Raft Thickness Rational Design for Megatall Skyscrapers: Case Studies

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ABSTRACT

The design process for tall buildings involves three main steps: Estimating roughly the sizes of foundation and superstructure components, verifying the determined sizes with full consideration of the interactions between soil, piles, raft, and superstructure to ensure the bearing capacity and deformation of all elements, and optimizing the design with parametric analysis. However, the thickness of the rafts in existing buildings appears to be very thick and varies to the point of confusion. It is noticeable that some buildings have a considerable height but a relatively small raft thickness and vice versa. To address this issue, a simplified graphical method is proposed to determine the raft thickness for the initial design phase. As megatall skyscrapers become increasingly common, a more comprehensive study of rafts is necessary. This article explores the process of designing and constructing rafts for tall and megatall skyscrapers. The study aims to validate and extend the graphical method and establish a basis for the raft thickness optimization process. The research shows that the number of floors strongly affects the thickness of the rafts. However, the elastic modulus is significantly influenced when the ratio of the raft thickness to the number of floors is less than 5% and vice versa.

Keywords-raft thickness; mega-tall building; design method; design procedure; case studies

I. INTRODUCTION

Rafts are intermediate structures positioned between the superstructure and the foundation. They help transfer loads and deformations from the superstructure to the pile group and vice versa. The thickness of the rafts has become a concern with the construction of many mega-tall skyscrapers, as it affects transmission capacity, deformation, stability, and economic issues. Rafts are commonly deployed in pile group and pile raft foundations. Pile foundations, also called pile groups, are widely utilized to increase the depth of the footing and transmit loads to the soil layers with a high bearing capacity. Pile groups [1, 2] are often put into service for high-rise buildings in improperly soft soil. The piles are designed to bear the entire loads from the superstructure. Examples include the Mega Tower (122 floors), Incheon Tower (151 floors), and Shanghai Tower (124 floors), which were built on subsoil with a low Young modulus. As a result, the foundation raft was relatively thick, with the Mega Tower requiring a raft thickness of about 8.0 m, the Incheon Tower requiring 5.5 m, and the Shanghai Tower requiring 6.0 m. Piled rafts [3] are currently exploited worldwide as a piled foundation for high-rise buildings in different soil conditions, from soft to stiff clay and medium to dense sand. Buildings utilizing piled rafts, such as the Kingdom Tower (over 200 floors), Khalifa Tower (165 floors), and Dubai Tower (80 floors), have relatively thin raft thicknesses of 4.5, 3.7, and 2.5 m, respectively. Piles in piled rafts are proposed to bear only a part of the superstructure loads, with the rest of the load borne by the raft. The piles are designed to control foundation settlement in some assumptions. Therefore, the raft thickness can be minimized during the piled raft foundation optimization process. The behavior of a piled raft as a foundation system for Frankfurt's over-consolidated clay [3], based on the well-monitored Messeturm building in Germany, indicates that piled raft concepts offer significant advantages over conventional pile groups and can be considered an optimized solution for high-rise buildings founded on over-consolidated clay.

In [4], it is suggested that the high infrastructural demand and unavailability of proper subsoil have increased the use of Combined Piled Raft Foundations (CPRF) at the current time. The utilization of CPRF in soft soils has been tremendously augmented over the past few decades. A piled raft design solution [5] can reduce the raft's thickness and the number of piles required while minimizing the foundation's settlement. In designing piled foundations, Poulos [6] examines the challenges designers face when creating foundations for tall buildings. Focus is mainly given on the geotechnical perspective. He proposes a three-phase procedure for foundation design and verification, emphasizing determining proper subsoil properties and evaluating geotechnical parameters. Authors in [7] describe the procedure for designing the foundation for the Burj Dubai. The research presents solutions to various design issues, such as maximum bearing capacity, overall stability under wind and seismic loads, and average and differential settlement. From these studies, the process of designing tall buildings involves three main phases: (i) Estimating the preliminary sizes of foundation and superstructure components; (ii) verifying all of the components with full consideration of their interactions to satisfy the bearing capacity and deformation, and (iii) optimizing the design with parametric analysis. The first design step of the procedure is to roughly determine the sizes of the foundation and superstructure components, which will be used in the second and third design steps. In these steps, geological and structural engineers should work closely together. Many programs based on the Finite Element Method (FEM), including Midas GTS, ABAQUS, Plaxis, ELPLA, and multiple simplified elastic simulation programs, such as DEPIG, CLAP, and VDISP [6, 8-10], are engaged to analyze the behavior of pile foundations. This procedure allows for the rational design of all building components.

Regarding the thickness of rafts, designers are now aiming for a thinner and more reasonable design due to better coordination between structural and geotechnical engineers. Structural engineers assume that superstructures are fixed to the raft and piled foundation, while geological engineers take the loads and deformation at column bases to design rafts and piles. The differential settlement of the piled foundation is then used as input data for structural engineers. This iterative calculation stops when the differential settlement at column bases calculated by structural engineers equals the differential settlement of the piled foundation calculated by geotechnical engineers. Authors in [5] point out that the current design of rafts is typically done by structural engineers, who deploy stress equations to analyze the foundation slab on springs. Using the FEM, Nguyen [11] analyzes rectangular plates on resting Winkler and two-parameter elastic foundation models and explores the advantages of adopting the piled raft solution for foundation design. The performance of a raft in a piled foundation [1, 2, 12] under dead and long-term live loads is influenced by various factors, such as the number of floors, the number and length of piles, and the soil properties where the raft is located. Studies have shown that the number of floors and soil properties are the main factors that affect the behavior of rafts. A graphical method is proposed for estimating the raft thickness, which can be later applied in detailed design phases. Statistical data demonstrate that the raft thickness of the high-rise buildings is still quite large in some cases, which raises the issue of investigating its role in resource conservation. The effect of seismic Structure-Soil Interaction (SSI) on the behavior of a building frame resting on a raft foundation has been evaluated by many researchers [10, 13-16]. Authors in [10] conclude that: (i) An increase in raft thickness increases the stiffness of the raft-soil system. However, natural frequencies decrease due to the increased mass involved in vibration. The frequency corresponding to maximum amplitudes also displays a similar trend. (ii) The fundamental frequencies increase with an increase in the soil modulus. For higher soil modulus, the magnitude of the amplitude is lesser compared to lower soil modulus for every raft thickness. As the soil modulus increases, soil stiffness increases, and fundamental frequencies corresponding to peaks increase while peak amplitudes decrease. Authors in [13, 14] investigated the effect of raft mass, its depth, and the soil modulus of elasticity on the response of structures. Modal analysis results disclose that the periods of vibration decrease as the soil modulus of elasticity increases. Nagao [15] asseses the effect of Foundation Width (FW) on Subgrade Reaction Modulus (SRM). If the structure is poorly seismic resistant, it is necessary to widen the FW. However, underestimating SRM can lead to structural overdesign. In this study, the horizontal SRM was found to be highly dependent on FW, whereas the vertical SRM was shown to be less dependent on FW.

A review of the literature in the field of soil-pile raft-structure interaction indicates that considerable research effort was made to achieve accuracy in the Dynamic Soil-Structure Interaction (DSSI) model. Authors in [16] reveal that the consideration of the DSSI condition results in inelastic deformation of the superstructure, exhibiting a marginal increase at higher stories. In fact, the initiation of smaller inelastic deformation of the piles will lead to further increment in story displacement, while such story deformation will gradually decrease with a higher inelastic range of deformation in piles and may be beneficial for superstructure systems. Hence, designing pile members with high flexibility may reduce the seismic risk of failure of the superstructure system.

This paper presents an analysis of the design and construction practices used in the existing tall and megatall buildings. The study includes the evaluation of pile foundation methods, calculation procedures, and methods determining the raft thicknesses. The objective of this research is to validate the proposed graphical method [1, 2, 12] and identify other factors that may impact the design of the raft thickness. Moreover, the study aims to gain valuable insights and experiences in the current design of mega-tall buildings.

II. MATERIALS AND METHODS

A. Raft Behavior

Raft thickness plays a significant role in reducing differential settlement. Several studies [1, 2, 17] indicate that numerous factors affect the raft thickness. These factors can be grouped into three main categories.

1) The Effects of Superstructure

The thickness of a raft is affected by the superstructure in several ways, including the spacing of columns, the number of floors, and the stiffness of the superstructure. The impact of column spacing is negligible [17] and can be disregarded. On the other hand, the influence of superstructure stiffness can be reduced by utilizing iterative calculation methods that involve collaboration between geotechnical and structural engineers. The influence of raft thickness can be determined as [18]:

$$t = 0.058\, n \text{ (m)} \tag{1}$$

where t is the raft thickness (m), n is the number of floors, and the coefficient 0.058 is taken from [18].

It is noticeable that some buildings have a considerable height but a relatively small thickness and vice versa. For instance, The Messertum Tower has a height of 256 m and a raft thickness of up to 6 m, while The Dubai Tower has a greater height of about 400 m but a raft thickness of only 2.5 m. Both projects utilize the pile raft foundation method, and the difference can be observed in the stiffness of the subsoil beneath the raft.

2) The Effects of the Subsoil/ Subsoil Effects

The influence of the subsoil at the bottom of the raft and the tip of the piles can be characterized by its elastic modulus. Authors in [19] analyzed piled rafts on the sand under three basic load combination intensity levels. It was found that the raft stiffness substantially impacts differential settlement. Poulos in [20] suggests that the differential displacement is significant when the ratio of pile-soil stiffness (E_p / E_s) is small. In contrast, the vertical displacement decreases quite strongly. When the pile-soil stiffness ratio is greater than 1000, the vertical displacement of the pile raft is not crucially reduced. The raft-soil stiffness ratio has only a minor effect on the average displacement of the pile raft under horizontal or vertical loads. According to [2, 17], the elastic modulus of the soil immediately below the raft significantly affects the raft thickness.

3) Pile Foundation Effects

According to [21], the thickness of a raft is influenced by several factors, such as quantity, distance, length, diameter, and pile arrangement scheme. Moreover, the foundation method used is crucial in determining the raft thickness. If the pile group foundation method is followed, the raft thickness should be capable of handling deformation, bending moment, and shear stress, which may result in a larger raft thickness. However, if the pile raft foundation is employed, the superstructure loads are distributed more evenly to the subsoil, allowing for a thinner raft. Proper pile arrangement can ensure an even displacement of piles, which can reduce the raft thickness. Therefore, geotechnical engineers must select the appropriate foundation type and pile arrangement to address these issues. With these assumptions, the effects of piles on raft thickness can be ignored.

B. Design Procedures

The procedure [6] of designing tall and megatall building foundations includes the following three stages:

- A preliminary design, which provides an initial basis for developing foundation concepts and costing.
- A detailed design stage in which the selected foundation concept is analyzed and progressive refinements are made to the layout and the details of the foundation system. This stage is desirably undertaken collaboratively with the structural designer, since the structure and the foundation act as an interactive system.
- A final design phase in which the parametric analysis and design are finalized.

C. The simplified method for raft thickness design

This method [2, 17] comprises an interactive graph and is portrayed in Figure 1. The method includes an interactive graph combined with multiplier factors, a factor of 1.0 for a piled raft, and factors ranging from 0.75 to 1.0 for a pile group foundation. Based on Figure 1, the raft thickness, assuming a differential settlement of 2%, can be determined. This method mainly relies on the number of floors, the elastic modulus of the soil layer with a thickness equal to the raft width, and the assumption of a properly designed pile foundation. The determined raft thickness can be deployed as a preliminary value for the detailed design phase when the structural and geotechnical engineers work together closely.

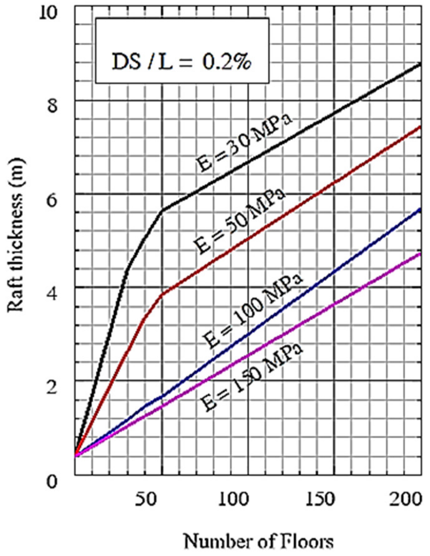

Fig. 1. Interactive chart determining raft thickness with 2% differential settlement. Notes: L: Raft length (m), DS: Differential settlement (m).

The method will be validated by comparing the raft thickness determined by this method with the actual raft thickness collected from the case study projects.

III. CASE STUDIES

This study analyzes the impact of the piled foundations and superstructures on the thickness of rafts used in the existing supertall towers. The study examines the design and construction of several existing and under-construction skyscrapers, such as Kingdom Tower (over 200 floors), Burj Khalifa (165 floors), Inch (over 151 floors), and Shanghai Tower (129 floors).

A. Kingdom Tower, Jeddah

Authors in [8] conducted a study on the geological survey and foundation design stages for Kingdom Tower, which is over 1,000 m high and is located in Jeddah city, Saudi Arabia. The study primarily focuses on selecting geotechnical parameters, soil-structure modeling, and ensuring effective interaction between structural and geotechnical engineers. The goal is to achieve convergence of foundation model analysis results of the soil-structure model. The proposed foundation solution for this tower is a pile raft. The raft is placed on a coral limestone foundation, with an elastic modulus ranging between 150 - 500 MPa. The thickness of the raft is 4.5 m at the foundation's center and gradually increases to 5 m at the wings. The pile foundation system consists of 226 bored piles with a diameter of 1.5 m and 44 bored piles with a diameter of 1.8 m connected to the raft. Pile lengths vary from 45 m at the wing area to 105 m at the tower's center. The authors applied ETABS and Midas GTS to analyze the foundation design. They expect that the settlement will not exceed 20 mm.

B. Burj Khalifa

This tower [6, 7, 9, 22] is 828 m high, and at the time of construction, it was the world's tallest building. The superstructure is made of reinforced concrete. The subsoil conditions comprise a horizontally stratified subsurface profile, which is complex and highly variable due to the nature of deposition and the prevailing hot, acid climatic conditions. The subsoil's elastic modulus is between 150 and 500 MPa. After evaluating the subsoil, it was concluded that a pile-raft foundation would suit the tower and podium construction. The foundation involves a 3.7 m thick raft supported by 194 cast-in-place bored piles. The piles are 1.5 m in diameter and about 43 m long, with a bearing capacity of 3,000 tons each (test pile load is up to 6,000 tons). To ensure the tower's foundation is stable, the minimum center-to-center spacing of the piles was verified. It was determined that the spacing should be 2.5 times the pile diameter. The foundation was assessed for vertical and lateral stability, assuming it acts as a block comprising the piles and soil/rock. The assessment showed a safety factor of just under 2 for vertical block movement, excluding base resistance, and a safety factor of more than 2 for lateral block movement, excluding passive resistance. Additionally, the assessment exhibited a safety factor of approximately five against overturning the block. Hyder Consulting Ltd. conducted a 3D foundation settlement analysis based on the geotechnical investigation and pile load test results. The analysis determined that the maximum settlement over time would be around 80 mm, with gradual curvature of the top of the subsoil over the large site. The maximum measured settlement to this point (after completion of the concrete frame) is 46 mm. Based on a rigid block analysis, a hand calculation by Clyde Baker predicts a settlement of 50-60 mm. The estimated differential settlement is about 14 mm.

C. Incheon Tower

A 151-story supertall tower project [6, 22] is being built in Songdo, Korea, on a reclaimed area with extensive sand/mud flats and nearshore intertidal areas. The foundation system comprises 172 bored piles with a diameter of 2.5 m, socketed into the soft rock layer and connected to a 5.5 m thick raft. A pile group was used as the foundation method. The challenges, in this case, relate to constructing a very tall building on a site with complex geological conditions sensitive to differential settlements. The site is situated in an area of reclamation, consisted of approximately 8 m of loose sand and sandy silt. This layer rests on about 20 m of soft to firm marine silty clay called the Upper Marine Deposits (UMD). Below the UMD, there is a layer of approximately 2 m of medium-dense to dense silty sand, known as the Lower Marine Deposits (LMD). The LMD layer is situated above the residual soil and a weathered rock profile. The geological structures in this area are complex and consist of geological boundaries and sheared and crushed seams, which may be related to faulting movements and jointing.

The foundation comprises a mat and piles supporting columns and core walls. The piles' number, layout, and size were determined through the collaboration between the geotechnical engineer and the structural designer. The geotechnical engineer identified the pile depth, considering the piles' performance and capacity. The pile layout was selected from the various options considered. The tower foundation's overall stability was assessed using Coffey's in-house computer program CLAP. This program computes the distributions of axial and lateral deflections, rotations, and axial and lateral loads and moments at the top of a group of piles subjected to a combination of vertical loads, lateral loads, moments, and torsion. The contribution of the raft to the overall stability of the foundation was ignored, and the overall stability is satisfied if the foundation system does not collapse under these conditions. The results from GARP reveal that the largest displacement is 67 mm and the deflection is 34 mm. Results from PLAXIS display a maximum displacement of 56 mm, and a deflection of 40 mm.

D. Shanghai Tower

The Shanghai Tower is an exceptionally tall skyscraper located in Lujiazui, Pudong, Shanghai [23]. It was considered the second-tallest building in the world during its construction, with a height of 632 m. The tower has a 124-story building, a 7-story podium, and a 5-story basement, with a foundation depth of 31.4 m. The groundwater level is about 0.5 to 1.5 m below ground level. The site's soil conditions are complex and highly variable, with a horizontally stratified subsurface profile. The subsoil below the ground level is a combination of clay, silty clay, and sand, underlain by completely decomposed granite. The subsoil is divided into nine layers and fourteen sub-layers based on the soil type and physical properties. The top layer is the bearing layer for a shallow foundation with an elastic modulus of about 60 MPa. According to the geotechnical investigation, the fifth, seventh, and ninth layers are the end-bearing layers for piles. The raft under the tower is 6 m thick and covers an area of 8945 m^2. It is supported by 955 bored piles, each with a 1.0 m diameter. The piles are spaced 3 m apart and distributed across four sub-areas: A, B, C, and D. In area A, the pile length is 56 m, whereas in the other zones, they are 52 m. The research conducted in [24] found that the settlement of the building's rigid core and mega columns was 6 0mm and 45 mm, respectively, under almost 75% of the building load. However, the calculated values were smaller than the actual ones because they did not consider the long-term settlement due to the consolidation of the clay layers. According to [25], the maximum settlement ranges from 101 mm to 143 mm and the differential settlement was 15 mm in February 2013. The ELPLA program's predictions suggest that the differential settlement will be around 60 mm.

E. Summary

Table I displays the raft thickness for the four considered case studies and three additional towers for which the author has information. The thickness values were determined following the simplified graphical method [2, 17] and are presented in Table I. The Table clearly shows that the raft thickness obtained by the graphical method is consistent with the actual designed thickness. This suggests that during the initial design phase, the thickness values obtained from the graphical method are reliable and can be used to optimize the final thickness in later design phases. Towers designed deploying the pile raft method, such as Dubai Tower, Khalifa Tower, and Kingdom Tower, generally have their raft placed on proper soil with an elastic modulus of 150 MPa or more. Their raft thickness is relatively thin, with the ratio of raft thickness to the number of floors being about 2.5%. On the other hand, towers founded on soft soil, such as Mega Tower, Shanghai Tower, Landmark 81, and Incheon Tower, often employ the pile group method. Their raft thickness values are relatively larger, with the ratio of raft thickness to the number of floors being about 4 to 9%.

TABLE I. RAFT THICKNESS VS NUMBER OF FLOORS

Project name	**As designed**				**Raft thickness by the simplified method (m)**
	Foundation type	**Number of floors**	**Elastic modulus (MPa)**	**Raft thickness (m)**	
Kingdom Tower	PR	200	>150	4.5	4.4
Khalifa Tower	PR	165	>150	3.7	3.9
Shanghai Tower	PG	128	~50	6.0	5.9
Incheon Tower	PG	151	~70	5.5	6.1
Mega Tower	PG	122	~30	8.0	7.5
Dubai Tower	PR	85	>150	2.5	2.8
Lanmark 81	PG	81	~30	7.5	6.5

Notes: PR: Piled Raft; PG: Pile Group; Fdn: Foundation.

The rafts of Mega Tower and Landmark 81 Tower are 1.5 to 2.0 m thicker than those of Shanghai Tower and Incheon Tower, despite the former two towers being lower than the latter. Additionally, implementing the graphical method, the calculated raft thickness of Mega Tower and Landmark 81 Tower is approximately 0.5 to 1.0 m thinner. This suggests that more extensive research is required to accurately determine and optimize rafts' thickness.

IV. DISCUSSION

In Figure 2, a statistical correlation is presented between the thickness of the raft (m) and the number of floors for 37 buildings constructed in Vietnam and around the world. The Figure also portrays the correlation between the raft thickness (m) and the number of floors calculated using (1). Based on this Figure, it can be inferred that the thickness of the raft is dependent on the number of floors in the building.

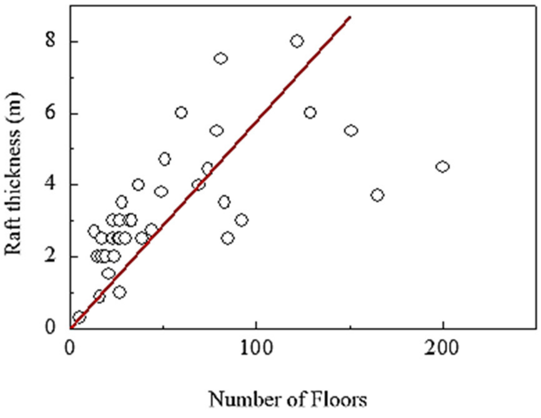

Fig. 2 Relationship between raft thickness and number of floors based on statistical data and (1) [18].

Figure 3 illustrates that the thickness of a raft is not solely dependent on the number of floors, as the trend curve is not linear. This is consistent with the conclusions of [1, 2, 17], which suggest that other factors, such as the subsoil beneath it, the pile system, and the stiffness of the superstructure, also influence the thickness of the raft. Some researchers, mentioned in [17], believe that the elastic modulus of the subsoil plays a significant role in determining the thickness of the raft. They also hold that the raft in a piled raft foundation is thinner than that in a pile group because it is recommended only when the subsoil underneath the raft has a sufficiently high elastic modulus.

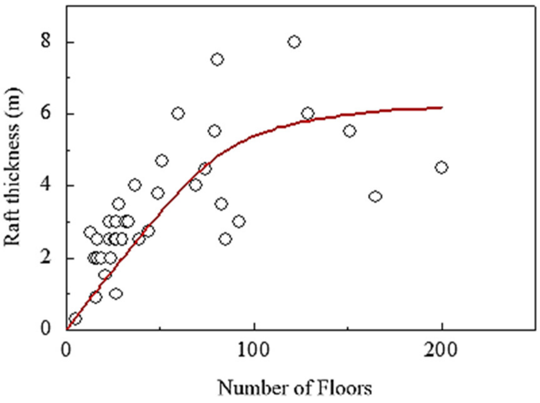

Fig. 3. Relationship between raft thickness and number of floors based on statistical data and its tendencies.

The statistical data in Figure 4 exhibit a correlation between the ratio of the raft thickness to the number of floors and the elastic modulus. The trend curve suggests that when the ratio is less than 1/20 (meaning the raft is relatively thin), the elastic modulus of the subsoil beneath the raft has a significant impact on the raft thickness. However, if the ratio is greater than 1/10 (meaning the raft is relatively thick), then the elastic modulus of the subsoil has an insignificant influence.

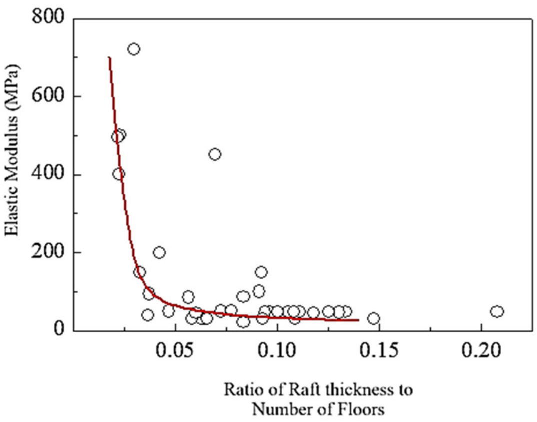

Fig. 4 Relationship between the elastic modulus and the ratio of raft thickness to the number of floors based on statistical data and their tendencies.

After analyzing the four case studies of the supertall towers, the following observations can be made: Jeddah Tower is over

1000 m high (200 floors) with a raft thickness of 4.5 m. Khalifa Tower is 829 m high (165 floors) with a raft thickness of 3.7 m. Shanghai Tower is 632 m high (128 floors) with a raft thickness of 6 m. Incheon Tower is 601 m high (151 floors) with a raft thickness of 5.5 m. The raft thickness of the towers calculated according to the graphical method (Table I) is 4.4 m, 3.9 m, 5.9 m, and 6.1 m, respectively. This indicates that the thickness of the raft is proportional to the number of floors and subsoil elastic modulus, and the results from the graphical method and the actual thickness are consistent. However, the rafts of Jeddah and Khalifa towers are on hard limestone foundations with an elastic modulus of about 150-200 MPa using the pile raft method. Hence, the raft thickness is relatively thin. The rafts of Shanghai and Incheon towers are on a weaker ground with an elastic modulus of about 50-60 MPa employing the pile group method, so their rafts seem to be thicker. This suggests that the thickness of the raft depends on both the number of floors and the subsoil under the raft.

Several studies [13-15] have focused on seismic SSI, specifically concentrating on the effect of raft mass and depth, soil modulus on structure response, and the impact of raft width on subgrade reaction modulus. However, very few studies have concerned raft behavior as a standalone structure. The raft's size and mass may impact the static and dynamic behavior of the pile-soil system and superstructure members. In the stability assessment of the Burj Khalifa and Incheon Tower [6, 9, 22], the effect of raft thickness has been ignored, regardless if they are subjected to static or dynamic loads. Additionally, the impact of raft mass on the raft-pile-soil and raft-superstructure was not evaluated. Therefore, further study of the roles of rafts on the dynamic behaviors of the superstructure, the raft, and the pile-soil system seems necessary.

V. CONCLUSIONS

This article examines the role of rafts by analyzing the design and construction experiences of several existing megatall skyscrapers. The thickness of their rafts was verified using a graphical method that has been previously proposed. Based on the findings obtained from this study, the following conclusions can be drawn:

- Experiences from the design of the projects show that applying a three-step process and close collaboration between geotechnical and structural engineers can result not only in reasonable raft thicknesses, but also in all other foundation and superstructure components.
- The raft thickness of seven megatall buildings determined with the graphical method is consistent with the designed ones. The results indicate that this method can be a valuable tool for engineers to determine appropriate raft thickness in the first step of the three-step design process.
- The raft thickness depends on the number of floors and the elastic modulus of the underlying soil layer. When the ratio of raft thickness to the number of floors is less than 5%, the elastic modulus has a significant influence. However, it has a negligible impact if this ratio exceeds 10%. This information can guide engineers in selecting appropriate foundation methods.

In this study, it was found that the designs of the Incheon Tower and Burj Khalifa Tower did not consider the impact of the raft width (raft length) on the overall stability. Additionally, the designs did not consider the effect of the raft mass on maintaining the stability and movement of the superstructure when subjected to dynamic loads. Therefore, future studies should investigate the role of the raft, including its thickness, width, length, and mass, in the behavior of the entire pile-raft-superstructure system.

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