Load-sharing ratio of prebored and precast piles in piled-raft foundations socketed in weathered rock

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ABSTRACT

The load sharing ratio of the prebored and precast pile in top-down method foundation was investigated by using a numerical analysis and a field case study. The emphasis was on quantifying the apparent load sharing ratio of the prebored and precast pile during the top-down method construction process. A series of 3D FE analysis were conducted with special attention given to the pile load sharing ratio under various conditions, such as pile geometry, pile length and structure load. In addition, the load sharing ratio of a single pile was also investigated based on the location of the pile in the raft (footing). The analysis model was verified by comparing the analysis model with the field data of an actual construction site using the prebored and precast pile and the top-down method. Based on the series of analysis results and the field measurements, when the soil condition is better than weathered rock and for moderate pile length, at least 15% of the total structure load was supported by the pile throughout the construction process. Furthermore, it was shown that the pile near the center of the raft carried more structure load compared to the piles in the side and the corner of the raft.

Keywords: Prebored and precast piles, percussion rotary drill (PRD) pile, 3D FE analysis, top-down method, load-sharing ratio

1 INTRODUCTION

To prevent public nuisance, such as noise, vibration and dust during construction, top-down construction method is widely used 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). Top-down construction method has the advantage of being able to protect nearby buildings as well as underground structures (Crawley and Stones, 1996; Song *et al.*, 2009) and can thus be applied as an alternative construction method to the conventional bottom-up construction method. The use of top-down method is also due to the ability to construct both super- and sub-structures simultaneously, which reduces the construction period significantly.

Main structural elements of the top-down method includes retaining walls, pre-installed columns, slabs (floors) and a mat foundation (footing). Among the structural elements, the pre-installed columns plays a critical role in stability during construction. The pre-installed column serves as a temporary foundation which supports the structural load during construction. Due the pre-installed columns, the top-down method is capable of constructing the super- and sub-structure simultaneously which leads to shorter construction period (Hong *et al.*, 2010).

However, recent field measurements indicate that the pre-installed column actually acts a foundation element and contributes in supporting the structural load even after the completion of the structure. Based on this measurements, the pre-installed columns and the footing can be assumed to support the structure as a piled-raft foundation. And under this assumption, the thickness of the footing can be reduced.

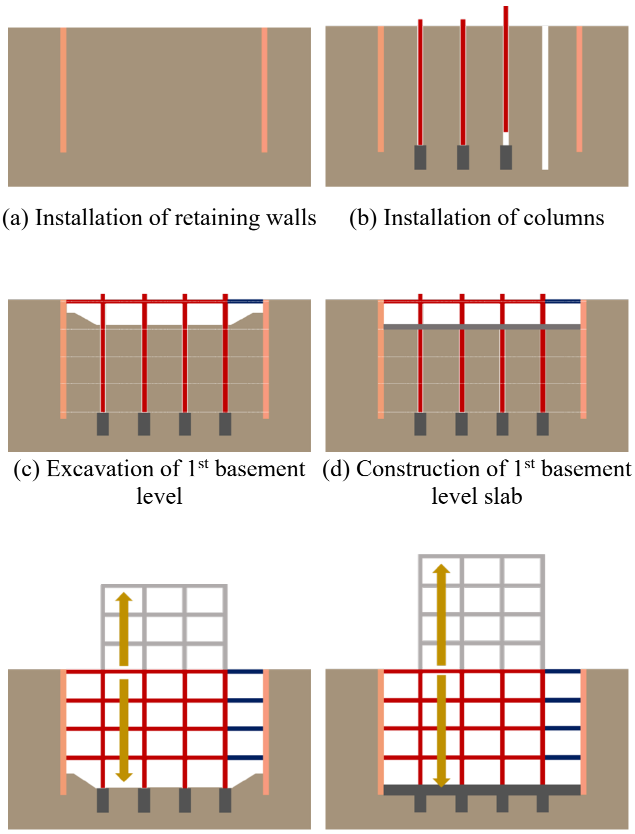
In this study, the load sharing ratio of the pre-installed prebored and precast pile of the top-down method is investigated through three-dimensional finite element analysis. The modelling and the analysis follows the construction process of the top-down method, and the sharing ratio of the prebored and precast pile is estimated individually for each process. The verification of the analysis model and the process is carried out through comparing the analysis results with the settlement and the load sharing ratio of a field data from an actual construction site in Korea, using top-down method with prebored and precast piles. The load sharing ratio of the prebored and precast pile will be estimated under various conditions – soil condition, pile geometry (spacing and configuration), pile length and structure load – and based on this, a considerable load sharing ratio will be suggested.

2 TOP-DOWN METHOD AND PRD PILE

2.1 Top-down method

The advantages of using top-down method in urban construction – less noise, vibration and dust, as well as the shortened construction period – is due to the unique construction process. The unique process involving the pre-installed retaining wall and temporary columns, reduces the exposure of noise and dusts, and secures stability of excavation surface during construction. For this reason, the top-down method is capable for deep excavation even in narrow urban construction sites and can be applied under various harsh soil conditions, such as high underground water flow and weak soil conditions (POSCO, 2001).

The construction process of top-down method is shown as a schematic in Fig. 1. The construction begins by installing retaining walls along the perimeter of the structure. Diaphragm walls are the most commonly used in this process. This retaining wall acts as a basement wall for the duration of the structure. After the installation of the retaining walls, columns which supports the structural load during the excavation and construction process, is installed. By using prebored and precast piles, the vibration during pile installation can be reduced significantly. With the temporary columns installed, the slab for the first floor is placed above the site ground.



(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

Fig. 1 Schematic of top-down construction process

After the construction of the 1st floor slab, the excavation of the 1st basement level is carried out. Since the excavation is executed under the slab, the exposure of noise, dust can be sealed by the slab, thus reducing negative effect on nearby structures and residence. 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. The upper structure construction continues until it reaches the targeted floor level.

2.2 Prebored and precast pile

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

The prebored and precast pile is installed by boring a hole in the ground and placing the precast PHC (Pretensioned Spun High Strength Concrete) pile or steel pile in the borehole and finished by pouring and casting cement milk around the pile. Due to the unique installation process of the prebored and precast pile, maximum mobilization of the skin friction is capable, which yields notably higher skin friction than the conventional piling methods. In addition, the preboring process induces significantly less noise, vibration and dust during installation compared to driven pile and is more cost effective compared to drilled shafts. For this reason, prebored and precast pile is commonly used for top-down construction, which mainly occupies in 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. PRD pile is a type of prebored and precast pile, which is installed through combination of rotation and percussion. The drilling is achieved by cutting and grinding (rotary) action at the same time as a chipping (percussive) action. Types of PRD method include the blasthole drill and the down-the-hole (DTH) hammer drill. PRD pile is used in this project to drill through various soil and rock conditions. In addition, by using the PRD pile method, the quality control can be achieved relatively conveniently by using the H-shape steel beam as a temporary support column.

3 3D FE ANALYSIS MODEL

3.1 FE mesh and boundary conditions

The soil and the structural elements are modeled with finite elements, which allow very rigorous analysis of the load sharing behavior among pile and the footing. The commercial FE package PLAXIS 3D Foundation (PLAXIS bv., 2008) was used for numerical analysis. PLAXIS 3D Foundation is widely used in geotechnical engineering and the accuracy of this program was

confirmed through various geotechnical engineering issues (Kim and Jeong, 2011). In addition, PLAXIS 3D Foundation can be easily adapted in modeling multi-story structures with piled-raft foundation, and can observe the acting load on top of each individual pile. Fig. 2 shows a typical idealized 3D FE mesh used in this study. The mesh consists of triangular shaped 15-node wedge elements.
Fig. 3 shows the overall dimensions of the model. The boundaries comprise a width of 4 times the mat width from the mat center and a depth of the ground is equal to 3 times the depth of the basement level. These dimensions were considered adequate through case studies, to eliminate the influence of boundary effects on the load sharing ratio between the PRD 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 the soil layers. The size of the mesh was modelled differently for the structure area and the outer area to prevent excessive time consumption. The effect of different mesh was studied by conducting a case study. The results shows that the difference (less than 1%) was found to be neglectable. In numerical analysis, the initial equilibrium state is important. The specified initial stress distributions should match the calculations based on the self-weight of the material. After initial equilibrium, the uniformly distributed vertical loading, which is assumed as a live load, was applied on the top of the 10 story super- and 5 story sub-structure.

3.2 Material parameters and interface model

In top-down method practice, the footing of the structure is bearing on typically 1) weathered rock, 2) soft rock, and 3) hard rock. Therefore, the 3 types of soils were adopted to analyze the changes of load sharing ratio under various soil conditions. The material properties were adopted from some typical values based on the results of a soil investigation in field cases as reported by Cho *et al.* (2011) and Jeong *et al.* (2014). An isotropic elastic model was used for the mat foundation, beam and column, and the material behavior of the soil and rock was modeled with a Mohr-Coulomb model. A mat Young's modulus

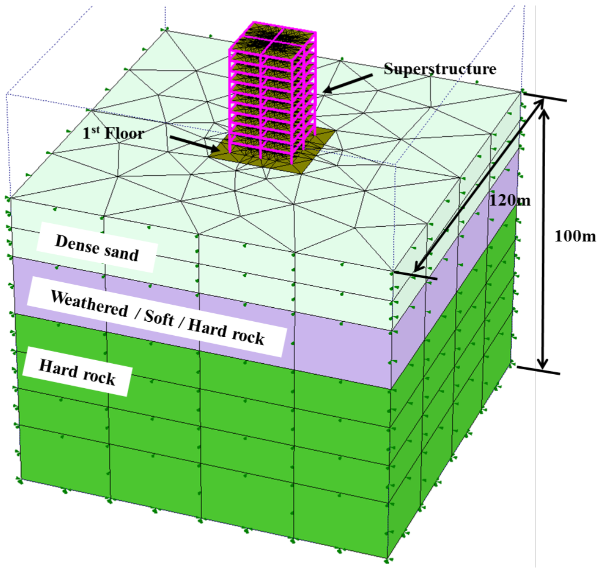


Fig. 2 Typical mesh for 3D finite element analysis

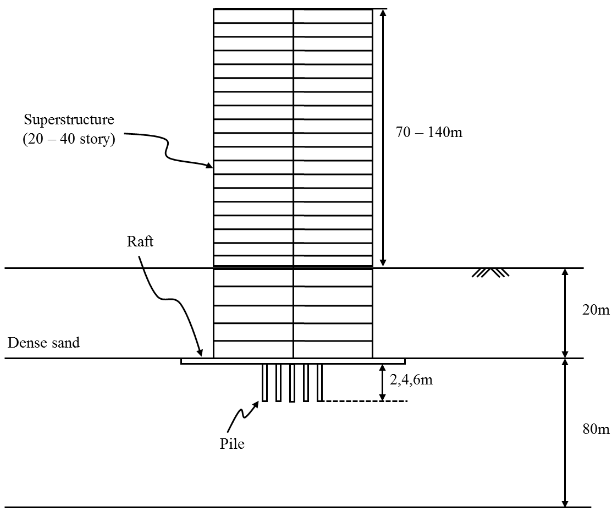


Fig. 3 Schematic of super- and sub-structure modeling

was applied to a general concrete material parameter. The property of beam and column is based on the field manual of a typical top-down method construction site in Seoul Korea, constructed by D Construction Company. The material properties used in the analyses are summarized in table 1. In addition, the diameter of the beam / column and the thickness of the wall / slab, footing is modeled as 0.8m, 1.0m, 1.5m respectively.

Table. 1 Summary of material properties (parametric study)

Type	E (MPa)	ν	γ (kN/m^3)	ϕ (deg.)	c (kPa)
Dense sand	50	0.32	20	30	15
Weathered rock	400	0.30	21	32	75
Column /Beam	34,000	0.15	25	Diameter = 0.8m	
Wall /Slab	24,500	0.20	25	Thickness = 1.0m	
Footing	28,000	0.15	24	Thickness = 1.5m	

3.3 Interpretation of the results

Studies on load sharing ratio of pile-raft foundation has been conducted intensively, due to the effectiveness of the piled-raft foundation on bearing capacity and settlement limitations. The load sharing ratio of pile (α_{pr}) in piled-raft foundation is defined as a ratio of load supported by the pile against the total structural load. The concept of the load sharing ratio of the piled-raft foundation is shown in Eq. 1 (Jeong *et al.,* 2014).

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

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

In this study, the foundation of the top-down method structure is assumed to behave similar to 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 against the total structural load. The total structural load is estimated based on the properties, geometry, and the number of the structural elements.

3.4 3D FE model validation

The validation of the 3D FE model used in this study was conducted by a comparison with field measurements for a vertically loaded top-down method structure on Korean rock. The objective structure for the validation process uses top-down method with PRD piles, which consists of 5-story sub-structure and 20-story super-structure. The geometry of the structure is 112.7 m × 32.9 m, and the shape of the structure is an irregularly shaped rectangular. For the model validation, the structure was simplified based on the size of the footing and the arrangement of beams and columns.

A sequential analysis, which reflects the process in the construction log provided by the D company, was carried out to investigate the load sharing ratio of the PRD piles. The load sharing ratio of the PRD piles in the actual structure was measured by monitoring the strain of three PRD piles of different locations (Pile #1 : center, Pile #2 : interior, Pile #3 : edge) due to axial load throughout the construction process, measured by the strain gauge attached to the H-shaped columns. According to the construction log, the strain of the PRD pile was measured continuously as the construction proceeds. By using the measured strain of the PRD pile, the axial load acting on the head of the PRD pile is calculated using Eqs. 2 and 3.

$$\sigma = E \times \varepsilon \tag{2}$$
$$P = \sigma \times A \tag{3}$$

where, σ is axial stress (kN/m^2), E is the elastic modulus of PRD pile (kN/m^3), ε is the strain of PRD pile (m), P is the axial load acting on the PRD pile (kN) and A is the area of the head of the PRD pile (m^2). The total structural weight of objective structure is estimated based on the structure design and calculation sheet. The validation process is carried out by comparing the measured load sharing ratio of a certain single PRD pile to a corresponding PRD pile in the 3D FE analysis model. The properties used in the 3D FE model validation process is shown in table 2.

The comparative results of the 3D FE analysis and three field measurements are shown in Fig. 4. The horizontal axis is the date of a significant construction process such as additional construction of the upper story, excavation or footing installation. The vertical axis shows the load sharing ratio of a single PRD pile. The numbers indicate the piles. Since the field measurement was continued for more than a year, the effect of the long-term behavior was studied prior to the actual analysis by using a dynamic FE analysis, considering time effect and consolidation. The analysis was conducted along the period through March 15th to April 14th 2012, when the significant changes in load sharing ratio occurred due to footing installation. The difference in the load sharing ratio was found to be insignificant and could be ignored (0.31%). The load sharing ratio of a single PRD pile measured in the field was in the range of 0.4 – 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 PRD

Table. 2 Summary of material properties (model validation)

Type	E (MPa)	ν	γ (kN/m^3)	ϕ (deg.)	c (kPa)
Fill	30	0.33	19	29	0
Dense sand	65	0.33	20	31	10
Weathered rock	550	0.31	21	33	65
Soft rock	3,200	0.25	23	35	400
Column /Beam	34,000	0.15	25	Diameter = 0.8m	
Wall /Slab	24,500	0.20	25	Thickness = 0.9m	
Footing	28,000	0.15	24	Thickness = 1.3m	

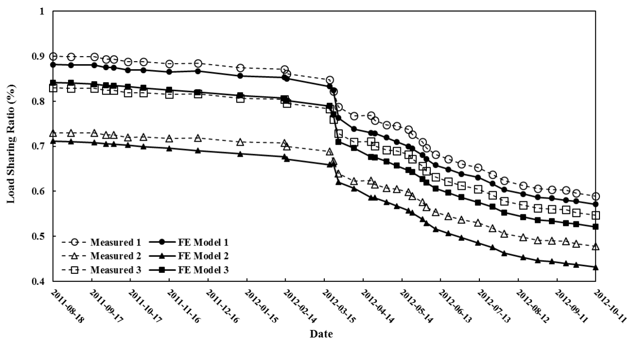


Fig. 4 Validation of the analysis model with single pile load-sharing field measurements

pile can be assumed to be in the range of 12.4 – 27.9%. As for the validation of the 3D FE analysis model, although most load sharing ratio of the 3D FE analysis model are generally lower than the load sharing ratio measured at the actual field, the predictions using 3D FE analysis model can be said to be in good agreement with the general trend observed in the field measurements. In addition, the axial load acting on the PRD piles and the settlement showed identical tendencies as the load sharing ratio.

4 PARAMETRIC STUDIES

In this study, the effect of pile spacing, pile embedded length and structure story on the prebored and precast pile load sharing ratio has been investigated. In addition, the effect of location of PRD pile in the footing has also been investigated. Table 3 shows the summary of the parametric study analysis cases. The parametric study was carried out on a 56 m × 56 m square structure with 5-story sub-structure and 20-, 30-, and 40-story super-structure as shown earlier in Figs. 2 and 3. The material properties for the representative structure used in parametric study is presented in table 1. Although many studies indicate the significant effect of the thickness of the footing, this study modelled a constant thickness of footing to focus on the effect of other major influence factors. Through analysis, the apparent load sharing ratio of the PRD piles in top-down method will be suggested. The apparent upper, lower boundary and the mid-value of the load sharing ratio of the PRD pile will be shown as a result. Furthermore, the difference of load sharing ratio of a single PRD pile according to the relative position in a pile group will also be investigated.

4.1 Effect of structure story

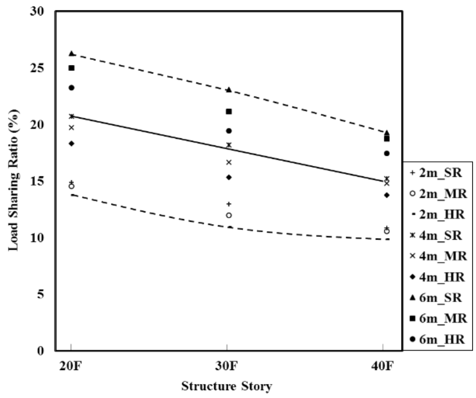
Top-down method is commonly used for structures with more than 20-story super-structures. In this section, the variation of the load sharing ratio as the construction super-structure proceeds is presented. As the construction of the structure proceeds, the load sharing ratio of the PRD piles decreases and this is shown in Fig. 5. The decrease rate of the load sharing ratio is about 25%, 15% and less than 5% for 15D, 10D, 5D respectively. Based on the analysis results, it was found that as the number of PRD piles increases, the variation of the load sharing ratio due to structure height was relatively insignificant.

Table. 3 Summary of the FE analysis cases

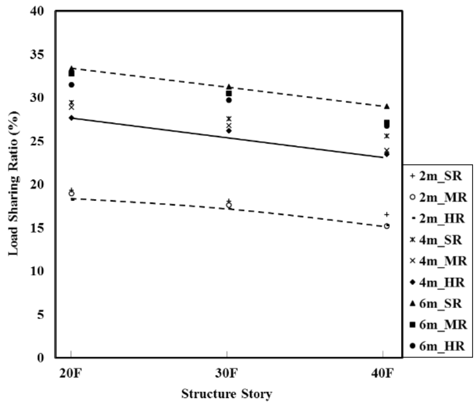
Structure geometry		
Pile spacing	Pile length (m)	Story
5×5 (15D)	2	20F
7×7 (10D)	4	30F
13×13 (5D)	6	40F

4.2 Effect of relative position in a pile group

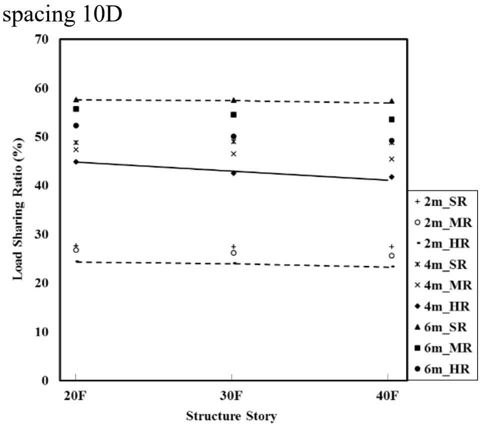
The load sharing ratio of the prebored and precast piles with different relative position in a pile group (center, corner, edge, interior) was investigated. Fig. 6 shows the relative position of PRD piles in the footing. The results of analysis is shown in table 4. The numerical results show that the average load sharing ratio of single PRD pile by pile spacing 15D, 10D, 5D 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, it was found that the load sharing ratio due to different location in footing follows the similar tendency of footing settlement due to axial loading.



(a) Pile spacing 15D



(b) Pile spacing 10D



(c) Pile spacing 5D
Fig. 5 Effect of structure story

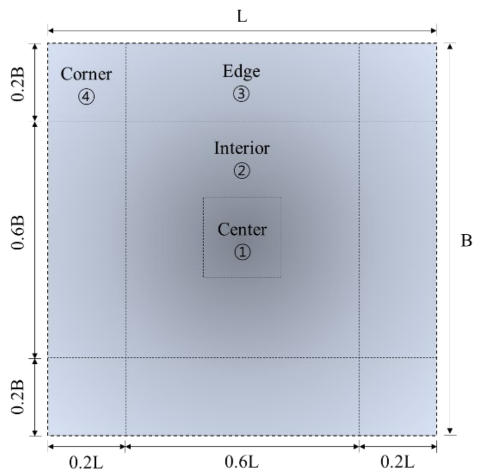


Fig. 6 The effect of cement milk thickness

Table. 4 Load-sharing ratio of single pile in a pile group

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

5 CONCLUSION

The objective of this study is to determine the load sharing ratio of PRD piles in top-down method. A series of 3D FE analyses are conducted to investigate the effect of influencing factors on the load sharing ratio of temporary support columns (PRD piles) in top-down method. Based on the measurements and the parametric studies, the conclusions of this study are as follows:

1) Based on the obtained results, the load sharing capacity of PRD piles in top-down method is significant throughout the construction and the service period. The field measurements shows that the load sharing ratio of the PRD piles in top-down method is in the range of 12.4 – 27.9%, or 0.4 – 0.9% per pile, which varies by the construction progress. The load sharing ratio of the PRD piles are significantly lower than the conventional piled-raft foundation. This was caused by the short pile length of the PRD piles used as a temporary support in the top-down method.

2) With increasing pile spacing, the load sharing ratio decrease significantly. As the pile spacing increases, the load sharing ratio decreases. Based on the field measurement, the load sharing ratio varies as the construction progresses. The PRD pile load sharing ratio as construction progresses was found to decrease. However, the changes in the load sharing ratio as the structure story increases were relatively insignificant compared to pile geometry and embedded length.

3) Based on the field measurement and series of numerical analysis, it can be concluded that the PRD pile in top-down method not only acts as a temporary support, but can also support notable portion of the structural load throughout the construction process and the duration of the structure. By considering the capacity of the PRD piles in the top-down method, optimized design of the raft can be achieved.

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