Foundation Design of the 151 Story Incheon Tower in a Reclamation Area

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ABSTRACT: A 151 storey super high-rise building located in an area of reclaimed land constructed over soft marine clay in Songdo, Korea is currently under design. This paper describes the design process in developing the foundation system of the super-tall tower, which is required to support the large building vertical and lateral loads and to restrain the horizontal displacement due to wind and seismic forces. The behaviour of the foundation system due to these loads and foundation stiffness influence the design of the building super structure, displacement of the tower, as well as the raft foundation design. Therefore, the design takes into account the interactions between soil, foundation and super structure, so as to achieve a safe and efficient building performance.
The site lies entirely within an area of reclamation underlain by up to 20m of soft to firm marine silty clay, which overlies residual soil and a profile of weathered rock. The nature of the foundation rock materials are highly complex and are interpreted as possible roof pendant metamorphic rocks, which within about 50m from the surface have been affected by weathering which has reduced their strength. The presence of closely spaced joints, sheared and crushed zones within the rock has resulted in deeper areas of weathering of over 80m present within the building footprint.

The foundation design process described includes the initial stages of geotechnical site characterization using the results of investigation boreholes and geotechnical parameter selection, and a series of detailed two- and three-dimensional numerical analysis for the Tower foundation comprising over 172 bored piles of varying length using finite element and boundary element methods. The effect of the overall foundation stiffness and rotation under wind and seismic load is also discussed since the foundation rotation has a direct impact on the overall displacement of the tower.

1. INTRODUCTION

The proposed 151 story Multi-use Tower is located in district 8 of the Songodo Incheon Free Economic Zone. The tower is composed of approximately Thirty (30) stories of office floors, Eight (8) stories of hotel & other supporting facilities, 100 stories of residential floors, and several levels of mechanical plant floors. The base of the tower consists of retail, future subway station, and several levels of parking. It is anticipated that the total area of the tower and the base for phase 1 construction would be approximately 412,000 square meters (see Figure 1). The structural system of the of the tower in the east-west direction consists of reinforced concrete core wall system linked to the exterior mega columns with reinforced concrete or composite panels to maximize the effect structural depth of the tower. However, the lateral load resisting system of the tower in the north-south direction consists of mega-frame structure, where the reinforced concrete core walls are linked through multi-story structural steel trusses at 3 levels at approximately every 30 floors. The tower superstructure is founded on pile supported raft foundation. The 5.5 meter thick reinforced concrete raft is supported on a total of 172-2.5m diameter bored piles with variable lengths extending 5 meters into soft rock for added stiffness, and overall reduction in overall and differential settlement.

Figure 1. 151 story Incheon Tower Rendering

The design of the 151 storey super high-rise building in Songdo, Korea is currently underway. The site lies entirely within an area of reclamation underlain by up to 20m of soft to firm marine silty clay, which in turn overlies residual soil and a profile of weathered rock. The tower superstructure is founded on bored pile supported raft that is required to support the large vertical loads due to gravity and lateral loads and to restrain the horizontal displacement of the tower due to wind and seismic loading. The behavior of the foundation system, due to gravity and lateral loads, influences the design of the building super structure, foundation design, and potentially the lateral drift of the tower, which is very much depended on the foundation system flexibility. Therefore, the foundation design needs to consider the interactions between the soil, foundation and super structure.

In this paper, the overall foundation system design process is explained and the outcomes of the design process are presented. The paper also presents the findings of a comparative soil/structure interaction study of the tower foundation system behavior that includes the stiffening effects of the tower structure and discusses the impact on the distribution of foundation loads within the pile group.

2. GROUND CONDITION

The Incheon area has extensive sand/mud flats and near shore intertidal areas. The site lies entirely within an area of reclamation, which is likely to comprise approximately 8m of loose sand and sandy silt, constructed over approximately 20m of soft to firm marine silty clay, referred to as the Upper Marine Deposits (UMD). These deposits are underlain by approximately 2m of medium dense to dense silty sand, referred to as the Lower Marine Deposits (LMD), which overlie residual soil and a profile of weathered rock.

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. A diagrammatic geological model is presented in Figure 2.

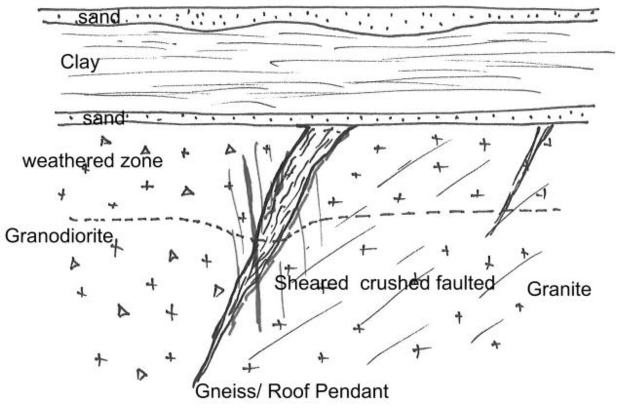

Figure 2. Diagrammatic Geological Model

From the available borehole data for the site, inferred contours were developed for the surface of the "soft rock" founding stratum within the tower foundation footprint. These are reproduced in Figure 3. It can be seen that there is a potential variation in level of the top of the soft rock (the pile founding stratum) of up to 40m across the foundation.

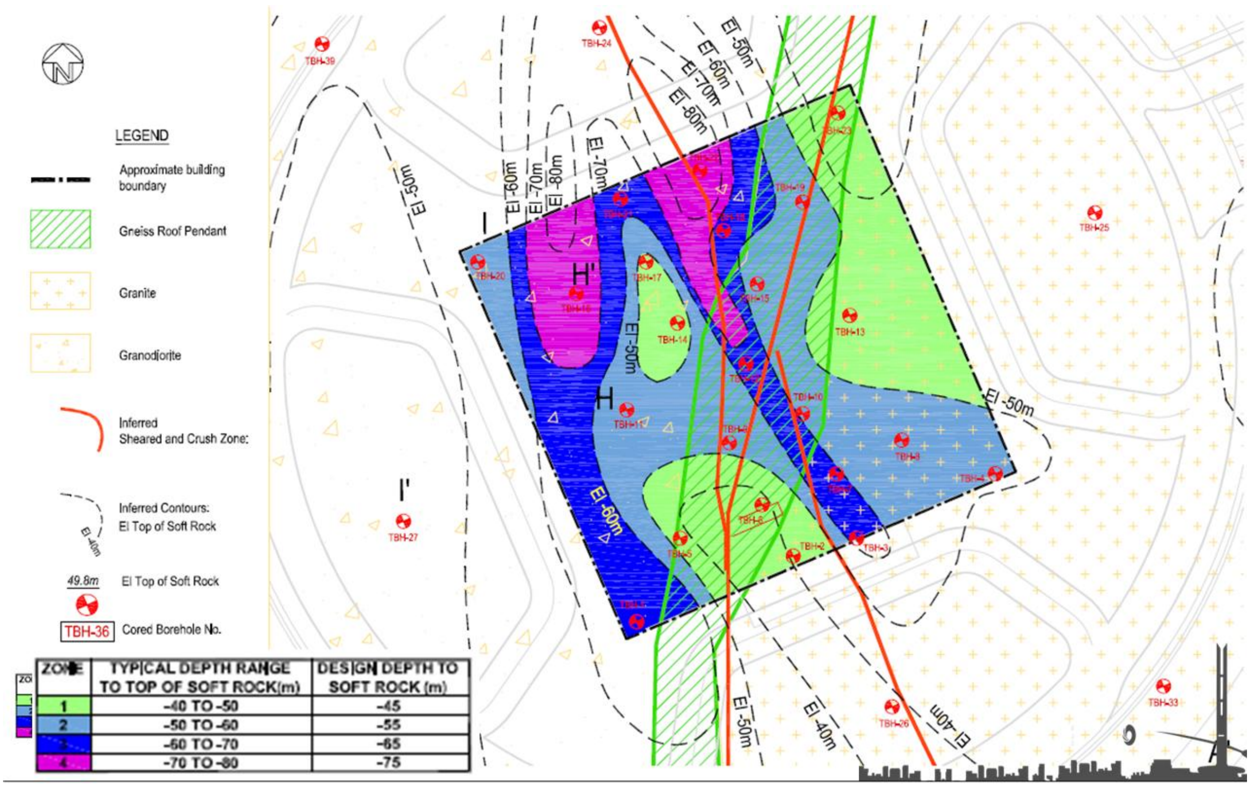

Figure 3. Inferred Contours of Top of Soft Rock

3. FOUNDATION DESIGN PROCEDURE

Generally, high-rise buildings on weak ground in Korea are supported on foundation systems comprising large diameter reinforced concrete bored piles socketed into rock and tied to a raft foundation. Adjacent to the Songdo 6 & 8 development site, a very large development with high-rise building and long span cable stayed structure have been constructed on reclaimed land with soil conditions similar to those encountered at the 151 story Incheon tower at the Songdo site. All the high-rise building projects and the long span cable stayed bridges are founded on pile supported rafts or pile caps. Therefore, this type of foundation system was also considered to be the likely option for the tower at concept design stage. Therefore the design plan, including the scope of the ground investigation, was generally focused for this foundation system.
The foundation design process adopted for the tower comprised the following three main stages: Stage 1 – Concept Design; Stage 2 – Detailed Design, and Stage 3 – Post Design (testing and monitoring). These three stages are briefly described in the following sections.

Concept Design

The aim of the Concept Design was to firstly establish the foundation system and to evaluate the approximate foundation behavior, based on a simplified ground model developed from the available geotechnical data. From this stage of the design, the following foundation design details were provided to the tower structural designers for preliminary design purposes:

- Pile capacities (geotechnical & structural) for a range of pile diameters.
- Horizontal and vertical pile stiffness values (single pile & group) for a range of pile diameters.

Using this information, the structural designer commenced the preliminary structural design process by including the different pile layout and raft into the 3-dimensional finite element analysis model in order to account for the effects of soil/structure interaction (see Figure 4). The foundation system development included the following:

- Development of pile layout options for various pile diameters.
- Preliminary selection of raft size.
- Preliminary evaluation of building performance, under gravity and lateral load effects.
- Assessment of the pile group efficiency.
- Assessment of the foundation stiffness and its impact on the overall behavior of the tower.
- Assessment of the superstructure stiffening effects on the load distribution between piles.

Based on the above, several foundation layout options were developed for further assessment and refinement at detailed design stage.

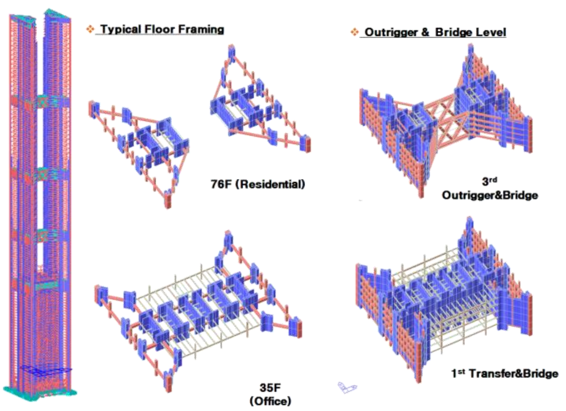

Figure 4. 3-D Finite Element Analysis Model for Soil-Structure Interaction. The piles stiffnesses (vertical& Lateral) are modeled as springs at the raft foundation level.

Detailed Design

The three main components to be considered in the detailed design stage of the tower foundation system are shown in Figure 5 and are discussed in the following sections.

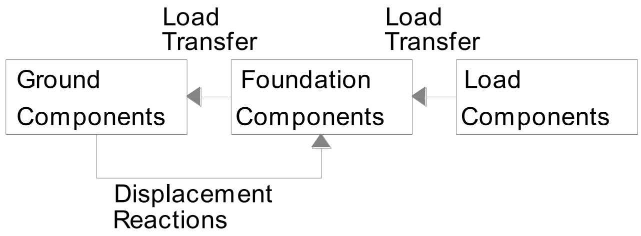

Figure 5. Main Components of Foundation Analysis

Load Components

The building loads can be classified according to their source or loading characteristics with direction. A typical plan of the tower basement floor, showing the building core and columns, is shown in Figure 6.

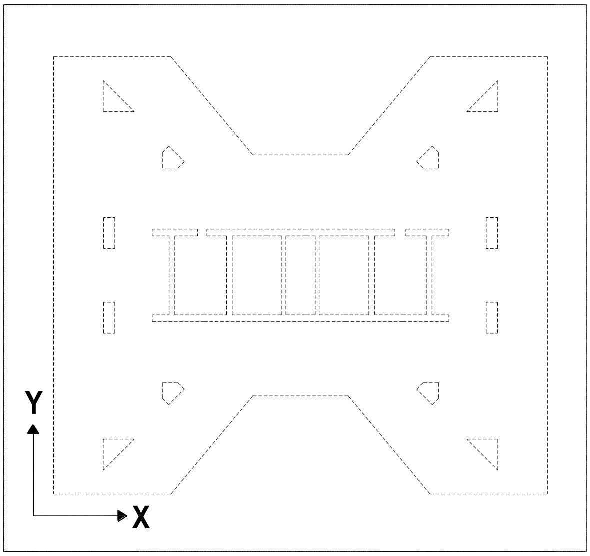

Figure 6. Tower Basement Floor Plan

The typical loads of the tower are summarized as follows:

- Vertical Load, P_z(Dead Load +Live Load) = 6622MN
- Lateral Load, P_x(Wind Load) = 146MN, P_y(Wind Load) = 112MN
- Lateral Load, P_x(Seismic) = 105MN, P_y(Seismic) = 105MN
- Overturning Moment, M_x(Wind Load) = 12578MNm, M_y(Wind Load) = 21173MNm
- Torsional Moment, M_z(Wind Load) = 1957MNm

The load combinations as provided by the structural designer were adopted for the geotechnical design of the foundation system. While a comprehensive seismic analyses were performed for the tower and the foundation system, including response spectrum and time history for frequent and extreme seismic events, Wind load still controlled the overall tower design and it will be referenced in this paper. For super high-rise buildings, the wind load is a critical load case for both the building foundation and the super structure. The wind load combinations of P_x, P_y and M_z are dependent on the wind direction, wind speed and the building shape, and can be determined from analysis or wind tunnel tests. Some 24 wind loading combinations were provided by the structural designer in the following format:

$$AP_x + BP_y + CM_z \qquad (1)$$

where *A*, *B* and *C* are factors applied to the various load components. Some examples of these factors are shown in Table 1.

Table 1. Examples of Wind Load Combination

Load Case	*A*	*B*	*C*
4	+100%	-45%	-70%
7	-90%	-60%	+40%
11	+45%	-100%	+30%
20	+70%	-40%	-100%

In addition to the wind and seismic loading described above, a very detailed site specific seismic hazard studies that includes the effect of near and far earthquakes were considered, including the potential for liquefaction of the reclaimed soil. The tower foundation system is located below the reclaimed soil and the tower superstructure is separated from the podium structure to avoid interaction between the podium structure and the tower structure. In addition, most of the podium structure is located above the water table to avoid liquefaction potential. The seismic and wind engineering approached are not the focus of this paper and it will be discussed in separate structural engineering paper. The design and behavioral characteristics of the pile, including strength and stability under combined axial load/bending moments/shear forces, considered the effect of the soft clay and their resistance to lateral loads under extreme wind and seismic events.

Foundation Components

The tower superstructure is founded on bored pile supported raft. The raft size and thickness was originally assessed by the structural designer based on the loading conditions, the pile layouts and the structural demands on the raft foundation to transfer the loads to the bored pile in the most optimum manner and with due consideration to the presence of deep elevator pits and other architectural requirements.

The pile size, number of piles and layout were determined from a series of trial analyses undertaken collaboratively by the geotechnical designer and the structural designers. The pile layout and raft foundation thickness were optimized to allow for even load distribution between the piles, minimize the overall and differential settlement, and to minimize the shear and bending moments in the raft. The depths of each pile within the group were assessed by the geotechnical designer, considering both the pile performance and capacity. The preferred mat and pile layout was selected from the various options developed during the concept design stage, and comprised a 5.5m thick raft, founding at a level of EL-8.7m supported on a total of 172 reinforced concrete bored piles 2.5 m in diameter founding a minimum of 2 pile diameters into the soft rock or below EL-50m, whichever is deepest. The layout of the piles is presented in Figure 7. In locations, where the piles are expected to be in the vicinity of sheared/crushed rock zones, the piles will be founded at rock level below the sheared zones whenever possible in order to bridge the weak soft layers of soil and to stitch the different layers to allow for transferring the loads into rock in the most efficient way for better behavioral aspects of the overall foundation system.

Ground Components

A detailed interpretation of the geological and geotechnical conditions based on the available comprehensive ground investigation (Halla 2008) was undertaken in order to:

- Assess anticipated ground conditions for the tower
- Develop geotechnical properties and characteristics for the various strata
- Develop geotechnical design parameters

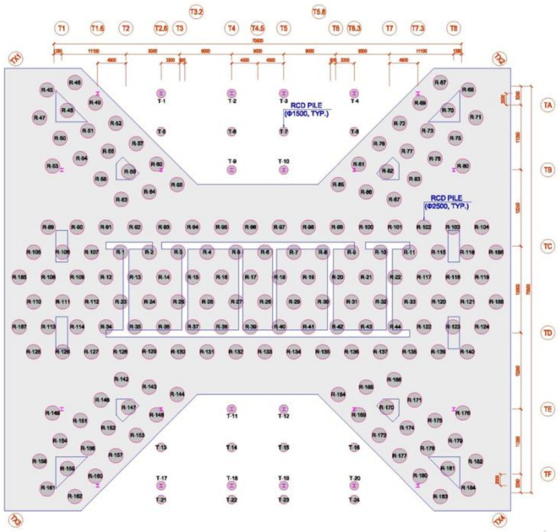

Figure 7. Pile Layout Plan

The footprint of the tower was divided into eight zones (refer Figure 2) 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 UMD under lateral and vertical loading, hence careful consideration was given to the selection of parameters for this stratum. Typical parameters adopted for foundation design are presented in Table 2.

Table 2. Typical Geotechnical Design Parameters

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 f_s = Ultimate shaft friction
E_h = Horizontal Modulus f_b = Ultimate end bearing

Main Design Process

Once the three components of loading, foundation layout and ground conditions are reasonably well defined, the foundation design can be undertaken. The following key issues needed to be addressed in the design of the tower foundations:

1. Ultimate capacity and global stability of the foundation system under vertical, lateral and moment loading combinations.
2. The influence of the cyclic nature of wind and earthquakes on foundation capacity and movements.
3. Overall settlements
4. Differential settlements, both within the tower 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 ongoing consolidation settlement of the UMD.

6. 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.
7. Dynamic response of the structure-foundation system to wind-induced and seismic forces.
8. Impact of the foundation stiffness on overall foundation rotation under wind and seismic dynamic/cyclic loadings, which has direct impact on the overall drift of the supertall and slender towers.
9. Structural design of the foundation system; including the load-sharing among the various components of the system (i.e. 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.

Post Design Studies

During the main design stage, the pile design is generally based on theoretical solutions and previous experience in similar conditions at adjacent sites. Pile load test data is invaluable in confirming design assumptions and finessing the foundation design. When the piles are instrumented, detailed information can be derived on the distributions of shaft friction and soil stiffness at various depths along the pile shaft. Therefore, a comprehensive vertical, lateral and cyclic pile load testing programme has been developed and executed for the tower foundation piles. In addition, monitoring of the piles and foundation raft behaviour during construction of the superstructure will be carried out in order to assess overall behavior of the foundation and compare with predicted performance as well as providing valuable information to the structural designer regarding the anticipated final behavior of the superstructure itself.

The objectives of the proposed pile load tests are summarized in Table 3 below and are summarized as follows:

- To assess and confirm the constructability and integrity of the piles using the proposed construction techniques (reverse circulation drilled piling techniques).
- To allow comparison of measured pile performance with design expectations and refinement of the geotechnical parameters adopted in design (e.g. ultimate skin friction and end bearing values, pile foundation stiffness, effect of dynamic loading on the pile stiffness, both vertical and lateral, etc.).
- To assess possible variability of pile performance in relation to variations in ground conditions across the foundation footprint.

Table 3. Summary of Pile Load Tests

Test Type	Purpose	Loading Method	Monitoring Items
■ **Vertical** **(4 No. test piles)**	● Estimation of the end bearing and shaft friction capacities within weathered/soft rock. ● Evaluation of the vertical pile stiffness ● Check of pile response and stiffness to due to static and dynamic/repetitive/cyclic loading such as wind and seismic loads	● Bi-directional load cells (O-cells) embedded at two locations in pile (1 in upper shaft and 1 close to pile toe)	● Pile movement of shaft and toe ● Stress, strain along piles. ● Pile stiffness under repetitive/cyclic loading due to wind and seismic loads
■ **Horizontal** (1 No. test & 1 No. reaction pile)	● Evaluation of the lateral pile stiffness ● Lateral deformation characteristics of UMD around pile head ● Check of pile response and stiffens due to static and dynamic/repetitive/cyclic to loading such as wind and seismic load	● Loading of the test pile against a reaction pile (static & dynamic loading)	● Lateral load and displacement ● Pile deflections along the shaft ● Pile stiffness under cyclic/repetitive loading.

3. ASPECTS OF THE DETAILED DESIGN STAGE

The challenge for the tower foundation design was to simulate the group interaction effects of the large pile group under vertical and lateral loading (including negative skin friction due to the consolidating soft UMD) in order to optimize the pile group design and provide accurate input parameters to the structural designer. In order to assess the performance of the piled raft foundation, a suite of foundation analyses were undertaken using both commercially available software and Coffey Geotechnics in-house developed programs, as summarized in Table 4.

Overall Stability of Tower Foundation

When considering the overall stability of a piled raft foundation system under vertical, lateral and bending moment loadings, conventional "text book" methods are generally not applicable or feasible. Therefore an assessment of the overall stability of the tower foundation has been undertaken using Coffey's in-house computer program CLAP, which 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 ultimate load combinations are applied in the analysis and the ultimate capacities of the piles are reduced by a geotechnical reduction factor of 0.65 (adapted from guidelines given in Australian Piling Code AS2159-1995). The contribution of the raft to the overall stability of the foundation was ignored and overall stability is satisfied if the foundation system does not collapse under these conditions. For the proposed foundation system comprising 172-2.5m diameter bored piles, the limit state requirements for overall stability of the tower foundation were satisfied for the six critical wind loading cases analyzed.

Table 4. Software Programs Employed for Foundation Design

Computer Program	Purpose of Analysis
PLAXIS 2D Foundation (axisymmetric analysis)	Preliminary assessment of overall settlement of tower foundation
PLAXIS 3D Foundation	Assessment of foundation under vertical and lateral loading
DEFPIG (University of Sydney)	Assessment of foundation under lateral loading
CLAP (Coffey Geotechnics)	Assessment of foundation under vertical, lateral, bending, and torsional loading
GARP (Coffey Geotechnics and University of Sydney)	Assessment of foundation under vertical and moment loading
ERCAP(Coffey Geotechnics)	Assessment of podium piles under lateral loading
ERLS (Coffey Geotechnics)	Assessment of ground behavior to seismic loading

Tower Foundation Settlement

An assessment of the Tower foundation settlement has been undertaken using the computer program GARP – (**G**eneral **A**nalysis of **R**afts with **P**iles) developed by Sydney University in conjunction with Coffey. GARP employs the boundary element method to calculate interactions between pairs of piles and between a pile and the raft and finite element analysis of raft behavior. GARP can take into account different pile types across the foundation assigning individual stiffness values and geotechnical capacities to each pile and has been successfully used by Coffey on numerous tall tower projects (Badelow et al, 2006); (Poulos & Davids, 2005).

The settlement of a pile group is always greater than the settlement of a corresponding single pile, as a result of the overlapping of the individual zones of influence of the piles in the group. One of the inputs therefore required by GARP is the pile group interaction factors(α) for a range of pile spacings. Appropriate interaction factors have been assessed using Coffey's in-house program CLAP, adopting the following assumptions:

- ■Varying geotechnical models present across the site (8 models).
- ■Develop Varying pile lengths (ranging from about 41m to 71m).
- ■A rigid boundary is assumed to be at the top of the Hard Rock at EL-86.5m.
- ■The interaction effects are negligible at a distance of 15 x pile diameter from each pile.
- ■The elastic modulus between the piles is assumed to be three times greater than that near the piles due to smaller strain levels existing between the piles.

Using a simplified boundary element approach, CLAP computes the single pile flexibility values and the two-pile interaction factors for each pile type specified. When calculating the pile flexibilities, it allows for non-linear pile-soil behavior by limiting the axial and lateral pile-soil pressures to the ultimate values specified by the user. Interaction factors are computed using a purely elastic analysis. The interaction effects of one pile on another pile are based on the elastic flexibility of the influencing pile, with non-linearity only being introduced for the effect of the influenced pile on itself.

Six load combinations were considered in the analysis and a summary of the assessed maximum and minimum settlement values together with the angular rotation of the foundation raft is presented in Table 5 below.

Table 5. Summary of Predicted Vertical Settlement due to combined gravity and wind loads

Load Case	Wind Load Combination	Settlement (mm)		Maximum Angular Rotation of the Raft
		Max.	Min.	
DL + LL	-	67	28	1:790
0.75(DL + LL + WL)	1	52	18	1:730
0.75(DL + LL + WL)	4	52	18	1:730
0.75(DL + LL + WL)	7	53	18	1:740
0.75(DL + LL + WL)	11	55	19	1:570
0.75(DL + LL + WL)	15	54	19	1:570
0.75(DL + LL + WL)	20	52	20	1:870

DL = Dead Load, LL = Live Load, WL = Wind Load

The maximum predicted settlement for all cases occurs within the heavily loaded core area, with the maximum value occurring as a result of DL + LL loading combination. The largest differential settlement of 36mm occurs under Wind Load Combination 11, corresponding to an angular rotation of 1:570, which is considered to be within the range generally acceptable for tall structures. It should also be noted that the analyses undertaken has not considered the stiffness of the superstructure, which is likely to be a conservative assumption as the superstructure will provide additional stiffness to the foundation system. In addition, this analysis does not take into account additional stiffness due to the dynamic nature of wind and seismic forces.

An independent assessment of the tower foundation settlement under (DL + LL) loading condition has been carried out using the 3-dimensional finite element program PLAXIS 3D Foundation developed by PLAXIS NL. The analysis assumes uniform ground conditions across the Tower foundation with the top of Soft Rock at EL-50m. All of the 172 piles are modeled with a toe depth of EL-55m and the top of the Hard Rock is assumed to be at EL-79m. The calculated maximum settlement of the tower foundation under (DL + LL) loading condition was 68mm, occurring within the heavily loaded core area. This value compares very well with the value of 67mm assessed using GARP for the same location and under the same loading conditions. A differential settlement of about 19mm was calculated using PLAXIS 3D between the centre and perimeter of the tower foundation. This magnitude of differential settlement is about 50% less than the value assessed using GARP (39mm). In the GARP analysis, variation in ground conditions across the tower footprint and associated variations in individual pile lengths have been modeled. Differences in the analysis methods and assumptions adopted therein are likely to account for the variation in the magnitude of the predicted differential settlement. In addition, this analysis model does not fully account for the stiffening effects of the tower superstructure during construction and under permanent and completed conditions.

Foundation Settlement

Critical input parameters for the 3-dimensional structural numerical analysis are the bored pile head stiffness values for the piled foundation. The assessment of these parameters is discussed in the following sections.

Assessment of Vertical Pile Behavior

The vertical pile head stiffness values for each of the 172 foundation piles under serviceability loading (DL + LL) were assessed using the computer programs CLAP and GARP. CLAP was used to assess the geotechnical capacities, interaction factors and stiffness values for each pile type under serviceability loading for input into the group assessment. CLAP 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. GARP has been used to assess the group foundation behavior of the Tower.

Figure 8 presents the individual pile vertical stiffness values computed, which suggest that the outer piles are stiffer. The analysis is non-linear, therefore the higher stiffness values for the outer piles degrade more rapidly under loading than the central piles. The concentration of loads on outer piles within a group is a real phenomenon that has been measured in the field. Therefore, it is considered that a more accurate foundation behavior can be simulated by using the individual pile stiffness values rather than an average value for all piles within the group. Lower and upper pile stiffness values were provided to the structural engineers to include in their analysis to capture the upper and lower bound behavior of the raft foundation and their potential impact of the tower superstructure.

Assessment of Lateral Pile Behavior

One of the critical design issues for the tower foundation is the performance of the pile group under lateral loading. Therefore, several numerical analysis programs were used in order to validate the predictions of lateral behavior obtained. The numerical modeling packages used in the analyses were:

- ■ 3D finite element computer program PLAXIS 3D Foundation;
- ■ Computer program DEFPIG developed by Sydney University in conjunction with Coffey; and

- Coffey's in-house computer program CLAP.
- 3_D finite Element Structural Analysis Programs (Midas Set, Etabs, Safe) that included the effect of soil structure interacation.

PLAXIS 3D provides an assessment of the overall lateral stiffness of the foundation. The programs DEFPIG and CLAP were used to assess the lateral stiffness provided by the pile group assuming that the raft is not in contact with the underlying soil and a separate calculation was carried out to assess the lateral stiffness of the raft and basement. Table 6 presents the computed lateral stiffness for the piled mat foundation obtained from the analyses.

Table 6Summary of Lateral Stiffness of Pile Group and Raft

Horizontal Load (MN)	Pile Group Disp. (mm)	Lateral Pile Stiffness (MN/m)	Lateral Raft Stiffness (MN/m)	Total Lateral Stiffness (MN/m)
149	17	8760	198	8958
115	14	8210	225	8435

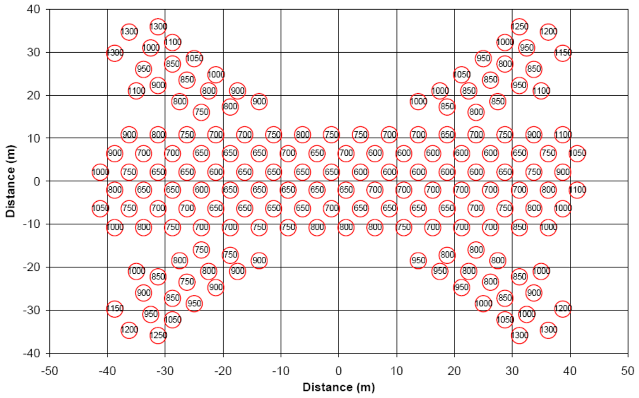

Figure 8. Computed Pile Head Vertical Stiffness Values (MN/m)

Assessment of Pile Group Rotational Stiffness

An assessment of the rotational spring stiffness values at selected pile locations within the foundation was undertaken using Coffey's in-house computer program CLAP. To assess the rotational spring constant at each pile location, the average dead load, horizontal load (x and y direction) and moment (about the x, y and z axes) were applied to each pile head. The passive resistance of the soil surrounding the raft and the friction between the soil and the raft were not included in the assessment as it was assessed that the base friction of the raft footing and the passive resistance of the soil on the raft are relatively small, when compared to lateral resistance of the piles. Table 7 presents a summary of the assessed rotational spring stiffness values obtained from the analysis for four piles considered to represent the range of values for different piles within the pile foundation.

Table 7. Rotational Spring Constants Including Horizontal Loads Applied at the Pile Heads

Pile		Pile Head Angular Rotation (rad.)	Pile Head Rotational Spring Stiffness (MN.m/rad)
3	Maximum	0.094	2680
	Minimum	0.036	1380
27	Maximum	0.144	1750
	Minimum	0.056	903
70	Maximum	0.126	2000
	Minimum	0.049	1030
78	Maximum	0.187	1350
	Minimum	0.073	700

The overall torsional stiffness of the piled mat was assessed using the computer program PLAXIS 3D Foundation. A schematic of the PLAXIS model analyzed is given in Figure 9

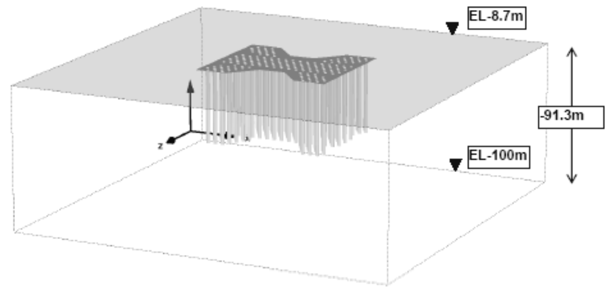

Figure 9. Schematic of PLAXIS 3D Model

The overall torsional stiffness of the piled mat estimated using PLAXIS was 10,750,000 MNm/radian, which is approximately equivalent to 16mm displacement at the edge of the raft for the applied torsional moment of 1956MN-m applied at the centre of the raft.

Cyclic Loading due to Wind Loading

Wind loading for the tower structure is quite severe, therefore in order to assess the effect of low frequency cyclic wind loading, an assessment based on a method suggested by Poulos and Davids (2005) was undertaken. The method suggests that adequate foundationperformance under cyclic loading will be achieved provided the following criterion is met:

$\eta R_{gs}^{*} \geq S_c^{*}$ (1)

Where: R_{gs}^{*} = design geotechnical shaft capacity
$_c^{*}$ = half amplitude of cyclic axial wind-induced load
η= a factor assessed from geotechnical laboratory testing.

Provided the criterion is met, there is a reduced likelihood that full shaft friction will be mobilized, reducing the risk of degradation of shaft capacity due to cyclic loading. The factor η was selected to be 0.5, based on experience with similar projects.

To assess the half amplitude of cyclic axial wind induced load, the difference in pile load between the following load cases was computed.

CASE A: 0.75(DL + LL)
CASE B: 0.75(DL + LL + WL_x + WL_y)
where: DL = Dead Load WL_x = Vertical Load resulting from *x*-Component of Wind
LL = Live Load WL_y = Vertical Load resulting from *y*-Component of Wind

The difference in axial load between the two load cases is assessed to be the half-amplitude of the cyclic load (S_c^{*}). Table 8 below summarizes the results of the cyclic loading assessment and Figure 10 shows the assessed factor □ for each pile within the foundation system. The assessment indicates that degradation of shaft capacity due to cyclic loading in unlikely to occur.

Table 8. Summary of Cyclic Loading Assessment

Quantity	Value
Maximum Half Amplitude Cyclic Axial Wind Load S_c* (MN)	29.2
Maximum Ratio $\eta = S_c^*/R_{gs}^*$	0.43
Cyclic Loading Criterion Satisfied?	Yes

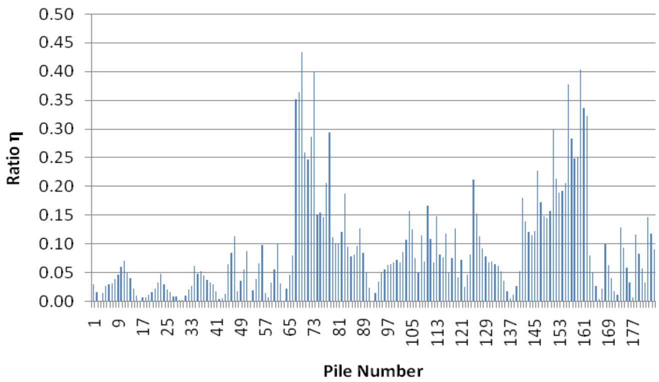

Figure 10. Results of Cyclic Loading Analysis

Cyclic Loading due to Wind Loading

An independent 3-D finite element analysis models using general analysis programs (MIDAS, ETABS, SAFE) were also performed to include the soil structure interaction and the stiffening effects of the superstructure. Refer to Figure 4 for Midas 3-D finite element analysis model. This analysis also includes the construction sequence of the tower and the superstructure stiffening effects that allows for better load redistribution between the piles because of the large stiffness of the superstructure.

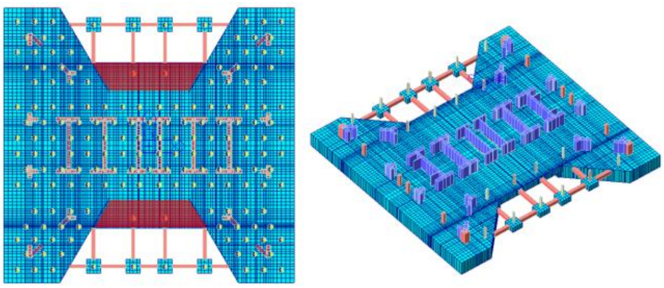

Figure 11. 3-D Finite Element Analysis Model at raft level.

This analysis model allows for the inclusion of the foundation rotation due to the pile flexibility on the overall drift and the dynamic characteristics of the tower, and the inclusion of different pile stiffnesses under dynamic/cyclic wind and seismic forces. Figure 11 depicts the structural analysis model at the raft foundation level superimposed over the pile layout; the piles in Midas analysis program are represented by springs with variable stiffness to simulate the predicted pile stiffness. Summary of the foundation analysis, including foundation settlement, behavior of the foundation under wind loads, the pile axial loads summary, and the effect of foundation stiffness on the tower lateral displacement is depicted in Figure 12. This kind of analysis is expected to be performed with several pile stiffnesses to study its impact on the overall foundation behavior and its impact on the raft and key structural element design.

This analysis model allows for the inclusion of the foundation rotation due to the flexibility of the pile foundation system on the overall drift and the dynamic characteristics of the tower, and the inclusion of different pile stiffnesses under dynamic/cyclic wind and seismic forces. Figure 11 depicts the structural analysis model at the raft foundation level superimposed over the pile layout; the piles in Midas analysis program are represented by springs with variable stiffness to simulate the predicted pile stiffness. Summary of the foundation analysis, including foundation settlement, behavior of the foundation under wind loads, the pile axial loads summary, and the effect of foundation stiffness on the tower lateral displacement is depicted in Figure 12. This kind of analysis is expected to be performed with several pile stiffnesses to study its impact on the overall foundation behavior and its impact on the raft and key structural element design.

Figure 12 depicts 1) the overall arrangement of the pile relative to the tower superstructure as modelled in the analysis, 2) the pile load distribution among the piles and their contribution to both gravity and lateral loads, 3) the overall raft foundation settlement undet gravity and lateral loads, showing perfect sectional behaviour, 4) impact of the pile stiffness on the overall rigid body rotation of the tower, which would have direct impact on the overall displacement and ad dynamic characteristics of the tower.

The soil structure interaction modelled developed herein by the Samsung will be used as a base for correlating the actual foundation system behaviour to those predicted for the tower during construction and for the permanent building conditions. An extensive monitoring program was developed for the foundation system of the tower that allows for actual load distribution in the pile, the foundation settlement under the tower raft and across the site, and the strains in the raft. These data collected during construction will provide immediate feedback on the foundation stiffness, which in turn be used for calibrating the overall structural analysis model and immediate feedback on the overall structural behaviour during construction and under permanent building conditions.

5 CONCLUSION

This paper has described the design process of a mega piled foundation system for a super high rise building to be located within the reclaimed area in Songdo, Korea, which generally involves three principal phases, namely concept design, the main design phase and the post design/study phase.

Geotechnical uncertainty is the greatest risk in any deep foundation design and construction process. Establishing an accurate knowledge of the ground conditions is essential in the development of economical foundation systems which perform to expectations.

It has been emphasized that collaboration between the geotechnical designer and the structural designer is important for the foundation design as the overall pile group behavior needs to be adequately captured in structural design and the wide range of loading conditions needs to be adequately assessed in the geotechnical design. Based on the geotechnical engineering assessment of the foundation system, a 3-dimensional finite element analysis model can be created by the structural engineers to assess to the overall behavior of super-tall and slender towers by creating a 3-D analysis model to simulate soil-structure interaction and the stiffening effects of the superstructure on the foundation.

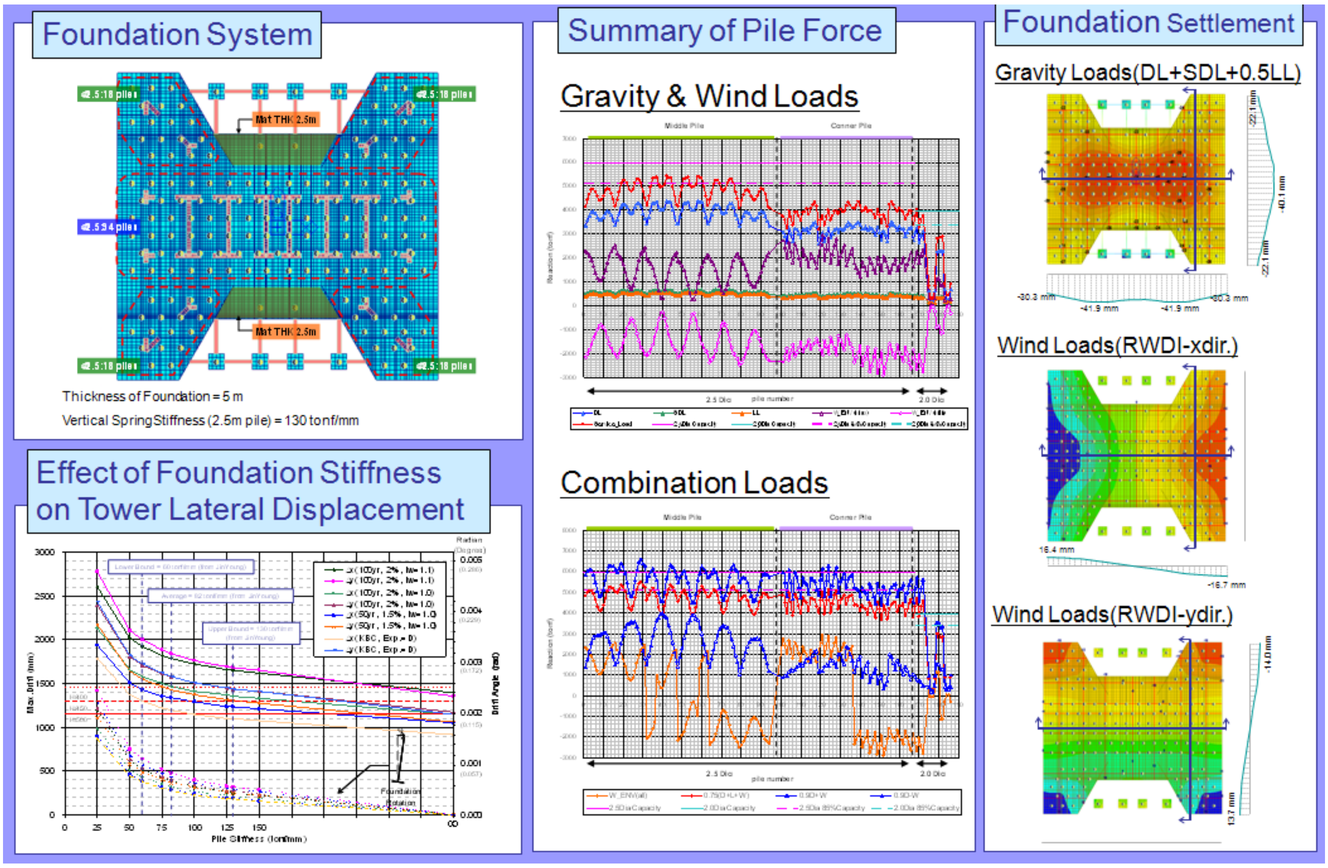

Figure 12. Summary of Foundation Analysis from Midas Program; Soil-Structure Interaction

The use of a suite of commercially available and in-house developed computer programs has allowed the detailed analysis of the large group of piles to be undertaken, incorporating factors that include pile-soil-pile interaction effects, varying pile lengths and varying ground conditions in the foundation design. An independent finite element analysis using readily available commercial programs had bee 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 post-design process was extended in order to obtain the actual response of the ground and the piles due to various loadings. From the results of pile load tests carried out in the post-design period, the prediction of pile behavior can be refined and the pile capacities can be updated which may result in confirmation or modification of the design, which may lead to a more cost-effective design.

The monitoring of the pile foundation during building construction and during service was recommended in order to better understand the overall building performance as well as the foundation performance during its operation.

Presently the tower site is fully reclaimed, the site is fenced, and the enabling work is in progress, and an extensive pile testing program has been completed and it will be discuss on a follow up paper.

6. REFERENCES

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