They demonstrated that micropiles have a significant effect on underpinning which carried approximately 75% extra loads during additional loading. They also proposed design guidelines for foundations underpinned by micropiles.

As a micropile's load transfer mechanism and material properties are different from conventional PC piles, when using micropiles to reinforce an existing foundation, it is essential to investigate the effect of stiffness and load transfer machnism on load distribution of micropiles and existing piles. However, little research has been done focusing on evaluating the load distribution of micropiles and existing piles subjected to an additional load. Cho et al. (2014) evaluated load distribution characteristics of existing and reinforcing piles by model tests. However, this study ignored the difference between existing and reinforcing piles.

The purpose of this research is to evaluate the load distribution behavior of existing and reinforcing piles before and after reinforcement by using a 3D FEM analysis. The specific objectives are to (1) evaluate load-displacement characteristics of a single conventional PC pile and a reinforcing micropile; (2) investigate load distribution behavior of each existing and reinforcing pile in terms of the pile's materials.

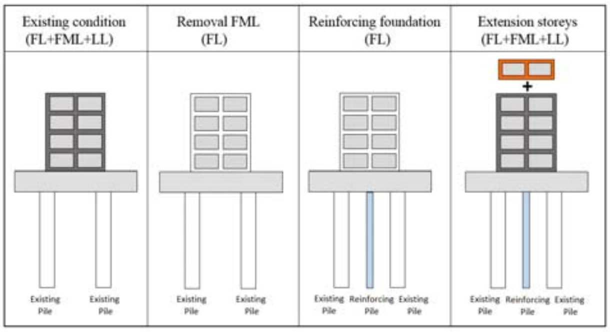


Figure 1. Construction stages of vertical extension

2 3D FEM MODELLING

PLAXIS 3D used in this research is a 3D finite element program for various geotechnical applications. The PLAXIS code and its soil models have been developed with great care. Quadratic tetrahedral 10-node elements are available in PLAXIS 3D (Plaxis, 2005).

The embedded beam model in PLAXIS, which can cross the bulky soil elements at any arbitrary position and with an arbitrary inclination, was used to simulate piles (Plaxis, 2005). The pile is connected to the surrounding soils by means of special interfaces which are skin interfaces and base interfaces.

The soils were modelled by Mohr-Coulomb model (MC). The MC model, linear elastic perfectly-plastic model represents a 'first-order' approximation of soil or rock behavior (Plaxis, 2005).

2.1 *Properties of Soil and Foundation*

The existing pile foundation consisted of a 3m x 3m x 1 m raft and 4 PC piles with a diameter of 350 mm and length of 15 m. In order not to take the raft effect on the load distribution to the soil into account, the pile's caps were not touching the soil. Soil stratigraphy was interpreted from a borehole in a case of XX apartment remodeling field construction in Korea given in Fig. 2. The properties of soil layers are shown in Table 1. Similarly, the properties of PC pile and micropile 1 were adopted by reference to this XX apartment remodeling field construction. The Young's modulus of micropile 1 was calculated by using the composite young's modulus of the concrete and the central steel bar. Moreover, in this study, micropile 2 was designed with a higher stiffness, which the young's modulus was 20% higher than micropile 1. The properties of piles are shown in Table 2.

Table 1. Soil layers and properties

Depth (m)	Description	c (kPa)	Φ (°)	γ (kN/m^3)	E (kPa)	υ
0-0.3	Clayey silt	20	15	16	2.8E3	0.3
0.3-13	Silty sand	20	30	19	1.4E4	0.3
13-15	Sandy gravel	0	40	20	1E5	03
15-17.7	Weathered rock	50	30	20	2E6	0.3
17.7-30	Soft rock	200	34	23	1E6	0.28

Table 2. Properties of piles (embedded pile)

Description	PC pile	Micropile 1	Micropile 2
E (kN/m^2)	4xE7	4.6xE7	5.6xE7
γ (kN/m^2)	5	5	5
Properties type	Massive circular pile	Massive circular pile	Massive circular pile
Diameter (m)	0.35	0.15	0.15
Skin friction distribution	Multi-layer	Multi-layer	Multi-layer
Base resistance (kN)	1000	50	50

Table 3. Loading phases of test cases

No.	Loading phase			
1	Loading P to existing 4 PC piles	Unloading 40% existing load	Reinforcing PC pile install	Reloading on 5 piles
2	Loading P to existing 4 PC piles	Unloading 40% existing load	Reinforcing micropile 1 install	Reloading on 5 piles
3	Loading P to existing 4 PC piles	Unloading 40% existing load	Reinforcing micropile 2 install	Reloading on 5 piles

2.2 *FEM Construction stage*

Three cases (i.e., case 1: 4 existing PC piles and 1 reinforcing PC pile, case 2: 4 existing PC piles and 1 reinforcing micropile 1, and case 3: 4 existing PC piles and 1 reinforcing micropile 2) were considered as shown in Table 3 and Fig. 3. In each case, after installing 4 PC piles and a raft, the load was applied on the raft at 1500kN, removing 40% of the existing load corresponding to removal FML phase in vertical extension construction. Then the reinforcing pile was installed and connected to the raft. After installation, the load was reapplied onto the plate from P(1500kN) to 3P(4500kN) gradually according to the vertical extension phase. The loading phases are given in Table 3

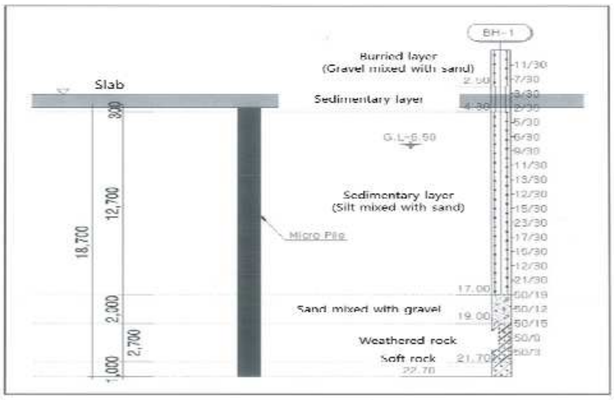


Figure 2. Soil stratigraphy from BH-1

3 FINITE ELEMENT ANALYSIS OF SINGLE PILE SUBJECTED TO VERTICAL LOAD

3.1 Vertical load-settlement response of single pile

Before the evaluation of load distribution, a single PC pile and micropile's behavior under vertical loading was investigated by sing PLAXIS 3D. Soil and pile properties are shown in Table 1 and Table 2.

The load was applied on the piles up to 1500kN. The load-displacement response was plotted in Fig. 4. As the load-displacement curve of micropiles have no distinct "plunge" point, it is difficult to obtain the values of the ultimate bearing capacity from the curve. However, if the service load of a pile is assumed about 400kN, at the load of 400kN, the settlement of piles are 3mm, 6mm, and 8mm, respectively, as seen from Fig.

4. The responses clearly show that the PC pile subjected to vertical load has a higher load capacity than micropiles.

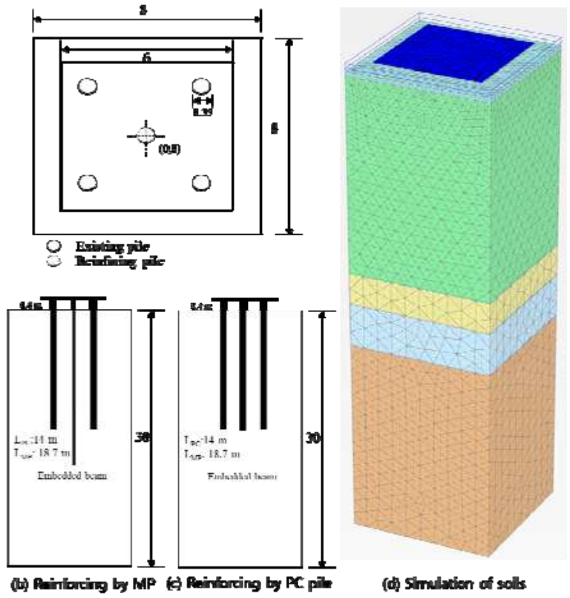


Figure 3. Geometry of pile groups

The stiffness of the equivalent piles (formed by interaction surface between soil and piles) can be considered as the initial slope of load-displacement curve. It can be seen in Fig. 5 that the stiffness of the PC pile and the micropiles are 12.3xE4 kN/m, 8.1xE4 kN/m, 9.2xE4 kN/m, respectively. Therefore, the PC pile shows the highest stiffness followed by MP2 and MP1.

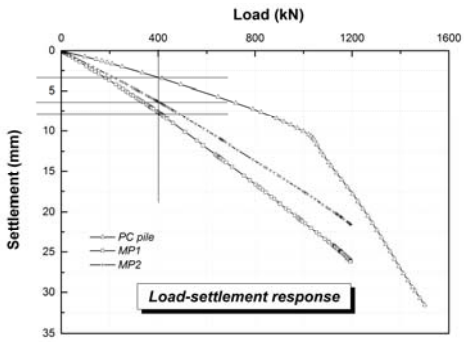


Figure 4. Load-settlement curve of PC piles and micropiles

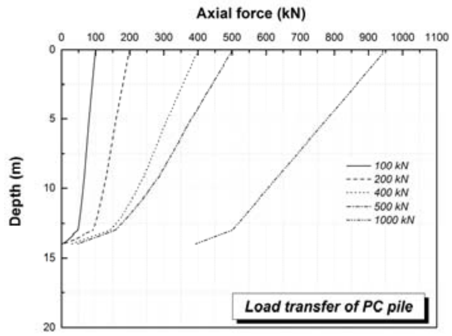
3.2 Load transfer behavior in piles

The load transfer behaviors in the piles with depth under compression are presented in Fig. 5. The results show that the axial forces increase with the applied load on the head of piles, but decrease with depth due to the part of the load resisted by the skin friction along the shaft. The tip resistance of PC pile increases noticeably with an increase in the applied load when the maximum skin capacity is fully mobilized. In comparison, the decrease of the axial force with depth for the PC pile is significantly larger than the micropiles due to the use of steel pipe in soil layer without skin friction, and the tip resistance of the PC pile is much higher than the micropile because of the smaller diameter of the micropiles. In the case of micropiles, construction method of micropile differs from conventional boring pile, which a steel casing pipe is installed while drilling a hole when expecting the collapse without casing. In Fig. 5 (b) and (c), it is obvious that load is not transferred by the skin friction along the shaft until 13m because of the steel casing's installation.

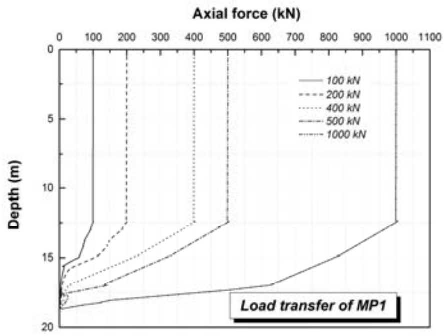
4 LOAD DISTRIBUTION CHARACTERISTICS OF PILES DURING FOUNDATION REINFORCEMENT

3 kinds of piles (PC pile, MP1, MP2) with different stiffness are used to underpin existing foundations. The reinforcing stage was based on the unloading with the 40% of existing load, 1500kN. After reinforcement, an additional load was applied up to 300% of the existing load on the pile foundation. The effects of the load distribution ratio on the head of each pile (existing pile and reinforcing pile) to the applied load under the loading stage, unloading stage, and reloading stage (after reinforcement) are shown in Fig. 6. The solid line displayed the loading stage, and dash line displayed the reloading stage.

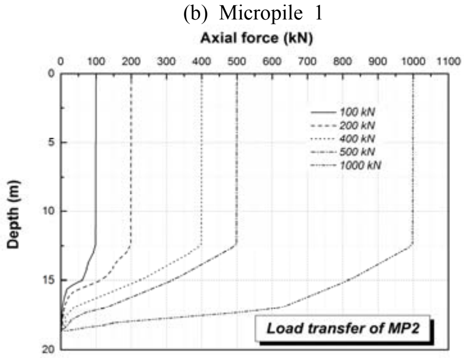
Fig. 6 (a) presents the load distribution ratio of the existing and reinforcing piles when using a PC pile to underpin the foundation. It can be seen that during the loading and unloading stage, each existing pile occupied 25% of the total load. After the reinforcing pile's installation and additional loading stage, the load distribution ratio of the existing pile decreases with the applied load while the reinforcing pile gradually increases. At the initial reloading stage, the load distribution ratio of the existing and reinforcing PC piles are 23% and 7.7% of the total load, respectively. However, when applying the load at 300% P, the load distribution ratio of the existing pile and reinforcing pile are 20.2% and 19.5%, respectively. Results illustrate that the load distribution curve of the existing and reinforcing piles will converge a little over 300% P, and then the load supported by the reinforcing PC pile will exceed the existing PC piles.



(a) Single PC pile



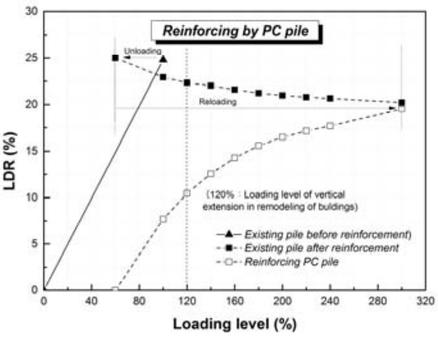
(b) Micropile 1



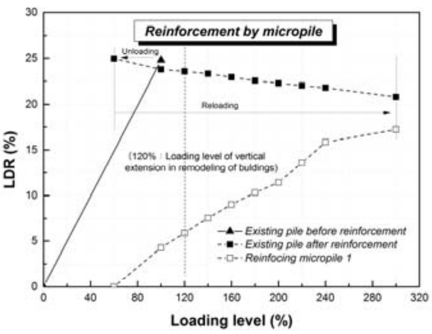
(c) Micropile 2

Figure 5. Load transfer of the PC pile and micropiles

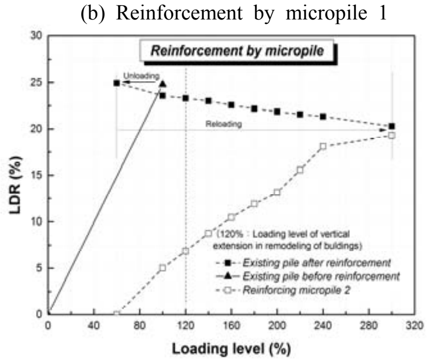
Fig. 6 (b) and (c) show the load distribution behavior of piles when being reinforced by micropiles with different stiffness, respectively. Load distribution ratios of reinforcing MP1 and MP2 increase with the applied load, and the curves of the existing and reinforcing piles converge gradually. As MP2 has a higher stiffness than MP1, it can be seen that the increasing rate of MP2's load distribution ratio is higher than MP1. At the loading level of 300% P, the load distribution ratio of MP2 is 19.3%, but the load distribution ration of MP1 is only 17.2%. In the 3 cases mentioned above, the stiffness has a significant effect on the behavior of the pile's load distribution.



(a) Reinforement by the PC pile



(b) Reinforcement by micropile 1



(c) Reinforcement by micropile 2

Figure 6. Load distribution ratio of the existing piles and the reinforcing pile during vertical extension process

In the real case of vertical extension of buildings, the additional load is known about 20% of existing load. In order to ensure that the allowable bearing capacity of the existing pile is not exceeded by additional load during the vertical extension phase, it is better that reinforcing piles support a larger additional load. If the existing piles and a reinforcing pile were installed at the same time, the load distribution would have been 20%. However, as shown in the Fig. 6, at the load level of 120%, the load distribution ratio of the reinforcing PC pile, MP1, and MP2 are 10.4%, 5.9%, and 6.9%, respectively. Therefore, during the remodeling process, in order to increase the load distribution of the reinforcing piles, other techniques should be taken. Possible solutions to this problem are to increase the stiffness of the reinforcing piles, or to apply preloading to the reinforcing piles in order to mobilize the bearing capacity in advance before reloading and reduce the loads of existing piles.

5 CONCLUSION

In this study, 3D FEM numerical modeling for the analysis of load-displacement response and load distribution behavior of existing and reinforcing piles during vertical extension were performed. The stiffness of the PC pile from the load-displacement curve was higher than micropiles. The load transfer mechanism was different between PC piles and micropiles, where the load resisted by micropiles was mostly dependent on the skin friction while the load resisted by PC piles was dependent on the skin friction in the early loading stages and on the tip resistance as the loading is larger. Additionally, the stiffness of reinforcing piles had a significant effect on load distribution of existing and reinforcing piles during reloading. Moreover, in the vertical extension process of the buildings, to prevent the allowable bearing capacity of piles from being exceeded, the stiffness of reinforcing piles should be increased. Otherwise, preloading on the reinforcing piles should be applied in order to mobilize the bearing capacity in advance before reloading and reduce the loads of existing piles.

6 ACKNOWLEDGEMENTS

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