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Estimation of the Load Sharing Ratio of Pre-installed Columns in Top-Down Buildings on Korean Rock

Sangseom Jeong* and Dohyun Kim**

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Abstract

The estimation of the load sharing ratio of the pre-installed column in typical top-down method building was carried out using three dimensional finite element analysis. The main focus was on quantifying the apparent load sharing ratio of the prebored and precast pile – which is the common form of a pre-installed column – throughout the construction process. Additional parametric study was conducted based on series of numerical analysis with special attention given to the pile load sharing ratio under different pile array, pile embedded length, structure height and rock type. Moreover, the load sharing ratio of a single pile was investigated based on the relative location of the pile in the raft (footing). The numerical model was verified based on the field data of two actual construction site using the prebored and precast pile and the top-down method. Based on the analysis results, it was shown that the pre-installed columns of top-down method building is capable of supporting a notable portion of the structural load throughout the construction process. Furthermore, it was also shown that the pile near the center of the raft carried more structure load compared to the piles in the side and the corner.

Keywords: *load sharing ratio, top-down method, prebored and precast pile, Percussion Rotary Drill (PRD) pile, finite element analysis, urban construction*

1. Introduction

An optimized foundation design which ensures stability and financial feasibility is one of the main issues in the field of foundation engineering. The environmental effect due to construction is another issue, especially in population-concentrated urban areas having buildings, roads, and residential facilities. To prevent detrimental issues during construction, such as noise, vibration, and dust, a top-down construction method is widely used for urban construction in major Asian cities in Korea, China, Japan, Singapore, and Taiwan (Moh and Chin, 1994; Zhu *et al.*, 2006; Yamamoto *et al*., 2009; Rhim *et al.*, 2012). The top-down method induces the minimum effect as well as protects nearby underground structures (Tatum *et al.*, 1989; Crawley and Stones, 1996; Song *et al.*, 2009). Therefore, the top-down method is considered to be an alternative construction method to the conventional bottom-up approach.

The main structural elements of the top-down method include retaining walls, pre-installed columns, slabs (floors), and a mat foundation (footing). Among the structural elements, the pre-installed columns serve as a temporary foundation to support the structural load during construction and play a critical role in structural stability during construction. Using the pre-installed columns, the top-down method is capable of constructing super- and sub-structure simultaneously which reduces the construction period (Hong *et al*., 2010).

A prebored and precast piling method that does not cause high noise, vibration, and dust during the installation process is widely used to install the pre-installed column in top-down construction (Jung *et al*., 2017). An H-shaped steel pile is commonly used as the pre-installed column to support the structural load during the top-down construction process. However, the pre-installed columns are not intended to support the structural load after the completion of the construction. Therefore, the pre-installed columns are designed to have a relatively short embedded length compared with typical piles. After the installation of the mat foundation (footing), even though the pre-installed column has not yielded, its bearing capacity is ignored (Rhim *et al.*, 2012; Tan and Li, 2011). Therefore, the design of the mat foundation (footing) tends to be conservative, leading to thick footing and high construction cost.

However, recent field measurements regarding the axial load acting on pile and settlement, indicate that the pre-installed column actually acts as a foundation element and contributes in supporting the structural load even after the completion of the structure. On basis of these measurements, the pre-installed columns and the footing can be assumed to support the structure as a piled-raft foundation. Under this assumption, the thickness

*Member, Professor, School of Civil and Environmental Engineering, Yonsei University, Seoul 03722, Korea (E-mail: soj9081@yonsei.ac.kr)
**Postdoctoral Research Fellow, School of Civil and Environmental Engineering, Yonsei University, Seoul 03722, Korea (Corresponding Author, E-mail: dohyun0403@nate.com)

of the footing can be reduced.

In this study, the load sharing ratio of the pre-installed prebored and precast pile of the top-down method was estimated through three-dimensional finite element analysis. The modeling and the analysis followed the construction process of the top-down method. The load sharing ratio of the prebored and precast pile was estimated individually for each process by dividing the axial load acting on the pile with the total load. The verification of the numerical model and the process was carried out through comparing the numerical results with the field data from an actual construction site in Korea. Most pile constructions in Korea are embedded at least in weathered rock conditions, which occupy two-thirds of the Korean peninsula. Majority of rocks in the Korean peninsula are generally the results of physical weathering of granite-gneiss having varied thickness up to 40 m (Kim *et al*., 1999). The load sharing ratio of the prebored and precast pile was estimated under various conditions – such as ground condition, pile geometry, pile length, and structure load. On this basis, a considerable load sharing ratio was estimated.

2. Top-down Method and Prebored and Precast Pile

2.1 Top-down Method

Land rent in urban areas has risen exponentially, and attempts to enhance the efficiency of the ground usage lead to high and deep structures. Based on the law of demand and supply, construction in populated urban areas is inevitable. Moreover, the demand for a construction method which induces a small effect on surrounding structures and residential buildings is increasing. Many heavily populated major metropolitan areas in Asia, such as in Seoul, Hong Kong, Shanghai, Singapore, and Tokyo, are struggling with prior issues. In this situation, the use of a top-down method becomes a common solution, substituting

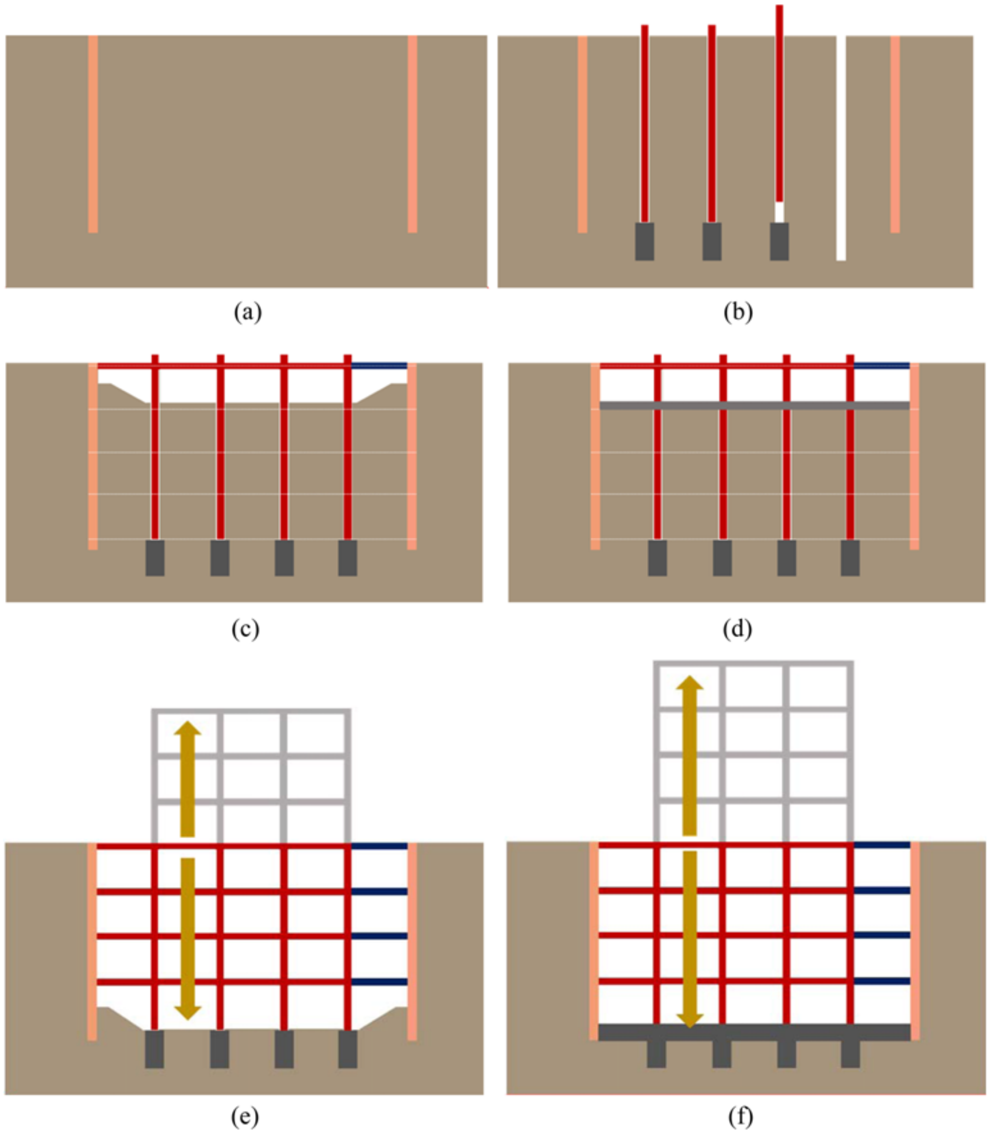

Fig. 1. Schematic of Top-down Construction Process: (a) Installation of Retaining Walls, (b) Installation of Columns, (c) Excavation of 1st Basement Level, (d) Construction of 1st Basement Level Slab, (e) Simultaneous Construction, (f) Construction of Base Footing

the conventional bottom-up method.

The unique process involving the pre-installed retaining wall and temporary columns reduces exposure to noise and dusts, which also secures stability of the excavation surface during construction. Therefore, the top-down method is capable for deep excavation even in narrow urban construction sites. It can be applied under various harsh ground conditions, such as high groundwater flow and weak ground conditions (POSCO, 2001). The top-down method process is shown in Fig. 1. The construction begins by installing retaining walls along the outline of the structure. Diaphragm walls are most commonly used in this process. The retaining wall acts as a basement wall for the duration of the structure. After the installation of the retaining walls, columns that support the structural load during the excavation and construction process, are installed. With the temporary columns installed in place, the slab for the first floor is placed above the site ground.

After the construction of the 1st floor slab, the excavation of the 1st basement level is carried out under the slab. Because the excavation is executed under the slab, exposure to noise and dust can be avoided. The construction of the 1st basement level is completed by installing the slab. The same procedure is carried out for the 2nd basement level, as the 1st upper level construction is completed simultaneously. This procedure continues until the targeted basement level is reached. After the excavation of the targeted basement level is completed, final footing (mat foundation) is installed. Construction of the upper structure continues until it reaches the targeted floor level.

2.2 Prebored and Precast Pile

The temporary column is the most distinctive element defining the top-down method process, stabilizing the upper and sub-structure during the duration of the construction process. In the installation of the temporary column for the top-down method, a prebored and precast pile or cast-in-place pile is commonly used.

The prebored and precast pile is installed by boring a hole in the ground and placing the precast pretensioned spun High Strength Concrete (PHC) pile or steel pile in the borehole before it is finished by pouring and casting cement milk around the pile. Owing to the unique installation process of the prebored and precast pile, the maximum mobilization of the skin friction is capable of yielding a notably higher skin friction than the conventional driven piles. In addition, the preboring process induces greatly less noise, vibration, and dust during installation compared with driven pile, and which is more cost-effective than drilled shafts. For this reason, the prebored and precast pile is commonly used for top-down construction, which mainly occupies population-concentrated urban area construction sites (Jung *et al.*, 2017). The objective construction site in this paper used Percussion Rotary Drill (PRD) piles as the temporary columns.

The PRD pile is a type of prebored and precast pile which was installed through the combination of rotation and percussion. The drilling was achieved by cutting and grinding (rotary) actions at the same time as a chipping (percussive) action. The PRD method procedure includes the blasthole drill and the down-the-hole (DTH) hammer drill. The PRD pile is used in this project to drill through various soil and rock conditions. In addition, quality control using the PRD pile method can be achieved relatively more conveniently than the one using the H-shaped steel beam as a temporary support column.

3. Numerical Analysis

3.1 Finite Element Modeling

The soil and structural elements were modeled using finite elements, which allowed rigorous analysis of the load sharing behavior among the pile and footing. The commercial package PLAXIS 3D Foundation (Brinkgreve and Swolfs, 2008) was used for analysis. PLAXIS 3D Foundation is commonly used in geotechnical engineering, and the accuracy of this program is confirmed through various geotechnical engineering issues (Kim and Jeong, 2011; Jeong *et al*., 2014; Ko *et al*., 2017). In addition, PLAXIS 3D Foundation can be easily adapted in modeling multi-story structures having piled-raft foundation. The acting load on top of each individual pile can be observed. Fig. 2 shows the three dimensional finite element mesh used in this study and the overall geometry of the model. The boundaries comprised a width of four times the mat width from the mat center. The ground is equal to three times the depth of the basement level. These geometries were considered to be adequate, through case studies conducted prior to the actual studies, to eliminate the influence of boundary effects on the load sharing ratio between the pile and the footing (Ko *et al*., 2017). A large square slab and footing were considered. The bottom boundary was restrained from all movements, and the side boundaries were assumed to be on rollers to allow the downward movement of soil layers. In numerical analysis, the initial equilibrium state is important. The specified initial stress distributions should match the calculations

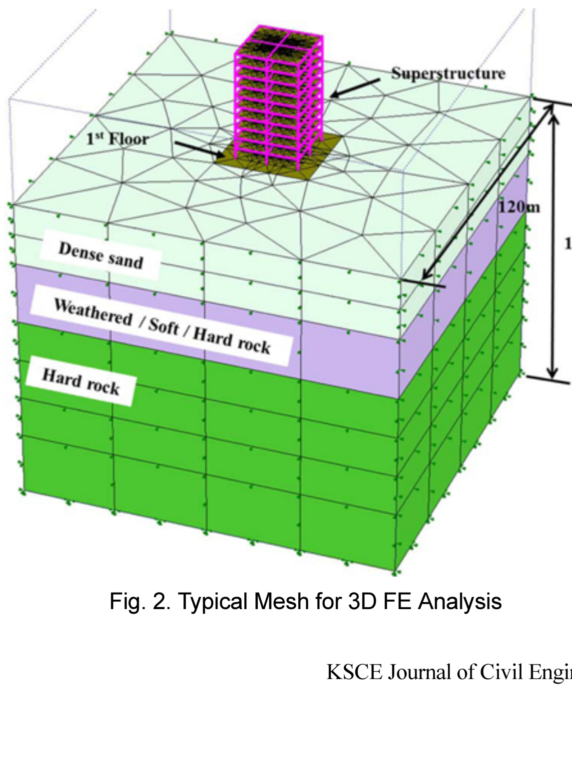

Fig. 2. Typical Mesh for 3D FE Analysis

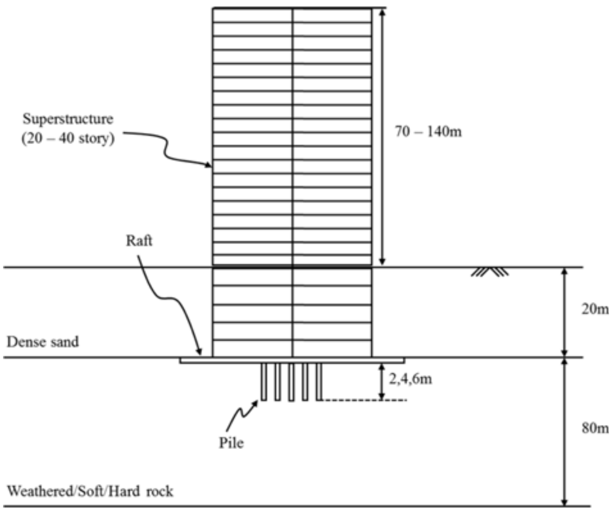

Fig. 3. Schematic of Super- and Sub-structure Modelling

based on the self-weight of the material. After initial equilibrium, the uniformly distributed vertical loading that was assumed as a live load, was applied on the top of the 10 story super-structure and 5 story sub-structure. The modeling of the super- and sub-structure is shown in Fig. 3.

3.2 Material and Analysis Model

In top-down method practice, the footing of the structure is set on weathered rock, soft rock, and hard rock for stable end-bearing capacity. The material properties were adopted from typical experimental values based on the results of a soil investigation in field cases as reported by Seol *et al.* (2008), Cho *et al.* (2011), and Jeong *et al.* (2014). The soft rock in this analysis was assumed to be equivalent to the 4th grade rock, and the hard rock was equivalent to the 2nd grade rock based on the Rock Mass Rating (RMR) system. An isotropic elastic model was used for the mat foundation, beam and column. The material behaviors of the soil and rock were modeled based on a Mohr-Coulomb model. Young's modulus of the mat (footing) was applied to a general concrete material parameter. The properties of the beam and column were based on the field manual of a typical top-down method construction site in Seoul Korea, constructed by Daewoo Construction Company. The material properties and the geometry of the elements used in the analyses are summarized in Table 1.

3.3 Load Sharing Ratio

Studies on load sharing ratio of pile-raft foundation have been conducted intensively, because the effectiveness of the piled-raft foundation on bearing capacity and settlement limitations. The load sharing ratio of pile the (α_{pr}) in piled-raft foundation is defined as the ratio of the load supported by the pile to the total structural load. The concept of the load sharing ratio of the piled-raft foundation is described in Eq. (1) (Poulos, 2001; Jeong and Hong, 2015; Lee *et al*., 2015).

$$\alpha_{pr} = \sum_{i=1}^{n} R_{pile,i}/R_{tot} \tag{1}$$

Where, $\sum R_{pile,i}$ is the sum of the load supported by the pile and R_{tot} is the total structural load.

In this study, the pre-installed columns of the top-down method structure were assumed to behave similar to the piles in the piled-raft foundation. The load sharing ratio of the top-down method using PRD pile foundation is defined as the ratio of the load acting in the head of the PRD to the total structural load. The total structural load was estimated based on the unit weight, geometry, and number of structural elements.

4. Verification of the Numerical Model

The verification of the three dimensional finite element numerical model was conducted based on two field measurements for a vertically loaded structure under typical Korean rock conditions.

4.1 "D" Residential Building Case

The first objective structure for the verification process used the top-down method having prebored and precast piles, which consisted of a 5-story sub-structure and a 20-story super-structure. The geometry of the structure was 112.7 m × 32.9 m, and the shape of the structure was an irregularly shaped rectangle. For model validation, the structure was simplified based on the size of the footing and the arrangement of the beams and columns, according to the actual design sheet.

A sequential analysis, was carried out based on the construction log provided by the "D" company, to investigate the load sharing ratio of the prebored and precast piles. The load sharing ratio of the prebored and precast piles in the actual structure was measured by monitoring the strain of the piles due to the axial load throughout the construction process. The field data were

Table 1. Material Properties Used for Parametric Study

Type	Elastic Modulus, E (MPa)	Poisson's Ratio, v	Unit Weight, γ (kN/m^3)	Friction Angle, ϕ (deg.)	Cohesion, c (kPa)	Model
Dense sand	50	0.32	20	30	15	Mohr Coulomb
Weathered rock (WR)	400	0.30	21	32	75	
Soft rock (SR)	4,000	0.26	23	35	500	
Hard Rock (HR)	12,000	0.22	26	40	2,000	
Column / Beam	34,000	0.15	25	Diameter, D = 0.8 m		Linear Elastic
Wall / Slab	24,500	0.20	25	Thickness, t = 1.0 m		
Footing (Mat)	28,000	0.15	24	Thickness, t = 2.0 m		

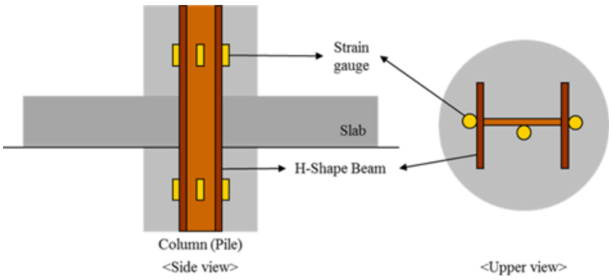

Fig. 4. Installation of Strain Gauge on Test Pile (1st case)

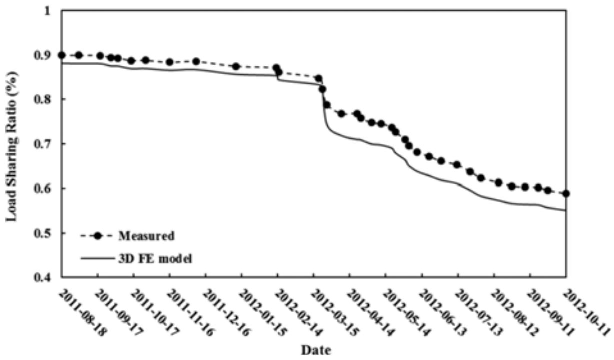

Fig. 5. Verification of the Numerical Model with Field Measurements (1st case)

measured by the strain gauge attached to the H-shaped column as shown in Fig. 4. According to the construction log, the pile strain was measured continuously as the construction proceeded. On the basis of the measured strain of the PRD pile, the axial load acting on the head of the pile was calculated using Eqs. (2) and (3).

$$\sigma = E \times \varepsilon \qquad (2)$$

$$P = \sigma \times A \qquad (3)$$

where, σ is the axial stress (kN/m^2), E is the elastic modulus of the PRD pile (kN/m^3), ε is the strain of the PRD pile (m), P is the axial load acting on the pile (kN), and A is the area of the pile head (m^2). The total structural weight of the objective structure was estimated based on the structure design and calculation sheet. The verification process was carried out by comparing the measured load sharing ratio of a certain single PRD pile with the corresponding PRD pile in the three dimensional finite element analysis model. The properties and element geometries used in the model verification are listed in Table 2.

The comparative results of the numerical analysis and field measurements are shown in Fig. 5. The x-axis represents the date of a significant phase of the construction process based on the construction log, such as excavation, construction of the upper story, and installation of slabs and footing. The y-axis represents the load sharing ratio (%) of a single pile. The time effect on the load sharing ratio was investigated through dynamic analysis which was conducted prior to the actual analysis. On the basis of the dynamic analysis from March 15 2012 to April 14 2012, where the greatest change in load sharing ratio occurred, it was found that the difference in the result was negligible (less than 1%).

The load sharing ratio of a certain single PRD pile measured in the field was in the range of 0.6-0.9%. According to the structure design sheet, there are 31 PRD columns acting as a temporary support during the construction process. Based on this, the total load sharing ratio of the prebored and precast pile can be assumed to be in the range of 18.6-27.9%. The estimated load sharing ratio results were relatively lower than the reported load sharing ratio of a typical piled-raft foundation because of the relatively thick footing and the short pile embedded length of pre-installed columns used in the top-down method. The results obtained based on the numerical model are in good agreement

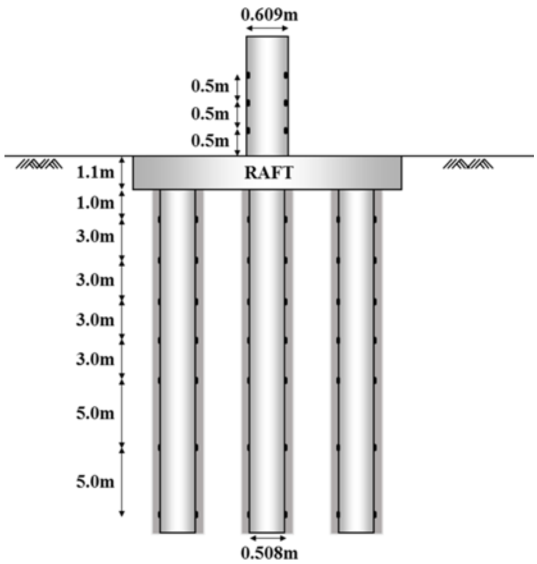

Fig. 6. Schematic of Piled-raft Foundation and Instrumental Setting (2nd case)

Table 2. Material Property used for Model Verification

Type	Elastic Modulus, E (MPa)	Poisson's Ratio, v	Unit Weight, γ (kN/m^3)	Friction Angle, ϕ (deg.)	Cohesion, c (kPa)	Model
Fill	30	0.33	19	29	0	Mohr Coulomb
Dense sand	65	0.33	20	31	10	
Weathered rock	550	0.31	21	32.5	65	
Soft rock	3,200	0.245	23	35	400	
Column / Beam	34,000	0.15	25	Diameter, D = 0.8 m		Linear Elastic
Wall / Slab	24,500	0.20	25	Thickness, t = 0.85 m		
Footing (Mat)	28,000	0.15	24	Thickness, t = 1.69 m		

with the general trend observed in the field measurements.

4.2 "Y" University Engineering Hall Case

The second case for the verification was based on a recently built 4th engineering hall of "Y" University in Seoul Korea. The load sharing ratio of the pile was measured based on a similar process to the first verification case. The schematic of the piled-raft foundation and the instrumental setting is shown in Fig. 6.

The measured load sharing ratio of the piles in the 2nd verification case converged up to 70% near the completion of the construction. The estimated load sharing ratio based on the numerical model used in this study showed about 65%, which is also in good agreement with the field measured data.

5. Parametric Study

In this study, the load sharing ratio of prebored and precast piles in the top-down method was estimated based on three dimensional finite element analysis. The effects of pile spacing, pile embedded length, structure story and rock type on the prebored and precast pile load sharing ratio were investigated. In addition, the effect of the location of the prebored and precast pile in the footing was also studied. Table 3 shows the summary of the parametric study analysis cases having three different pile spacing, pile lengths, structure stories and rock types. As shown in Figs. 2 and 3, the parametric study was carried out on a 56 m × 56 m square structure having a 5-story sub-structure as well as 20-, 30-, and 40-story super-structures. The material properties of the representative structure used in the parametric study are listed in Table 1. Many studies indicate the significant effect of the thickness of the footing. In this study, we focused on the effect of other major influencing factors and kept the thickness

Table 3. Summary of the FE Analysis Cases for Parametric Study

Structure geometry			Rock type
Pile spacing	Pile length (m)	Story	Weathered Rock (WR) & Soft Rock (SR) & Hard Rock (HR)
15D (5 × 5)	2	20F	
10D (7 × 7)	4	30F	
5D (13 × 13)	6	40F	

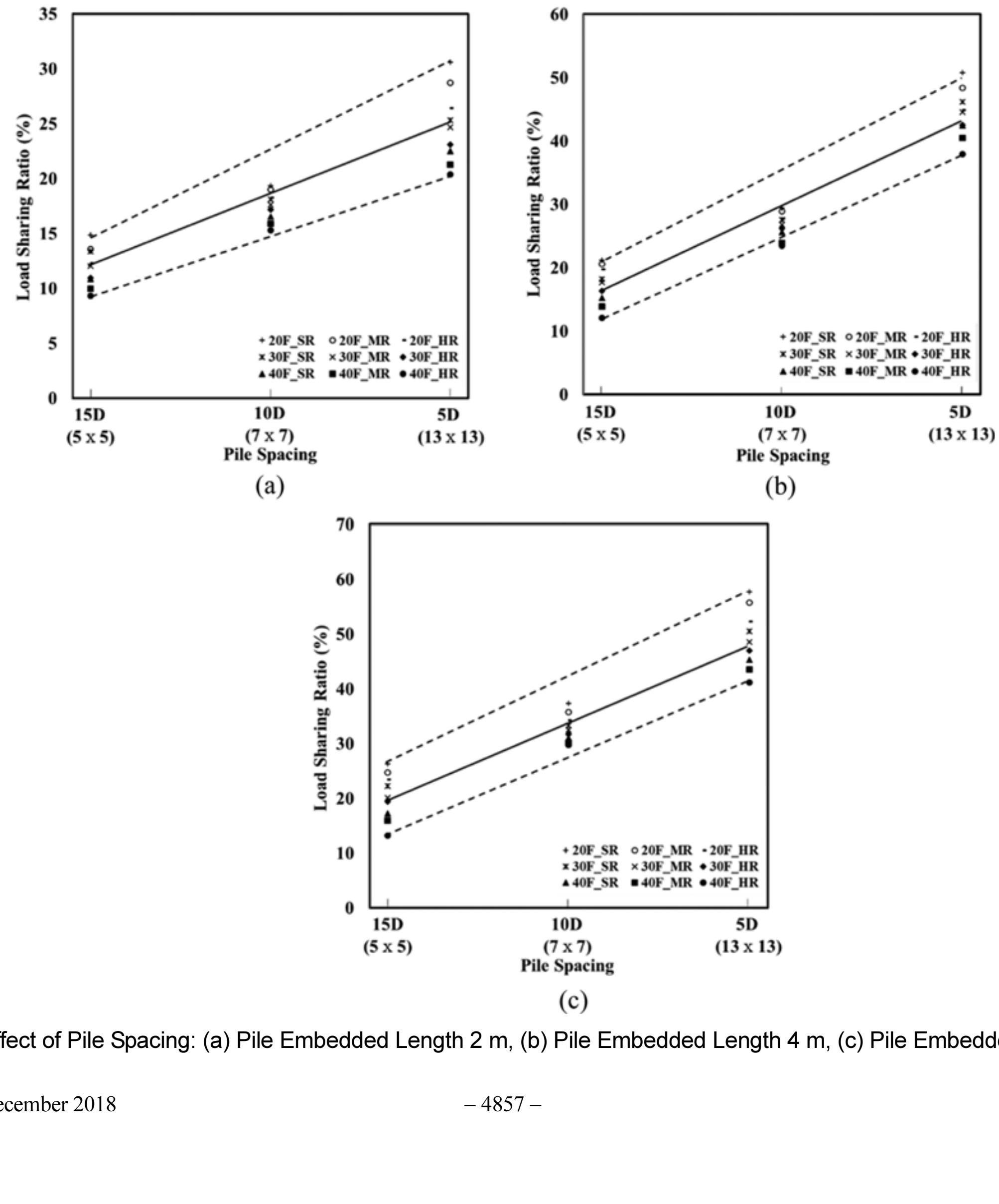

Fig. 7. The Effect of Pile Spacing: (a) Pile Embedded Length 2 m, (b) Pile Embedded Length 4 m, (c) Pile Embedded Length 6 m

Through a total of 81 cases of analysis, the apparent load sharing ratio of the prebored and precast piles in the top-down method is presented here. The apparent upper boundary, lower boundary and mid-value of the load sharing ratio of the prebored and precast piles are shown. Furthermore, the difference of load sharing ratios of a single prebored and precast pile according to the location in the footing is presented as a reference on optimal pile arrangements to limit the settlement and secure the serviceability of the structure.

5.1 The Effect oF Pile Spacing

A series of numerical analyses on the top-down structure using prebored and precast piles were performed for different pile spacing. 15D (5 × 5), 10D (7 × 7), 5D (13 × 13) cases were investigated. The number of piles differed by pile spacing of 25, 49 and 169 piles respectively. The analysis results show that the decrease in pile spacing tended to increase the load sharing ratio of prebored and precast piles notably. The load sharing ratio increased in the range of 89-214%, as the pile spacing decreased from 15D to 10D and 5D. However, the load sharing ratio of a single prebored and precast pile decreased as the number of prebored and precast piles increased because of small pile spacing. The analysis results are shown in Fig. 7.

5.2 The Effect Of Pile Embedded Length

The effect of pile embedded length on the prebored and precast pile load sharing ratio was investigated by varying the pile embedded length: L = 2, 4 and 6 m. The embedded length was relatively short compared with the typical pile due to the distinctive characteristic of the pre-installed column in the top-down method. To focus on the effect of pile length, the end bearing condition and the rock surrounding the pile were modeled identically. Through numerical analysis it was found that, as the pile length increased to 300%, the increase in total load sharing ratio of the PRD pile was observed in the range of 70-110%, and the results are presented in Fig. 8.

5.3 The Effect of Structure Story

The top-down method is commonly used for structures having

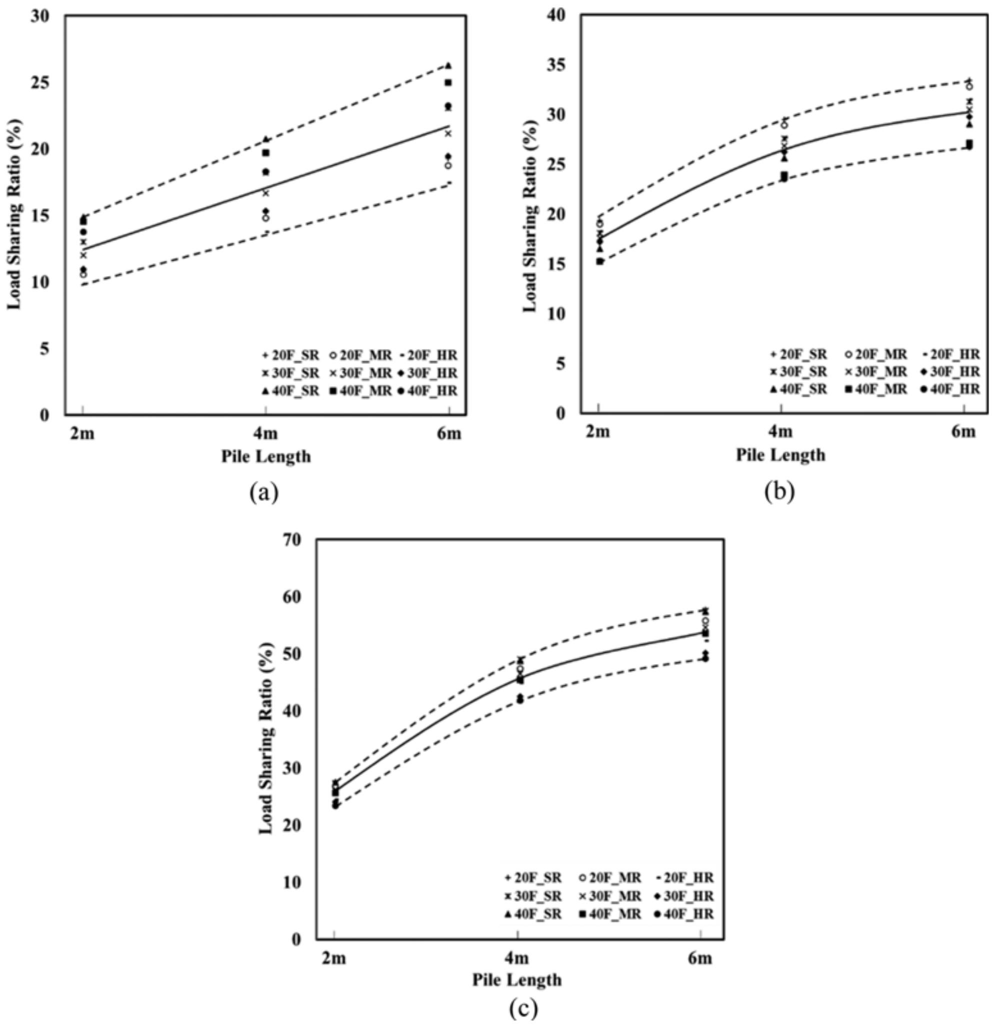

Fig. 8. The Effect of Pile Embedded Length: (a) Pile Spacing 15D, (b) Pile Spacing 10D, (c) Pile Spacing 5D

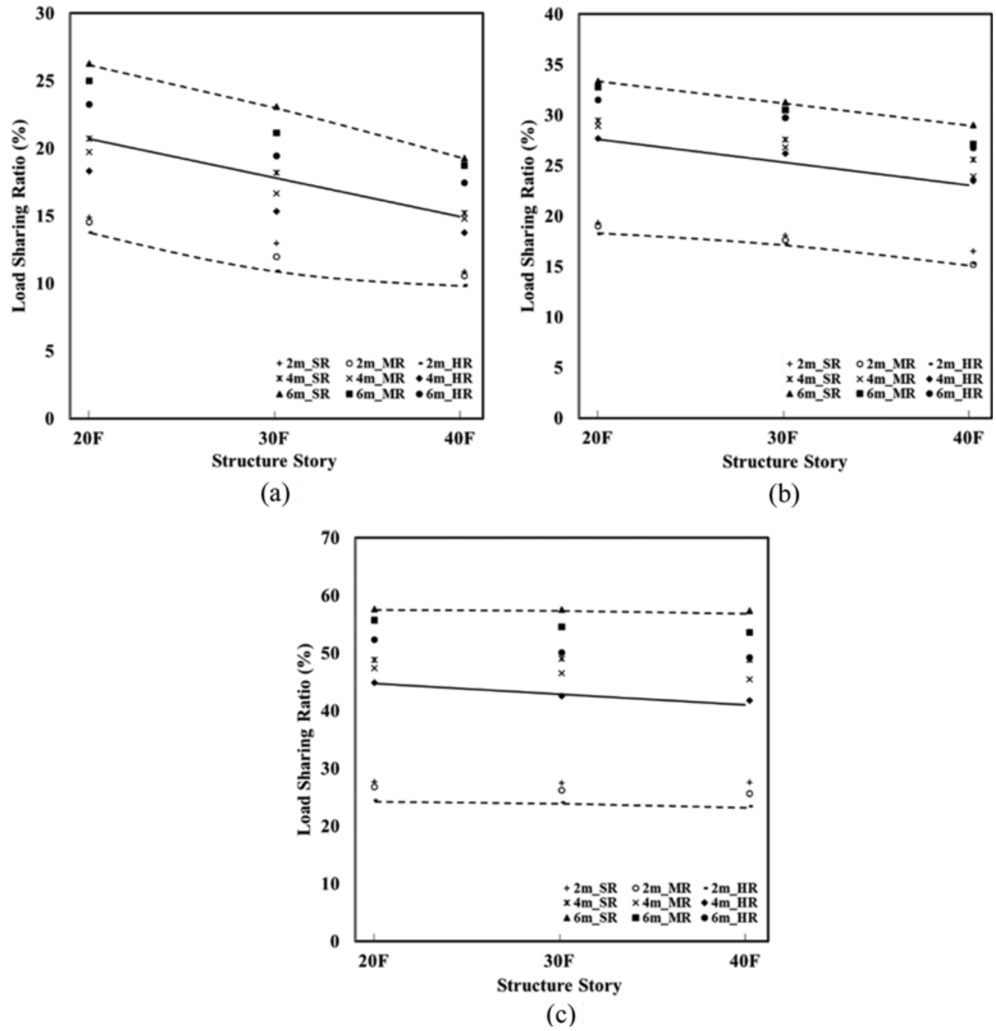

Fig. 9. The Effect of Structure Story: (a) Pile Spacing 15D, (b) Pile Spacing 10D, (c) Pile Spacing 5D

more than 20-story super-structures. In this section, the variation of the load sharing ratio as the construction of the super-structure proceeds is presented. As the construction of the structure proceeded, the load sharing ratio of the prebored and precast piles decreased as shown in Fig. 9. The decrease rates of the load sharing ratio were about 25%, 15% and less than 5% for 5 × 5 (15D), 7 × 7 (10D), 13 × 13 (5D) respectively. On the basis of the results, it was found that as the number of prebored and precast piles increased, the variation of the load sharing ratio due to structure height was relatively insignificant.

5.4 The Effect of Rock Type

The footing and the pile of a top-down method structure are usually constructed on bedrock for high stability. In this study, the footing and the prebored and precast pile were assumed to be set on weathered rock, soft rock and hard rock, respectively. The effect of rock type is shown in Fig. 10. By increasing the hardness of the rock condition, the load sharing ratio of the prebored and precast pile tended to decrease in the range of 5-15%. Based on the numerical results, it could be concluded that the rock type has the least effect on the load sharing ratio of prebored and precast piles.

5.5 The Effect of Relative Position in a Pile Group

The load sharing ratio of the prebored and precast piles was investigated based on the relative position in a pile group (center, corner, edge, and interior). Fig. 11 shows the relative position of PRD piles in the footing.

The results of analysis are shown in Table 4. The numerical results show that the average load sharing ratios of a single PRD pile by pile spacing 15D (5 × 5), 10D (7 × 7), 5D (13 × 13) are, 0.644%, 0.548% and 0.277%, respectively. According to the numerical results, the order of load sharing ratio by pile location is interior > center > side > corner. Based on the results and numerous studies, it was found that the load sharing ratio of PRD piles due to different locations in footing followed a similar tendency of the footing settlement due to axial loading (Jeong *et al*., 2014; Ko *et al*., 2017).

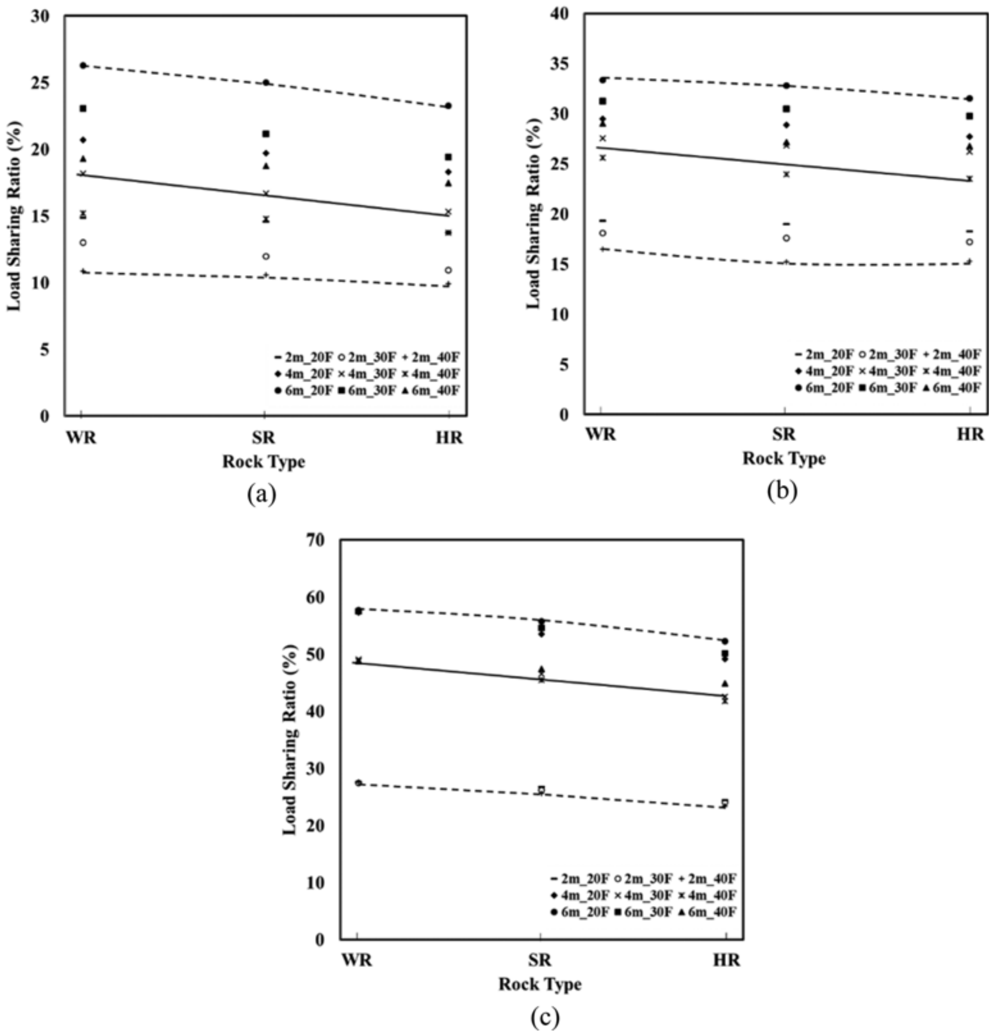

Fig. 10. The Effect of Rock Type: (a) Pile Spacing 15D, (b) Pile Spacing 10D, (c) Pile Spacing 5D

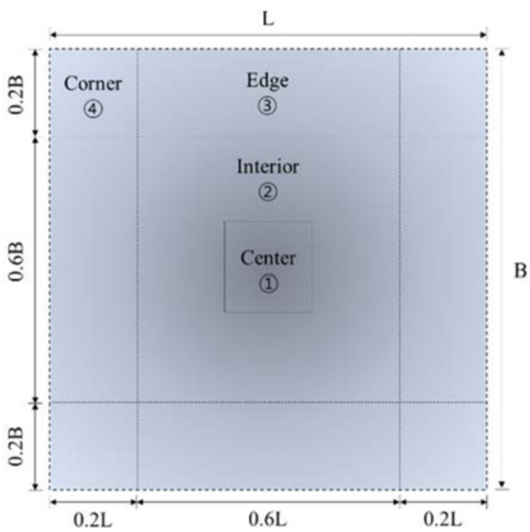

Fig. 11. A typical Mat Foundation Divided Into Zones

Table 4. FE Analyses Results of Load Sharing Ratio of Single Pile Based on Relative Location

Pile spacing	Average (%)	Center (%)	Corner (%)	Side (%)	Interior (%)
15D (5 × 5)	0.644	0.798	0.443	0.577	0.827
10D (7 × 7)	0.548	0.665	0.342	0.440	0.669
5D (13 × 13)	0.277	0.314	0.213	0.248	0.316

6. Conclusions

The main objective of this study is to investigate the apparent load sharing ratio of pre-installed columns (prebored and precast piles; PRD piles) in the typical top-down method building. Parametric studies on influencing factors were carried out through three dimensional finite element analyses; this effect could not be fully clarified in field and laboratory tests. Numerical modeling techniques were also verified based on the field measurements. Based on the studies conducted, following conclusions can be drawn:

On the basis of the obtained results through field measurements and numerical analysis, the load sharing capacity of prebored and precast piles in buildings using the top-down method was significant. The measured load sharing ratio of two objective sites was about 30% and 70%, respectively, which varied by construction progress.

As the pile spacing increased, the load sharing ratio decreased greatly. This was also closely related to the number of piles supporting the structure.

The increase in the embedded length of the prebored and precast pile piles, caused a proportional increase in the load sharing ratio. The end bearing condition of the pile and the pile surrounding condition were set constantly to solely focus on the effect of the pile length.

Based on the field measurement of load sharing ratio on the top-down method structure using prebored and precast piles, the load sharing ratio varied as the construction progresses. Through a series of numerical analysis, the prebored and precast pile load sharing ratio as construction proceeded from, 20 to 30 and to finally 40 stories, was found to decrease.

The effect of the rock condition supporting the footing as well as the prebored and precast pile was also examined. By modeling the rock condition, as the hardness of the rock condition increased, the higher portion of the structural load was supported by the footing than the prebored and precast pile. However, the rock condition was found to have the least effect on the variation of load sharing ratio compared with other factors.

On the basis of the field measurement and series of numerical analysis, it can be concluded that the prebored and precast pile in the top-down method not only acted as a temporary support during construction but also supported a notable portion of the structural load throughout the duration of the structure.

Acknowledgements

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