Challenges in the Design of Tall Building Foundations

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ABSTRACT: This paper reviews some of the challenges that face designers of foundations for very tall buildings, primarily from a geotechnical viewpoint. Some characteristic features of such buildings will be reviewed and then the options for foundation systems will be discussed. A three-stage process of foundation design and verification will be described, and the importance of proper ground characterization and assessment of geotechnical parameters will be emphasized. The application of the foundation design principles to meet the challenges will be illustrated via three high-rise projects.

Keywords: Case histories; design**; f**oundations; piles; piled raft; settlement; tall buildings

1. INTRODUCTION

The last two decades have seen a remarkable increase in the rate of construction of "super-tall" buildings in excess of 300m in height. Figure 1 shows the significant growth in the number of such buildings either constructed (to 2010) or projected (2015 and beyond). A large number of these buildings are in the Middle East or in China. Dubai has now the tallest building in the world, the Burj Khalifa, which is 828m in height, while in Jeddah Saudi Arabia, the Kingdom Tower is currently under construction and will eventually exceed 1000m in height.

Super-tall buildings are presenting new challenges to engineers, particularly in relation to structural and geotechnical design. Many of the traditional design methods cannot be applied with any confidence since they require extrapolation well beyond the realms of prior experience, and accordingly, structural and geotechnical designers are being forced to utilize more sophisticated methods of analysis and design. In particular, geotechnical engineers involved in the design of foundations for super-tall buildings are leaving behind empirical methods and are increasingly employing state-of-the art methods.

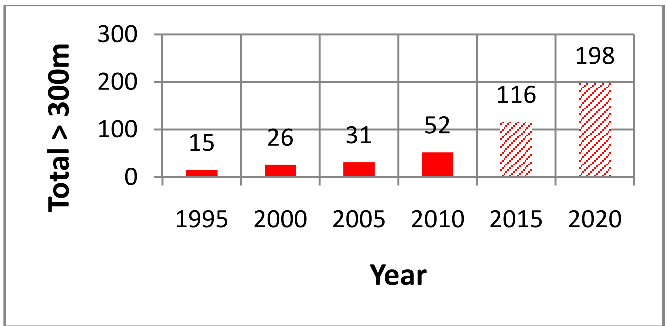

Figure 1 Total number of buildings in excess of 300m tall (after CTBUH, 2011)

This paper will summarize, relatively briefly, some of the challenges that face designers of foundations for very tall buildings, primarily from a geotechnical viewpoint. Some characteristic features of such buildings will be reviewed and then the options for foundation systems will be discussed. The process of foundation design and verification will be described and then some case histories will be presented to illustrate how some of these challenges have been addressed.

2. CHARACTERISTICS OF TALL BUILDINGS

There are a number of characteristics of tall buildings that can have a significant influence on foundation design, including the following:

- The building weight, and thus the vertical load to be supported by the foundation, can be substantial. Moreover, the building weight increases non-linearly with height, and so both ultimate bearing capacity and settlement need to be considered carefully.
- High-rise buildings are often surrounded by low-rise podium structures which are subjected to much smaller loadings. Thus, differential settlements between the high- and low-rise portions need to be controlled.
- The lateral forces imposed by wind loading, and the consequent moments on the foundation system, can be very high. These moments can impose increased vertical loads on the foundation, especially on the outer piles within the foundation system. The structural design of the piles needs to take account of these increased loads that act in conjunction with the lateral forces and moments.
- The wind-induced lateral loads and moments are cyclic in nature. Thus, consideration needs to be given to the influence of cyclic vertical and lateral loading on the foundation system, as cyclic loading has the potential to degrade foundation capacity and cause increased foundation movements.
- Seismic action will induce additional lateral forces in the structure and also induce lateral motions in the ground supporting the structure. Thus, additional lateral forces and moments can be induced in the foundation system via two mechanisms:
  - Inertial forces and moments developed by the lateral excitation of the structure;
  - Kinematic forces and moments induced in the foundation piles by the action of ground movements acting against the piles.
- The wind-induced and seismically-induced loads are dynamic in nature, and as such, their potential to give rise to resonance within the structure needs to be assessed. The risk of dynamic resonance depends on a number of factors, including the predominant period of the dynamic loading, the natural period of the structure, and the stiffness and damping of the foundation system.

3. FOUNDATION OPTIONS

The common foundation options include the following:

1. Raft or mat foundations;
2. Compensated raft foundations;
3. Piled foundations;
4. Piled raft foundations;
5. Compensated piled raft foundations.

The majority of recent high rise buildings are founded on the latter three foundation types. In particular, piled raft foundations have been used increasingly. Within a piled raft foundation, it may be possible for the number of piles to be reduced significantly (as compared with a fully piled system) by considering the contribution of the raft to the overall foundation capacity. In such cases, the piles provide the majority of the foundation stiffness while the raft provides a reserve of load capacity. In situations where a raft foundation alone might be used, but does not satisfy the design requirements (in particular the total and differential settlement requirements), it may be possible to enhance the performance of the raft by the addition of piles. In such cases, the use of a limited number of piles, strategically located, may improve both the ultimate load capacity and the settlement and differential settlement performance of the raft and may allow the design requirements to be met. It has also been found that the performance of a piled raft foundation can be optimized by selecting suitable locations for the piles below the raft. In general, the piles should be concentrated in the most heavily loaded areas, while the number of piles can be reduced, or even eliminated, in less heavily loaded areas (Horikoshi and Randolph, 1998).

4. THE DESIGN PROCESS

There are commonly three broad stages employed in foundation design:

1. A preliminary design, which provides an initial basis for the development of foundation concepts and costing.
2. A detailed design stage, in which the selected foundation concept is analysed and progressive refinements are made to the layout and details of the foundation system. This stage is desirably undertaken collaboratively with the structural designer, as the structure and the foundation act as an interactive system.
3. A final design phase , in which both the analysis and the parameters employed in the analysis are finalized.

It should be noted that the geotechnical parameters used for each stage may change as more knowledge of the ground conditions, and the results of in-situ and laboratory testing, become available. The parameters for the final design stage should ideally incorporate the results of foundation load tests.

5. DESIGN ISSUES

The following issues will generally need to be addressed in the design of foundations for high-rise buildings:

1. Ultimate capacity of the foundation under vertical, lateral and moment loading combinations.
2. The influence of the cyclic nature of wind, earthquakes and wave loadings (if appropriate) on foundation capacity and movements.
3. Overall settlements.
4. Differential settlements, both within the high-rise footprint, and between high-rise and low-rise areas.
5. Possible effects of externally-imposed ground movements on the foundation system, for example, movements arising from excavations for pile caps or adjacent facilities.
6. Dynamic response of the structure – foundation system to wind - induced (and, if appropriate, wave – induced) forces.
7. 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.
8. Structural design of the foundation system, including the load-sharing among the various components of the system (for example, the piles and the supporting raft), and the distribution of loads within the piles. For this, and most other components of design, it is essential that there be close cooperation and interaction between the geotechnical designers and the structural designers.

The analyses required to examine the above design issues range from hand calculation methods for preliminary design to detailed three dimensional finite element analyses for final design. However, the latter analyses should always be checked for reasonableness by comparison with simpler methods and with available prior experience.

6. GROUND INVESTIGATION , CONDITIONS , AND CHARACTERIZATION

The assessment of a geotechnical model and the associated parameters for foundation design should first involve a review the geology of the site to identify any geological features that may influence the design and performance of the foundations. A desk study is usually the first step, followed by site visits to observe the topography and any rock or soil exposures. Local experience, coupled with a detailed site investigation program, is then required. The site investigation is likely to include a comprehensive borehole drilling and *in-situ* testing program, together with a suite of laboratory tests to characterize strength and stiffness properties of the subsurface conditions. Based on the findings of the site investigation, the geotechnical model and associated design parameters are developed for the site, and then used in the foundation design process.

The in-situ and laboratory tests are desirably supplemented with a program of instrumented vertical and lateral load testing of prototype piles (e.g. bi-directional load cell (Osterberg Cell) tests) to allow calibration of the foundation design parameters and hence to better predict the foundation performance under loading. Completing the load tests on prototype piles prior to final design can provide confirmation of performance (i.e. pile construction, pile performance, ground behaviour and properties) or else may provide data for modifying the design prior to construction.

7. ASSESSMENT OF GEOTECHNICAL DESIGN PARAMETERS

For contemporary foundation systems that incorporate both piles and a raft, the following parameters require assessment:

- The ultimate skin friction for piles in the various strata along the pile.
- The ultimate end bearing resistance for the founding stratum.
- The ultimate lateral pile-soil pressure for the various strata along the piles
- The ultimate bearing capacity of the raft.
- The stiffness of the soil strata supporting the piles, in the vertical direction.
- The stiffness of the soil strata supporting the piles, in the horizontal direction.
- The stiffness of the soil strata supporting the raft.

It should be noted that the soil stiffness values are not unique values but will vary, depending on whether long-term values are required (for long-term settlement estimates) or short-term values are required (for dynamic response to wind and seismic forces). For dynamic response of the structure-foundation system, an estimate of the internal damping of the soil is also required, as it may provide the main source of damping. Moreover, the soil stiffness values will generally vary with applied stress or strain level, and will tend to decrease as either the stress or strain level increases.

The following techniques are used for geotechnical parameter assessment:

1. Empirical correlations – these are useful for preliminary design, and as a check on parameters assessed from other methods.

2. Laboratory testing, including triaxial and stress path testing, resonant column testing, and constant normal stiffness testing. In-situ testing, including various forms of penetration testing, pressuremeter testing, dilatometer testing, and geophysical testing.
3. Load testing, generally of pile foundations at or near prototype scale. For large diameter piles or for barrettes, it is increasingly common to employ bi-directional testing to avoid the need for substantial reaction systems.

8. TYPICAL HIGH-RISE FOUNDATION SETTLEMENTS

It can be useful to review the settlement performance of some high-rise buildings in order to gain some appreciation of the settlements that might be expected from various foundation types founded on various deposits. Table 1 summarizes details of the foundation settlements of some tall structures founded on raft or piled raft foundations, based on documented case histories in Hemsley (2000), Katzenbach et al (1998), and from the author's own experiences. The average foundation width in these cases ranges from about 40m to 100m. The results are presented in terms of the settlement per unit applied pressure, and it can be seen that this value decreases as the stiffness of the founding material increases. Typically, these foundations have settled between 25 and 300mm/MPa.

Table 1 Examples of Settlement of Tall Structure Foundations

Foundation Type	*Founding Condition*	*Location*	*No. of Cases*	*Settlement per Unit Pressure mm/MPa*
Raft	Stiff clay	Houston; Amman; Riyadh	2	227-308
	Limestone		2	25-44
Piled Raft	Stiff clay	Frankfurt	5	218-258
	Dense sand	Berlin; Niigata	2	83-130
	Weak Rock	Dubai	5	32-66
	Limestone	Frankfurt	1	38

Some of the buildings supported by piled rafts in stiff Frankfurt clay have settled more than 100mm, and despite this apparently excessive settlement, the performance of the structures appears to be quite satisfactory. It may therefore be concluded that the tolerable settlement for tall structures can be well in excess of the conventional design values of 50-65mm. A more critical issue for such structures may be overall tilt, and differential settlement between the high-rise and low-rise portions of a project. Typically, angular rotations of no more than 1/500 are sought, although for some particularly sensitive structures, 1/1000 may be more appropriate. It must however be borne in mind that some of the angular rotations will be "built out" during construction, and prior to the architectural finishes being applied, and so it may be necessary to carry out time-settlement analyses to assess the operative angular rotations more accurately.

9. CASE HISTORIES

9.1 The Burj Khalifa, Dubai

The Burj Khalifa project in Dubai comprised the construction of a 160 storey high rise tower, with a podium development around the base of the tower, including a 4-6 storey garage. The Burj Khalifa Tower (originally denoted as the Burj Dubai prior to completion and opening) is currently the world's tallest building at 828m. It is founded on a 3.7m thick raft supported on bored piles, 1.5 m in diameter, extending approximately 47.5 m below the base of the raft. Figure 2 shows the completed tower.

Figure 2 The Burj Khalifa

The key challenges in this case were to undertake an economical foundation design for the world's tallest building, where the founding conditions were relatively weak rock and where significant wind loadings were to be resisted. The foundation design was undertaken by Hyder Consulting UK, with peer review by Coffey Geosciences. The final design involved the use of advanced three dimensional finite element analyses. A detailed description of this case is given by Poulos and Bunce (2008).

The geotechnical investigation was carried out in four phases and involved the drilling of 33 boreholes, with SPT testing, pressuremeter testing and geophysical testing being undertaken.

Two programs of static load testing were undertaken for the Burj Khalifa project:

- Static load tests on seven trial piles prior to foundation construction.
- Static load tests on eight works piles, carried out during the foundation construction phase (i.e. on about 1% of the total number of piles constructed).

In addition, dynamic pile testing was carried out on 10 of the works piles for the tower and 31 of the 750 piles for the podium, i.e. on about 5% of the total works piles. Sonic integrity testing was also carried out on a number of the works piles.

Both the preliminary test piling program and the tests on the works piles provided very positive and encouraging information on the capacity and stiffness of the piles. The measured pile head stiffness values were well in excess of those predicted, and of those expected on the basis of the experience with the nearby Emirates Towers. The capacity of the piles also appeared to be in excess of that predicted, and none of the tests appeared to have fully mobilized the available geotechnical resistance.

The works piles performed even better than the preliminary trial piles, and demonstrated almost linear load-settlement behaviour up to the maximum test load of 1.5 times working load.

The settlements measured during construction were consistent with, but comfortably smaller than, those predicted, with a maximum settlement of about 44mm being measured near the end of construction. Overall, the performance of the piled raft foundation system exceeded expectations.

As with other high-rise projects, the Burj Khalifa involved close interaction between the structural and geotechnical designers in designing piled raft foundations for the complex and significant high-rise structures. Such interaction has some major benefits in avoiding over-simplification of geotechnical matters by the structural engineer, and over-simplification of structural matters by the geotechnical engineer, thus promoting more effective and economical foundation and structural designs.

9.2 Incheon 151 Tower, South Korea

A 151 storey super high-rise building project is currently under design, located in reclaimed land constructed on soft marine clay in Songdo, Korea, and is illustrated in Figure 3. This building is described in detail by Badelow et al (2009) and Abdelrazaq et al (2011).

Figure 3 Incheon 151 Tower (artist's impression)

The challenges in this case relate to a very tall building, sensitive to differential settlements, to be constructed on a site with very complex geological conditions.

The site lies entirely within an area of reclamation, and comprises approximately 8m of loose sand and sandy silt, over approximately 20m of soft to firm marine silty clay. These deposits are underlain by approximately 2m of medium dense to dense silty sand, which overlie residual soil and a profile of weathered rock.

The footprint of the tower was divided into eight zones which were considered to be representative of the variation of ground conditions, and geotechnical models were developed for each zone. Appropriate geotechnical parameters were selected for the various strata based on the available field and laboratory test data, together with experience of similar soils on adjacent sites. One of the critical design issues for the tower foundation was the performance of the soft silty clay under lateral and vertical loading, and hence careful consideration was given to the selection of parameters for this stratum.

The foundation comprised a concrete raft 5.5m thick with 172 piles, 2.5m in diameter, with the number and layout of piles and the pile size being obtained from a series of trial analyses by the geotechnical and structural designers. The piles were founded a minimum of 2 diameters into the better quality weathered ("soft") rock, or below a minimum toes level of El -50m, which was deeper.

The use of a suite of commercially available and in-house computer programs allowed the detailed analysis of the large group of piles to be undertaken, incorporating pile-soil-pile interaction effects, varying pile lengths and varying ground conditions in the foundation design. During final design, an independent finite element analysis was used to include the effect of soil-structure interaction and to include the impact of the foundation system on the overall behavior of the tower.

The overall settlement of the foundation system was estimated during all three stages of design, using the available data at that stage, and relevant calculation techniques. The predicted settlements ranged from 75mm from a simple equivalent pier analysis to 56mm from a PLAXIS 3D finite element analysis.

A total of five pile load tests were undertaken, four on vertically loaded piles via the Osterberg cell (O-cell) procedure, and one on a laterally loaded pile jacked against one of the vertically loaded test piles. For the vertical pile test, two levels of O-cells were installed in each pile, one at the pile tip and another at between the weathered rock layer and the soft rock layer.

The vertical test piles were loaded up to a maximum one way load of 150MN in about 30 incremental stages, in accordance with ASTM recommended procedures. The lateral pile load test was performed after excavation of about 8m of the upper soil, to simulate a similar ground condition as for the tower foundation. The lateral test pile was subjected to a maximum lateral load of 2.7MN.

The results of pile load tests indicated that the actual performance, under both vertical and lateral loads, was superior to that predicted initially, thus providing scope for the development of a more cost-effective design.

Presently the tower site is fully reclaimed and fenced, and enabling works are being planned.

9.3 Tower on Karstic Limestone, Saudi Arabia

The identification of cavities in karstic limestone often creates a sense of anxiety among foundation designers, who may then proceed to take extreme measures to overcome the perceived dangers and high risks associated with the proximity of cavities to a foundation system.

For a high-rise project in Jeddah Saudi Arabia, involving a tower over 390-m high, potentially karstic conditions were identified in some parts of the site. Figure 4 shows an architectural rendering of the tower.

The key challenges in this project were to assess whether the adverse effects on foundation performance of cavities within the limestone would be within acceptable limits, or whether special treatment would be required to provide an adequate foundation system. A more complete description of this case is given by Poulos et al (2013).

All the available boreholes indicated the presence of coastal coralline limestone (coral reef deposits) which contained fresh shells and was typically cavernous in nature. Above these limestone deposits was a surficial soil layer which consisted mainly of aeolian sands and gravels that were deposited in Holocene times.

Originally, 12 boreholes were drilled to depths of between 40 and 75m, and subsequently, two deeper boreholes were drilled to 100 m. The borehole data shows that the soil profile consists mainly of coralline limestone deposits that are highly fractured, and can contain cavities.

The quantitative data from which engineering properties could be estimated was relatively limited, and included the following:

1. Unconfined compression test (UCS);
2. Shear wave velocity data;
3. Pressuremeter testing;
4. SPT data in the weaker strata.

Figure 4 Architectural rendering of tower in Jeddah, Saudi Arabia

A piled raft foundation system was developed for this tower, as it was considered that such a system would allow the raft to redistribute load to other piles in the group if cavities caused a reduction of capacity or stiffness in some piles within the group.

The basement of the building was to be located at shallow depth above the water table, and the raft beneath the tower was 5.5m thick. It was to be supported on 145 bored piles 1.5 m in diameter, extending to a depth of 40m below the raft.

At the design stage, analyses indicated that the maximum settlement was approximately 50 mm. The initial analyses assumed that no significant cavities existed below the pile toes. If cavities were to be found during construction, then it would be necessary to re-assess the performance of the foundation system and make provision for grouting of the cavities if this was deemed to be necessary. Thus, subsequent to the foundation design, a further series of analyses was undertaken to investigate the possible effects of cavities on the settlements and also on the raft bending moments and pile loads. For these analyses, the commercially-available program PLAXIS 3D was used.

From this post-design investigation of the piled raft foundation system, it was demonstrated that the consequences of cavities, while not insignificant, may not be as serious as might be feared, because of the inherent redundancy of the piled raft foundation system. The analyses undertaken were insufficient to enable an accurate quantitative assessment of risk to be made, but they did enable a good appreciation to be gained of the sensitivity of the computed foundation response to the presence of random cavities. Clearly, using a redundant piled raft foundation system may not only reduce the risks associated with building towers on karstic limestone, but may also provide a much more economical foundation than using deep foundation piles which attempt to carry foundation loads through the karstic zones.

10. CONCLUSIONS

This paper has set out the following three-stage process for the design of high-rise building foundations.

1. A preliminary design stage, which provides an initial basis for the development of foundation concepts and costing.
2. A detailed design stage, in which the selected foundation concept is analysed and progressive refinements are made to the layout and details of the foundation system. This stage is desirably undertaken collaboratively with the structural designer, as the structure and the foundation act as an interactive system.
3. A final design phase, in which both the analysis and the parameters employed in the analysis are finalized.

It has been emphasized that the geotechnical parameters used for each stage may change as knowledge of the ground conditions, and the results of in-situ and laboratory testing, become available. The parameters for the final design stage should desirably incorporate the results of foundation load tests.

The application of the design principles has been illustrated via three projects, each of which has presented a different challenge to the foundation designers:

1. The Burj Khalifa in Dubai – the world's tallest building, founded on a layered deposit of relatively weak rock.
2. The Incheon 151 Tower in Incheon, South Korea- a settlement sensitive building on reclaimed land, with variable geotechnical conditions across the site.
3. A high rise tower in Jeddah, Saudi Arabia – karstic conditions were present and it was necessary to assess the sensitivity of performance to the possible presence of cavities in the supporting ground.

The value of pile load testing, in conjunction with advanced methods of analysis and design, has been emphasized, as has the importance of constructive interaction between the structural and geotechnical designers.

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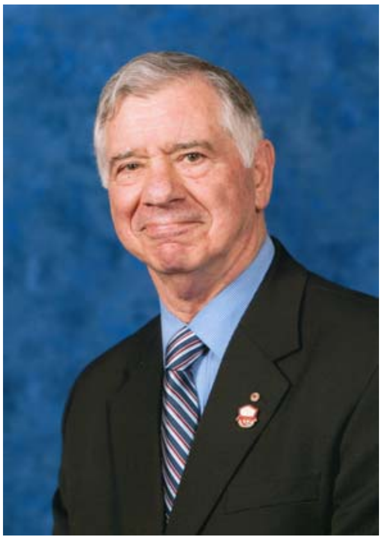

SPECIAL FEATURE STORY ON "Challenges in the Design of Tall Building Foundations"
by Prof Harry G Poulos

Prof Harry G. Poulos

Harry Poulos obtained a Civil Engineering degree from the University of Sydney in 1961, and then went on to do a PhD degree in Soil Mechanics, graduating in 1965. He worked with the consulting firm of McDonald Wagner and Priddle for a year before joining joined the Department of Civil Engineering at Sydney University in 1965. He was appointed a Professor in 1982, a position which he held until his retirement in 2001. In 1989, he joined the consulting firm of Coffey Partners International, and is currently a Senior Principal with Coffey Geotechnics. He is also an Emeritus Professor at the University of Sydney, and an Adjunct Professor at the Hong Kong University of Science and Technology.

He has published books and technical papers on foundation settlements, pile foundations, and offshore geotechnics. His main research interests continue to be in deep foundations and their application to high-rise buildings, and to problems relating to ground movements near foundations.

He has been involved in a large number of major projects in Australia and overseas including the Docklands Project in Melbourne, the Crown tower development in Sydney, Egnatia Odos highway project in Greece, high-rise foundation problems in Hong Kong, the Emirates twin Towers in Dubai. the Burj Khalifa tower in Dubai, the Incheon 151 Tower in Korea, and the Dubai tower in Doha, Qatar.

He was elected a Fellow of the Australian Academy of Science in 1988 and a Fellow of The Australian Academy of Technological Sciences and Engineering in 1996, and in 1999 was made an Honorary Fellow of the Institution of Engineers Australia. In 2010, he was elected a Distinguished Member of the American Society of Civil Engineers, the first Australian to receive this honour, and in 2014, he was elected as a Foreign Member of the US National Academy of Engineering.

He has received a number of awards and prizes, including the Kevin Nash Gold Medal of the International Society of Soil Mechanics and Geotechnical Engineering in 2005. He was the Rankine Lecturer in 1989 and the Terzaghi Lecturer in 2004, and was selected as the Australian Civil Engineer of the Year for 2003 by the Institution of Engineers Australia. In 1993, he was made a Member of the Order of Australia for services to engineering.