Challenging Design: Foundations for Tall Buildings


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The design of foundations for tall buildings is a challenging task for geotechnical engineers as they are required to consider all geotechnical aspects of the project, with the aim of identifying and managing the geotechnical risks. In the design of foundations for tall buildings, lateral loadings are of great importance as are the vertical loadings. A small rotation at the foundation will be magnified to a very large magnitude at the top of the structure due to the height of the building, which will affect the serviceability and functionality of the building. This paper presents the foundation design process for two cases - the 1km high Nakheel Tower in Dubai and the 151 storey Incheon Tower in South Korea. The role of the authors as an internal reviewer of the analyses and an engineer undertaking the numerical analyses during the different project phases will be discussed. Analyses of the proposed foundation were carried out by computer programs using the boundary element method and 2D & 3D finite element methods based on the limit state approach. Key issues, in particular the overall performance of the foundation, will be addressed. The paper concludes with a summary of the design processes and the basic design criteria for tall buildings.

In the design of foundations for tall buildings, engineers face a challenging task as a conventional design approach may not be able to address all the key design issues. The foundation design team has to employ innovative approaches to tackle the problem. Due to the size of the tall building, it is necessary to design a cost-effective foundation system that meets the long term performance requirements.

This paper will describe the involvement of female engineers in tall building projects. Details of the design approach and its application to the Incheon Tower in South Korea and Nakheel Tower in Dubai will also be discussed.

Foundation Design Team

Organisation Chart

The major tasks of the tall building geotechnical designers are to provide professional recommendations for the foundation design, undertake geotechnical review services and independent analysis of foundation performance. The tall building design team will often comprise a project principal, a project manager and design engineers as shown in the organisation chart in Figure 1.

The major roles for each member of the team are outlined below:

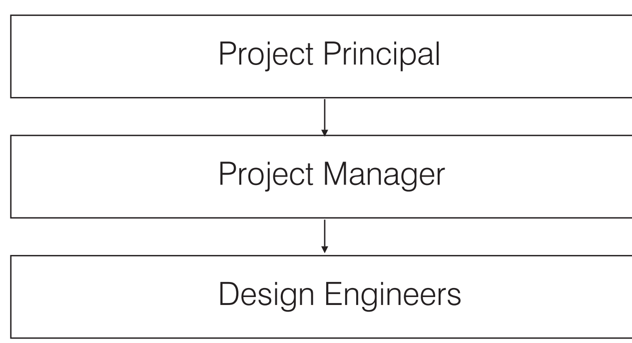

Fig. 1: Organisation Chart for Tall Building Foundation Design Team

- Project Principal–supervision of the design team and review process and providing technical advice to the design team and the clients.
- Project Manager–preparation of proposal and cost estimation of the design services, liaison with the clients and supervision of design process.
- Design Engineers – development of geotechnical models and parameters and undertaking foundation analyses.

Roles and Responsibilities of Authors

Coffey Geotechnics have been appointed as the geotechnical

designer for Incheon Tower and as geotechnical peer reviewer for Nakheel Tower.

The second author, Frances Badelow, was acting as the project manager for the Incheon Tower and also the peer reviewer for Nakheel Tower. The first author, Helen Chow, was acting as the design engineer for Incheon Tower and the peer reviewer for Nakheel Tower.

Project Manager – Frances Badelow

As a project manager, Ms Badelow was involved in the preparation of the proposal and estimation of the design and peer review services costs based on the scope of services provided by the clients.

For Incheon Tower, she set out the design steps for the design process, provided guidance to the design engineers in the development of geotechnical models and parameters, which were then used to carry out the design and reviewed the foundation design at various stages of the design process. She also liaised with the client and the structural engineers. As the superstructure and the foundation are interacting components of a single system, it is important that the geotechnical design engineers work closely with the structural design engineers to provide an effective design of the foundation for the client.

For Nakheel Tower, she set out the steps for peer review process and was part of the geotechnical peer review team for the foundation design provided by the foundation designer.

Design Engineer– Helen Chow

As a design engineer for Incheon Tower, Ms Chow was involved in the interpretation of ground conditions and assessment of foundation performance for different pile layouts and load combinations using different numerical methods. For Nakheel Tower, she undertook independent analyses of the foundation system proposed by the foundation designers.

Prior to becoming a design engineer, Ms Chow carried out extensive research and developed a computer program for numerical analysis of piled raft foundations at the University of Sydney. The computer program employs the finite layer and finite element methods in the analysis. Upon the completion of this research, Ms Chow began work as a design engineer and has been involved in projects such as foundation design for bridges, buildings and embankments, soft soil ground treatment design, and retaining wall and slope stability analysis which allowed her to apply the knowledge she acquired through research to design work and further developed her design skills through the exposure to different kinds of project.

Foundation Systems and Design Issues

Piled raft foundations are a cost-effective form of foundation for tall buildings and have been extensively used by geotechnical engineers in the past two decades. For most piled raft foundations, the primary purpose of the piles is to act as settlement reducers. The proportion of load carried by the piles is considered to be a secondary issue in the design.

Unlike the conventional piled foundation design in which the piles are designed to carry the majority of the load, the design of a piled-raft foundation allows the load to be shared between the raft and piles and it is necessary to take the complex soil-structure interaction effects into account.

The performance of a piled raft can be influenced by several factors such as the conditions of the supporting soil, relative stiffness between piles and soil, loading conditions, size and length of the piles, and pile arrangement. Therefore, the design has to take account of these factors to achieve the objective of economic construction with satisfactory performance.

In the design of foundations for tall buildings, design engineers have to understand the mechanism of load transfer from the raft to the piles and to the soil and then to address the following issues (Poulos, 2009):

- Ultimate capacity of the foundation subjected to vertical, horizontal and moment loading combinations.
- Influence of the cyclic nature of wind and earthquake on foundation capacity and movements.
- Overall settlement of the foundation.
- Differential settlements, both within the high-rise footprint and between high-rise and low-rise areas.
- Load-sharing between raft and piles and load distributions along the piles.
- Possible effects of externally - imposed ground movements on the foundation system, for example movement arising from excavations for pile caps or adjacent facilities or movements arising from ongoing consolidation settlement of soft soils.
- Earthquake effects, including the response of the structure-foundation system to earthquake excitation and the possibility of liquefaction in the soil surrounding and/or supporting the foundation.
- Dynamic response of the structure–foundation system to wind-induced forces.

Design Process

Prior to the commencement of a project, it is necessary to

have a well planned design process. The design process should include several phases as follows:

- Phase 1 – Subsurface exploration
- Carry out a 'desktop' study of all the geotechnical engineering data and work available from previous investigations and geotechnical engineering recommendations in the vicinity of the site.
- Perform site specific geotechnical investigation to explore the soil strata profiles and groundwater conditions across the site and carry out in-situ and laboratory testing to obtain the properties of each soil strata.
- Phase 2 – Foundation Design
- Develop geotechnical models and parameters based on the available geotechnical information obtained from Phase 1.
- Preliminary selection of a foundation system using simplified geotechnical profiles and analysis methods.
- Detailed design of a foundation system based on detailed geotechnical models and structural loads provided by the structural engineers to predict the performance of the foundation including the ultimate capacity of the foundation and anticipated settlement of the foundation under loading combinations.
- If excavation is required, design the retention system. The design has to consider a system of controlling groundwater inflow during construction and for the completed project.
- Assessment of seismicity of the site including changes in soil and rock conditions during earthquakes and possible effects on the foundation system.
- Assess the effects of construction on adjacent properties and on other facilities within the site.

-Phase 3 – Foundation testing and monitoring

- Perform a pile load test for the verification of design assumptions in Phase 2. If necessary, refine the foundation design based on the interpreted test results.
- Monitor the performance of the foundation and compare the measured performance with the predicted performance.

Incheon Tower, Korea

Incheon Tower is a super high rise twin tower, where each tower consists of 151 storeys with a height of 601m and is connected by three skybridges as illustrated in Figure 2. The tower is proposed to be constructed on reclaimed land underlain by soft marine clay in Songdo, Korea. Coffey Geotechnics was appointed as the geotechnical designer.

Ground Conditions

The Incheon site is located within an area of reclaimed land and as such is subjected to variable ground conditions. Detailed geotechnical aspects of the site are described by Badelow et al (2009).

The reclaimed land is comprised of approximately 8m of loose sand and sandy silt which is constructed over approximately 20m of soft to firm marine silty clay (Upper Marine Deposits – UMD) underlain by approximately 2m of medium dense to dense silty sand (Lower Marine Deposits – UMD), followed by residual soil and a profile of weathered rock.

Fig. 2: 151 Incheon Tower (artist's impression)

The lithological rock units present under the site comprise granite, granodiorite, gneiss (interpreted as possible roof pendant metamorphic rocks) and aplite. The rock materials within about 50m from the surface have been affected by weathering which has reduced their strength to a very weak rock or a soil-like material. This depth increases where the bedrock is intersected by closely spaced joints, and also sheared and crushed zones that are often related to the existence of the roof pendant sedimentary / metamorphic rocks. The geological structures at the site are complex and comprise geological boundaries, sheared and crushed seams - possibly related to faulting movements, and jointing.

The inferred contours of the 'soft-rock' surface within the tower foundation footprint were developed based on the available borehole data. It was found there was a variation in level of the top of soft rock of up to 40m across the foundation as presented in Figure 3.

To take into consideration the variation of ground conditions, the footprint of the tower was divided into eight zones with the appropriate geotechnical models and parameters developed based on field and laboratory tests and experience of similar soils on adjacent sites. As the performance of the UMD under vertical and horizontal loadings is of great importance in the design of the tower foundation, the selection of parameters for this stratum has to be carefully considered. Table 1 presents the typical parameters adopted for the foundation design.

Foundation Layout and Load Combinations

The tower foundation consists of a 5.5m thick raft supported by 172 no. bored piles socketed into the 'soft rock' stratum. The pile arrangement and pile sizes were obtained from a

series of trial analyses conducted by the geotechnical and structural engineers.

The primary purpose of the piles is to control settlement of the foundation. The pile lengths were determined by the geotechnical designers based on the pile settlement performance as the first priority and pile capacity as the second priority.

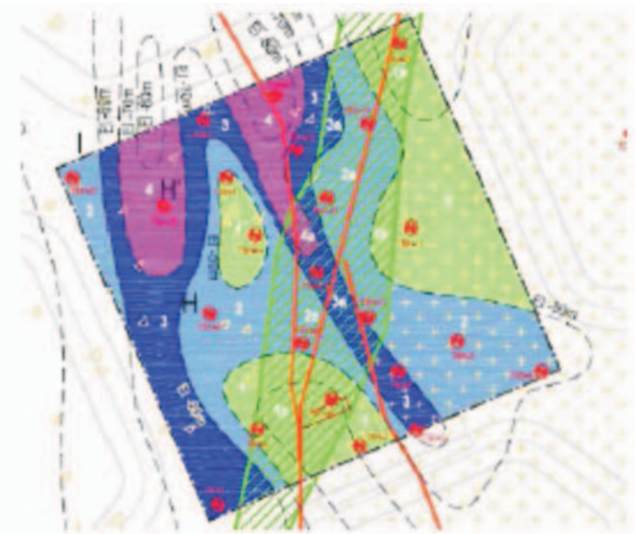

Fig. 3: Inferred Contours of Soft Rock Surface

Stratum	E_v (MPa)	E_h (MPa)	f_s (kPa)	f_b (MPa)
UMD	7 - 15	5 -11	29 – 48	-
LMD	30	21	50	-
Weathered Soil	60	42	75	-
Weathered Rock	200	140	500	5
Soft Rock (above EL-50m)	300	210	750	12
Soft Rock (below EL-50m)	1700	1190	750	12
E_v = Vertical Modulus E_h = Horizontal Modulus	f_s = Ultimate shaft friction f_b = Ultimate end bearing			

Tab.1: Summary of Adopted Geotechnical Parameters

The final design adopted a diameter of 2.5m as the pile diameter with a minimum socket length of two pile diameters into soft rock. The pile lengths vary from 36m to 66m, depending on the depth of the founding soft rock stratum. The raft is embedded into the ground with the base of the raft located at about 14m below the ground surface level. The pile layout of the foundation is presented in Figure 4.

Load combinations used for the foundation design were provided by the structural engineers. The typical loads of the tower are summarised as follows:

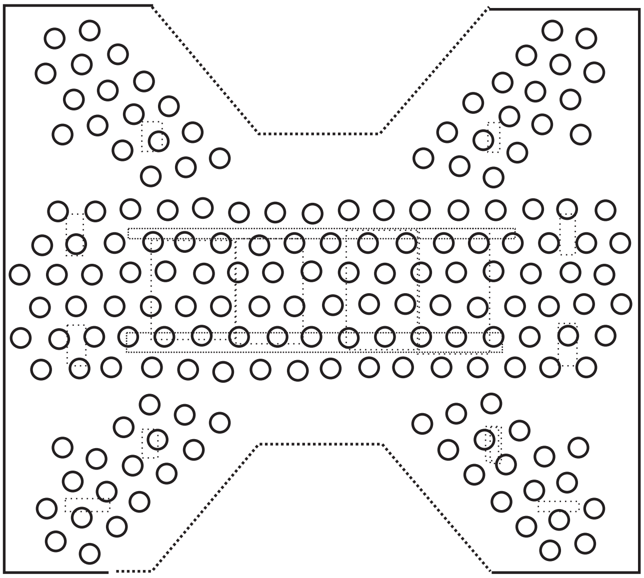

Fig. 4: Pile layout Plan for Tower Foundation

- Vertical Load (Dead Load + Live Load): Pz(DL+LL) = 6622MN
- Horizontal Load (Wind Loads): Px(WL) = 146MN, Py (WL) = 112MN
- Horizontal Load (Earthquake Loads): Px(EQ) = 105MN, Py (EQ) = 105MN
- Moment due to Wind Loads: Mx(WL) = 12578MNm, My (WL) = 21173MNm
- Torsional Moment: Mz(WL) = 1957MNm

Foundation Performance

The performance of the foundation has been assessed using the following computer programs:

- CLAP (Combined Load Analysis of Piles)–for the assessment of overall stability under ultimate load combinations
- GARP (General Analysis of Rafts with Piles)–for the assessment of foundation settlement under vertical and moments loading
- PLAXIS 3D – for the assessment of the foundation under vertical and horizontal loading

Vertical Loading

Computer program GARP was used as the main design tool. In the GARP assessment, the piled raft is in contact with the underlying soil but not with the surrounding soil. The predicted maximum settlement for the load combination of dead load + live load was about 67mm with a differential settlement of 34mm. In the analysis, the resistance provided by the soil surrounding the raft has been ignored.

The commercially available program PLAXIS 3D Foundation was used to provide an independent check of the foundation settlement. Analyses have been carried out for two

cases

(a) Case 1: Similar to the GARP analysis, the piled raft is in contact with the underlying soil.

(b) Case 2: The piled raft is in contact with the underlying soil and the soil surrounding the raft and basement walls is included (the soil above the base of the raft).

The finite element mesh used in PLAXIS 3D for case 2 is shown in Figure 5 with basement walls supporting the sides of the excavation. The soil layers are modelled as

Mohr-Coulomb materials to allow for non-linear behaviour. Figure 6 presents a plot of percentage of applied load versus vertical displacement at the centre of the raft which shows that the deflection of the foundation is reduced when the resistance provided by the surrounding soil is considered.

Horizontal Loading

The performance of the foundation under lateral loading is a critical issue in the foundation design for tall buildings. Computer program CLAP was used to assess the lateral stiffness of the pile group (assuming no contact between the raft and underlying soil) and a separate calculation was carried out to assess the lateral stiffness of the raft and basement walls. The predicted lateral deflection of the pile group from CLAP was about 22mm.

PLAXIS 3D was used to assess the overall lateral stiffness of the piled raft foundation. Three cases were analysed by PLAXIS which included cases 1 and 2 as above and an additional case 3 that is similar to the CLAP analysis which considers the pile group only.

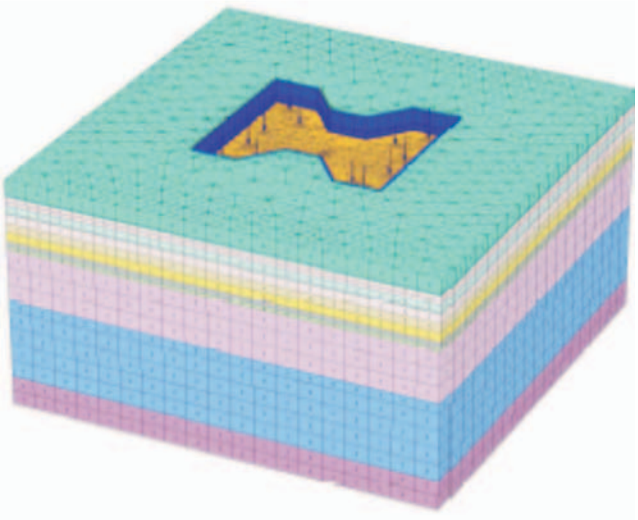

Fig. 5: Finite Element Mesh for PLAXIS 3D

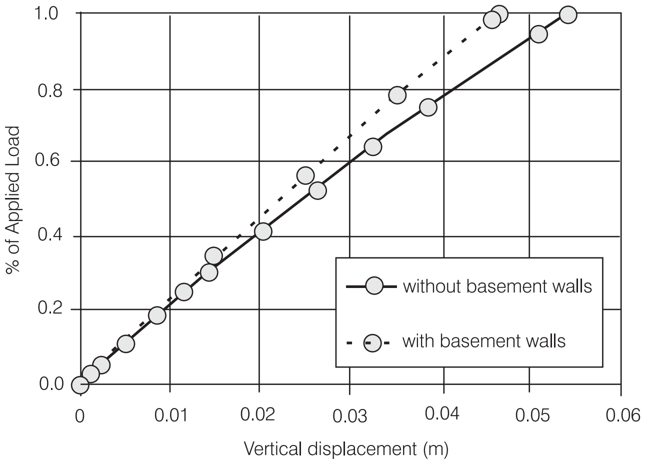

Fig. 6: Load Deflection Behaviour at Centre of Piled Raft (Vertical Loading)

The lateral displacement predicted by PLAXIS 3D agreed well with the CLAP results. Figure 7 presents a plot of percentage of applied load versus horizontal displacement of the raft which shows that the lateral deflection decreases when the raft is in contact with the underlying soil and decreases further when the surrounding soil resistance is considered. In this case, because of the large number of piles, the effect of the raft burial on lateral deflection is small.

The Nakheel Tall Tower

Nakheel Tower, one of the multi-billion dollar projects in Dubai, will be one of the centre-pieces of Nakheel Harbour. The tower is proposed to have a height in excess of 1 kilometre with more than 200 floors and will be the tallest structure in the world when completed.

Golder Associates have been appointed as the foundation designer and Coffey Geotechnics appointed as the geotechnical peer reviewer.

A brief summary of the foundation design is described

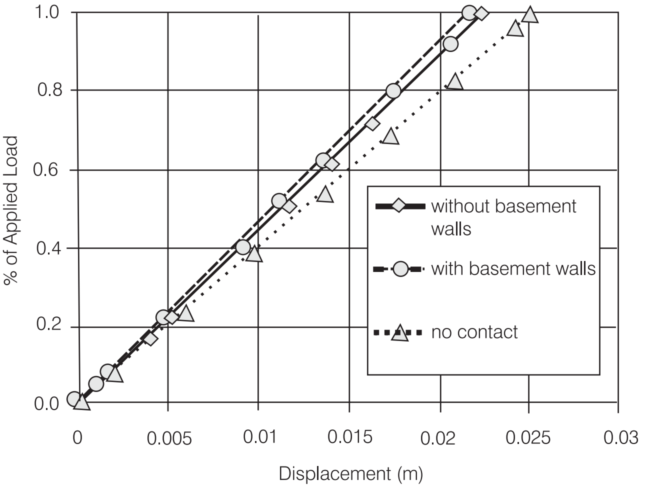

Fig. 7: Load Deflection Behaviour at Centre of Piled Raft (Horizontal Loading)

below, detailed analyses have been presented by Haberfield et al (2008)

Ground Conditions

The geotechnical profile consists of a 20m thick sand layer, underlain by cemented carbonate siltstone (calcisiltite) with gypsum layers up to 2.5m thick occurring at depths in excess of about 75m below ground level. Laboratory and in-situ tests were carried out to estimate the properties of the soil materials.

One of the features of the foundation materials was the existence of a 'bond yield strength' which controls the compressibility of the materials. If the imposed stress on the ground is less than the 'bond yield strength', the soil will behave as a very stiff material, otherwise, the compressibility would increase by an order of magnitude. In the foundation design, it is necessary to limit the stresses on the ground to be below the bond yield strength to avoid excessive settlement.

Foundation Layout

The foundation system consists of a raft with a thickness that varies up to a maximum of 8m supported by a total of 392 barrettes. The barrettes have sizes of 2.8m x 1.2m and 2.8m x 1.5m and extend to depths of 37m, 42m and 72m below the carbonate cemented siltstone where the base of the raft is to be founded. Figure 8 presents the foundation layout for Nakheel Tower.

Geotechnical Peer Review

Geotechnical peer review involves the tasks of reviewing the geotechnical designers' report and the foundation design method, and then developing independent geotechnical models based on the available geotechnical information and then undertaking independent analyses for the foundation for different loading conditions.

The independent geotechnical model adopted for the foundation design was developed based on the available

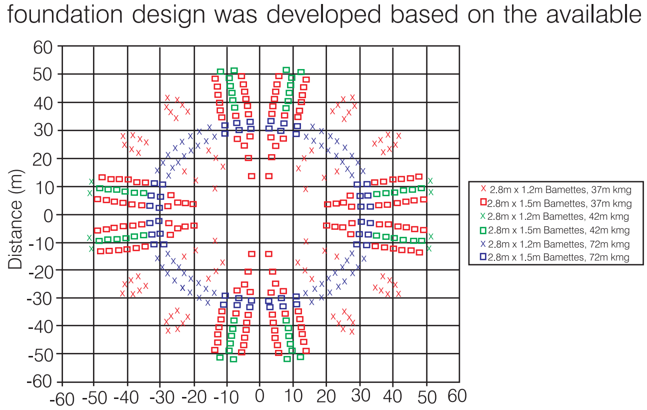

Fig. 8: Foundation Layout for Nakheel Tower

information and the barrette test results. Computer programs PIGS and CLAP were used to assess the overall stability of the foundation under the ultimate limit state load combinations in which the foundation capacities were reduced by a factor of 0.65. The assessment has shown that the foundation satisfied the ultimate state limit design criterion.

Computer program GARP was used to carry out the settlement assessment of the foundation system. Simplified finite element analysis using the commercially available PLAXIS 2D was carried out to check the GARP results. As the pile layout is symmetrical, a quarter of the foundation was modelled in GARP and an asymmetric model was used in PLAXIS 2D. The barrettes were modelled as equivalent circular rings in PLAXIS 2D.

From the GARP analysis, the maximum settlement was 95mm which was in good agreement with the computed settlement of 92mm obtained by Golder (designer) using a three-dimensional finite element analysis (PLAXIS 3D).

Conclusion

In the past few decades, there have been an increasing number of females choosing engineering as their career. Female engineers have been involved in many different aspects of engineering works from academic research to working in industry. They are often given the opportunity to undertake different roles in major projects.

This paper outlines two of the super-tall building projects that the two authors have been involved with. Key design issues and design processes have been discussed. Ground conditions should be well understood in the development of geotechnical models and parameters. In the design, the performance of a foundation under lateral loadings is a critical issue, therefore special consideration has to be given in the evaluation of parameters for the assessment of lateral response.

For the Incheon Tower where the raft is embedded, it is necessary to consider the resistance provided by the soil beneath and surrounding the raft in the design.

References

- Badelow, F., Kim, S., Poulos, H.G. and Abdelrazaq, A. (2009). "Foundation design for a tall tower in a reclamation area". Proc. 7th Int. Conf. Tall Buildings, Hong Kong, Ed. F.T.K. Au, Research Publishing, 815-823.
- Haberfield, C.M., Paul, D. and Ervin. M. (2008). "Case History – Geotechnical; Design for the Nakheel Tall Tower". ISSMGE Bulletin, Vol. 2, Issue 4, 5-9.
- Poulos, H.G. (2009) "Tall buildings and deep foundations – Middle East challenges". Proc. 17th Int. Conf. Soil Mechs. Goet. Eng., Alexandria, (Hamza M, Shahien M, and El-Mossalamy Y (eds), IOS Press, Armsterdam, 4: 3173-3205. ☐