Piled Raft Foundation System for Tall Buildings

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Abstract Design of a safe and economical foundation system is an important task in tall build-ing design. Deep foundations such as piled foundations are generally adopted to transfer heavy loads from superstructure to the bearing stratum. Providing adequate geotechnical capacity and limiting the deferential settlement are two important design considerations in the design of piled foundations. The foundation design becomes economical when both the criteria of bearing capacity and settlement are satisfied in an optimum way. A piled raft foundation is an advanced concept in which the total load coming from the superstructure is partly shared by the raft through bearing from soil and the remaining load is shared by piles through skin friction and end bearing. Consequently, piled raft system is generally adopted when pile foundations for tall buildings become uneconomical or unsatisfactory. Due to the three dimensional nature of the load transfer, piled raft foundations are regarded as very complex systems involving many interaction factors such as pile-to-raft, raft-to-soil, and pile-to-soil. This paper intended to present a detailed discussion on the analysis of piled raft system addressing available analytical methods to analysis piled raft system. Considering of deferent factors influencing the pile raft behaviour are summarized in this paper. A detailed numerical analysis approach for the analysis of piled raft foundation is discussed. Further, a case study investigating the performance of piled raft system for an eighty-one storied tall building is presented.

Keywords Piled raft foundation · Soil-Structure interaction · Finite element analysis (FEA) · Settlement

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1 Introduction

As the inevitable results of rising population and growing land scarcity, high-rise buildings have become more predominant in many capitals in recent years. This phenomenon has forced the designers to design a suitable foundation system to satisfy the safety and economy for any kind of ground condition. The aspect of balancing the performance and cost of the foundation system is a challenge for the geotechnical and structural engineers. Also, geotechnical capacity and the settlement are the most key consideration during the designing of tall buildings. Due to the difficulty involved in the soil-structure interaction, proper foundation with systematic design guidelines, specified by both geotechnical and structural designers, is needed to predict the performance of the foundation system accurately.

Raft, pile and the piled raft foundations are the three major types of foundations commonly used in tall buildings. Generally, shallow foundations can be the most economical option for buildings loaded on subsoil with good load-bearing capacity. But the challenge in tall buildings is, due to heavy load from the super-structure, the thickness of the raft should be increased. It results excessive settlement and expensive. Further, due to the relatively low thickness-to-width ratio, the raft foundations exhibit flexible characteristics to some extent even under stiff ground environments. Uneven loading and varying ground conditions may increase the flexible features and result the differential settlement. These effects made up the building foundation design as crucial. Due to these limitations in the raft foundation systems, the idea of using piles as settlement-reducers was started in the seventies.

The other option of traditional pile foundation system are limiting the settlement and also satisfy the safety and the serviceability requirements in an effective manner. Under pile foundation all the loads from the superstructure is directly transferred to bedrock or underlying hard soil layer. This is the most common method currently used around the world. However, it is an uneconomic solution for both perspective of cost and time due to the requirement of higher number and larger length of piles required for tall buildings. Following that the concept of piled raft foundation system had been brought out by the re-searchers Randolph, Davis and Poulos [6].

This paper discusses background of piled raft foundation system and its analysis and design approach through a case study in Sri Lanka.

2 Pile Raft Foundation

The piled raft foundation is a combined system of piles and raft where both are partly shared loads of the superstructure. The Superstructure loads are shared between the piles using shaft friction and end bearing, while the raft supported on direct soil bearing. In this system the pile group typically carrying about 80% of the total load directly into the deeper strata. This system can be categorized into two major forms such as the raft-enhanced pile group and the pile-enhanced raft.

The piled raft foundation system transfers the loads by involving complicated three-dimensional interaction among the fundamental elements of pile, raft and the soil. In the traditional pile group, the interaction is acting only between piles and the soil. In case of piled raft foundation system, four interactions are trendy namely,

1. Pile-Soil Interaction.
2. Pile-Pile interaction.
3. Raft-Soil Interaction.
4. Pile-Raft Interaction.

In addition, the safety of the system depends on the combined system of raft, pile and the soil instead of only in the pile group as in the pile foundation. Therefore, design and the analyses of the piled raft system seems as complicated. Additionally, several issues needed to be addressed when designing the piled raft foundation. Such as, ultimate load capacity for vertical, lateral loadings, maximum settlement, differential settlement, raft moments and shears for the structural design of the raft and pile loads and moments for the structural and geotechnical design of the piles [6].

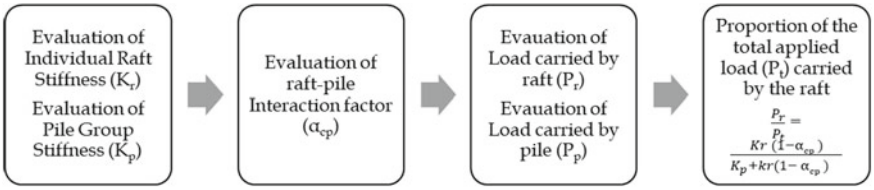
Pile raft shall be favourable when the soil underneath the raft has a profile with relatively stiff clay or relatively dense sand. But in the cases where soil profile beneath raft with soft cays, loose sand, soft and compressible layers at shallow depths risk of having consolidation settlement considering the pile raft action is unfavourable. These kinds of soils can lead to long term settlement and reduce the contribution to load sharing. Consolidation settlement could lead to losing the contact between the soil and the raft and finally, all the loads shall be shared by the Piles [6].

The design process of the pile raft foundation can be categorized as three stages, starting with the preliminary stage to evaluate feasibility, followed by assessing the number of piles required and locations finally end up with gaining the detailed design information including optimum number, location, and layout of the piles. In the preliminary stage, it is important to evaluate the performance of a pile and raft foundations individually if the raft or piles unable to satisfy the design criteria such as geotechnical capacity, settlement in an optimum manner a combined system is adopted.

In the piled raft design, several approaches are adopted to find the bearing capacity and the settlement. Such as:

1. Poulos and Davis [7].
2. Randolph [8].
3. Strip on springs analysis, using the program GASP (Poulos 1991).
4. Plate on springs approach, using the program GARP [5]

Poulos Davis method describes method of calculating the stiffness of the pile group and raft separately to find the amount of load sharing among them [7]. Flow Chart 1 describes the process of the analysis.



Flow Chart 1 The process of analysis for settlement

2.1 *Finite Element Analysis of Pile Raft System*

Real problems encountered in the application of piled raft systems for tall buildings are more complex. In solving such complex cases in practice with irregular pile layout and loading arrangements most accurate results cannot be obtained using those conventional analysis methods. Almost all the designs of tall buildings nowadays carried out by three-dimensional (3D) finite element model (FEM) analysis. With the aid of FEM analysis technics complex non-leaner behavioural pattern of materials and interactions as discussed above can be easily and more precisely accounted.

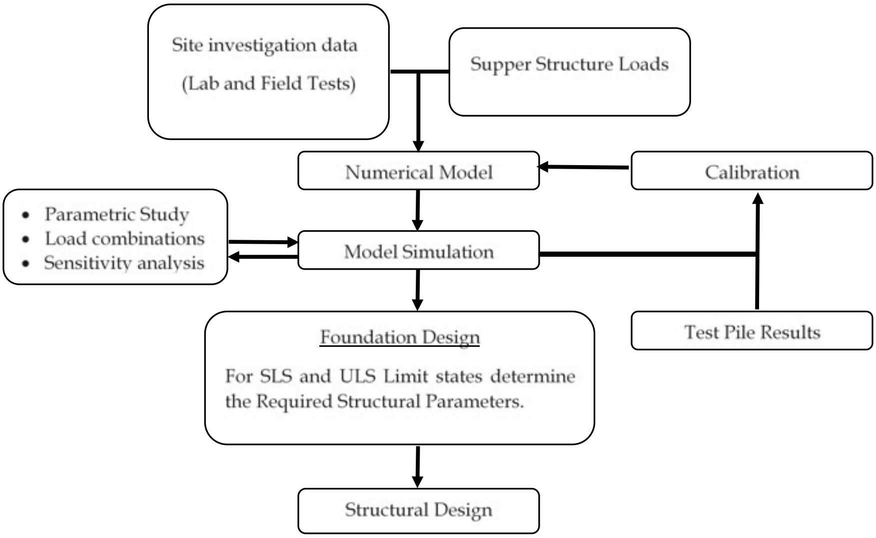
Under FEM analysis firstly it is important to select a software that capable to handle the designer's requirement. The Software should be included with good element library, array of material behaviour models and provisions for mesh refinement [1]. In the FE model that used for pile raft should be able to consider three-dimensional behaviour of a pile raft foundation and simulate the behaviour of a single pile to check its reliability and adjust the applied parameters depending on the chosen pile type. The 3D model should be able to take account of non-linear behaviour of pile and soil at pile and the pile shaft and stress-strain behaviour of the soil according to the applied stresses and strain to the soil. Finally, this model should able to consider the interactions mentioned above that govern the functionality of the pile raft System.

The processes of 3D FEM pile raft analysis can be summarized as below Flow Chart 2. According to the Flow Chart 2, 3D FEM model and the parameters shall be validated by a test pile results and recalibrate the model parameters.

In modelling piled raft system piles can be modelled using three finite elements such as;

1. Solid element model.
2. Beam solid connectivity model.
3. Line to solid interface model (Embedded pile).

In solid element modelling all the piles and the soil are modelled as 3D solid elements and an inter-face element is used for allow relative moment within the pile and the soil. This type of models, consumes much time on model definition, messing and computation. Pile Forces and moments cannot be directly taken in these types of models. In beam solid connectivity models, piles are modelled as line elements and



Flow Chart 2 Steps of pile raft FEM analysis

surrounding soil is modelled as solid elements. In this approach relative moments between pile and the soil is not allowed.

The line to solid interface modelling approach is the most ideal approach for modelling the pile in FEM model. In this method pile and soil meshing can be done independently as the interface element connects them. Nonlinear friction slip properties between pile and soil can be assigned to the interface element. The refinement of mesh is a minimum than previous two approaches which reduce computational time. A most suitable modelling approach shall be selected by the designers based on the objective of the analysis.

2.2 *Piled Raft Foundation-Case Histories*

There are many case histories available for piled raft foundations worldwide. Among those, some projects are summarized in Table 1. Other than the above-mentioned project the world tallest building Burj Khalifa was also supported on a pile raft system.

Table 1 Piled Raft foundation-case histories [4]

Tower	Structure (height/stories)		Load share (%)		Instrumentation	Settlement S_{max}
	Height (m)	Storey	Piles	Raft		
Messe-Torhaus, Frankfurt	130	30	75	25	Yes	NA
Messeturn, Frankfurt	256	60	57	43	Yes	144
Westend1, Frankfurt	208		49	51	Yes	120
Petonas, Kuala Lampur	450	88	85	15	Yes	40
QVI, Perth, West Australia.		42	70	30	NA	40
Treptower, Berlin	121		55	45	Yes	73
ICC, Honhg Kong	490	118	70	30	NA	NA
Commerzbank, Frankfurt	300		96	4	Yes	19
Skyper, Frankfurt	153		63	27	Yes	55

3 Case Study

3.1 Description of the Building

A detailed conceptual study carried out for the foundation system of an 81 storied tall building proposed in Colombo, the capital city of Sri Lanka is discussed in this section, which consists of 81 stories residential tower integrated with a 5 story podium for car parks and amenity at Level 6. Column loads extracted from the 3D finite element analysis carried out by the structural engineer are present in Fig. 1.

3.2 Sub-soil Condition

A detailed site investigation was carried out exploring 31 number of boreholes. A residual soil layer was found up to completely weathered rock (Biotite Gneiss) which was found at a depth of about 12–24.2 m. Basement rock level was encountered in between 18.00 and 36.00 m depth from the existing ground.

In general, the top layer consists of a 1 m filling layer overlaying 9 m of sandy soil. Below the sandy soil layer 6 m thick sandy clay layer overlaying 10 m thick highly weathered rock was identified. Below the highly weathered rock grade III moderately weathered rock was observed at 24 m below the ground level. Groundwater level was established at a range of 0.00–4.15 m depth.

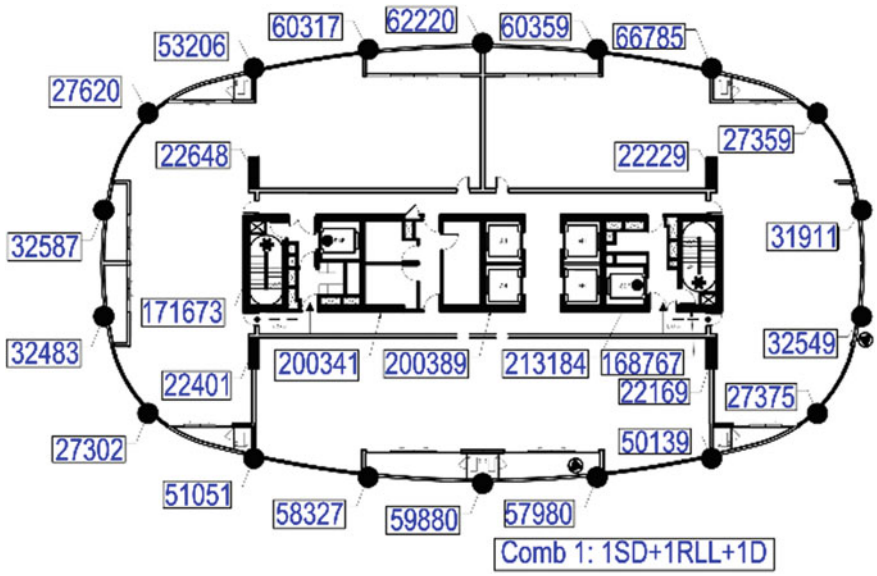


Fig. 1 Column load map at foundation level obtained with the aid of ETABS model (Gravity load case-kN)

Geological characteristics of the project area were analyzed from the review of the borehole investigation data, field observations, published and unpublished literature, and existing geology maps. Soil and rock characteristics, soil type and chemical and organic contents in groundwater and soils were determined during the field investigations.

Generalized borehole log data for tower area and geotechnical parameters recommended by the geotechnical consultant for different sub-soil conditions and rock categories are presented in Table 2.

3.3 Pile Foundation Design for Proposed Tower Foundation

Initially, a traditional pile foundation system was considered for the proposed building according to the above geological information. 138 of Bored and cast-in situ piles of diameter 1500 mm have been used based on the loading intended from the super-structure. Figure 2 shows the layout of the proposed piled foundation system. Symmetrical arrangement with the same spacing between piles was used.

A 4000 mm thick pile cap has been proposed to connect all the piles at 4 m below the ground level. The formation level of the pile cap at lift core is 3800–5200 mm below the ground Level.

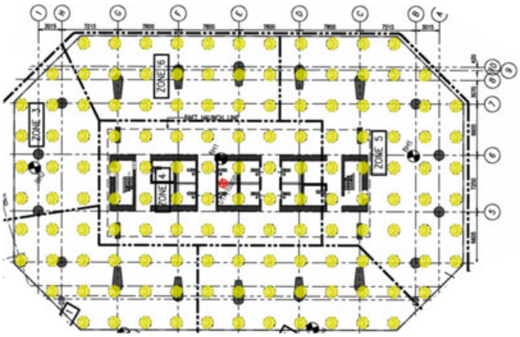
Table 2 Sample borehole details

Depth (m)	State	SPT value	Ultimate skin friction (kN/m^2)	Allowable end bearing (kN/m^2)	CR (%)	RQD[a] (%)	UCS (MPa)
3.30	Very dense sand with clay	50	65	–			
6.30	Medium dense SAND with clay	13	15	–			
13.80	Medium dense to dense sand with clay	19	25	–			
21.30	Very dense sand with clay and mica	>50	70	–			
25.70	Completely weathered rock (Hornblend biotite gneiss)		150	–	100	57	12.04
29.50	Moderately weathered rock (Garnet biotite gneiss)		200	3000	97	60	10.51
31.50	Moderately weathered rock (Garnet biotite gneiss)		200	3000	46	–	–
34.70	Moderately weathered rock (Biotite gneiss)		200	3000	77	15	26.12
39.70	Slightly weathered rock (Biotite gneiss)		200	4000	100	44	24.13

[a]*RQD* Rock quality designation *CR* Rock Recovery Ratio

According to the geotechnical data and geotechnical engineer's recommendation, the calculated pile capacity with minimum 4.5 × pile diameter rock socketing is presented in Table 3.

A three-dimensional finite element model of tower with a proposed pile arrangement was developed with the aid of a commercially available computer software CSI ETABS as shown in Fig. 3.



Pile colour	Diameter	No. Piles
	1500	138

Fig. 2 Proposed piles layout

Table 3 Summary of the pile foundation design

Pile diameter (mm)	Pile geotechnical capacities (kN)	No of piles
1500	15,450	138

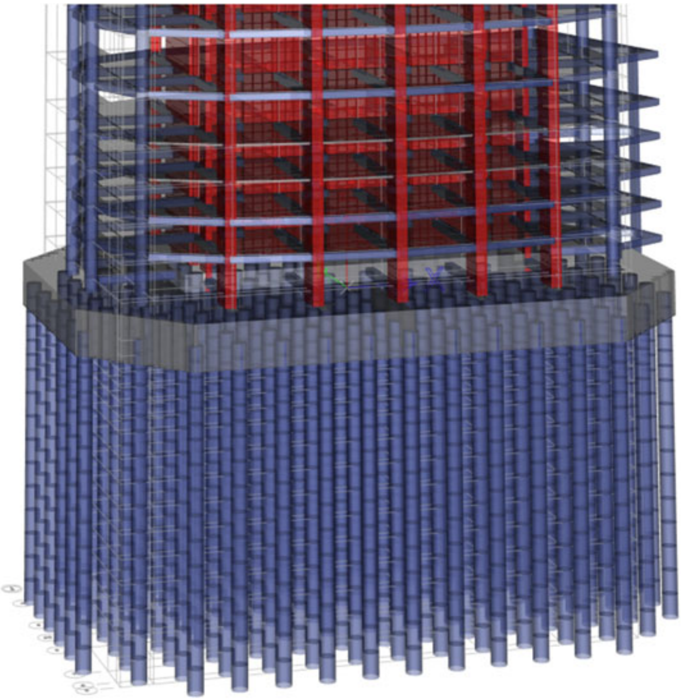


Fig. 3 Etab Model with Piles

Lateral support from soil was modeled as springs and lateral soil subgrade modulus used in the piled supported analysis model is calculated based on the geotechnical parameters given in the site investigation report and the approach presented by Glick [3] and Bowles [2].

$$k_s' = \frac{22.4E_s(1-\mu)}{(1+\mu)(3-4\mu)\left[2\ln\left(\frac{2L_p}{B}\right)-0.433\right]} \quad (1)$$

$$k_s = \frac{k_s'}{B} \quad (2)$$

E_s Stress Strain Modulus.
μ Poissons's Ratio.
L_p Pile Length.
B Pile Width
k_s Lateral Spring Constant

For the soil, lateral spring constants between 25,000 and 45,000 kN/mm and for the rock between 80,000 and 550,000 kN/mm were used. Figure 4 shows the final pile loads from the analysis. The raft action from the pile cap was neglected in the analysis and raft is only utilized to transfer load within the piles.

From, the analysis result it can be observed that piles under the center core wall are heavily-loaded whereas at the boundary piles are lightly-loaded. According to the analysis loads from the tower were not properly distributed among the pile was due to ignoring soil-structure interaction of piles (pile settlement behaviour).

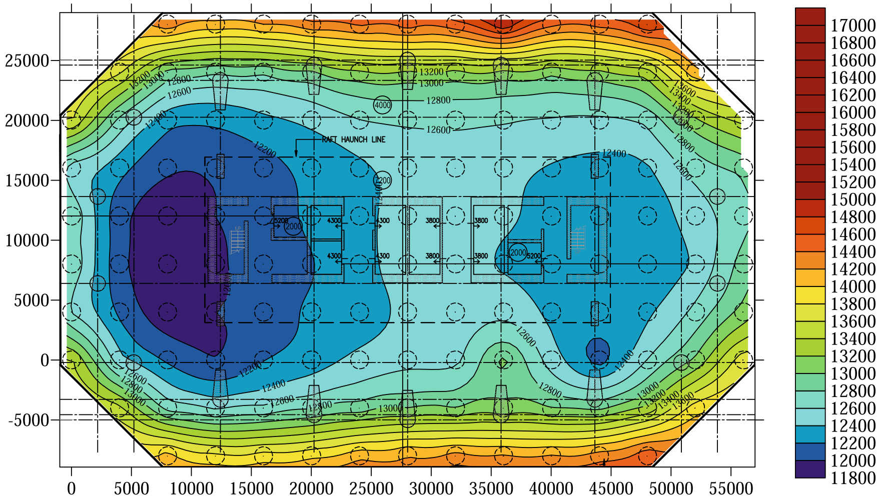


Fig. 4 Pile load contour for pile foundation option

Finally, a comprehensive soil-structure interaction analysis was carried out to find the pile loads. In order to satisfy the geotechnical capacity for pile option minimum 10 m rock socketing was needed. This leads to an increase in foundation costs and reduces construction efficiency. In order to address this problem a piled raft system with treating the piles in combination with raft founded 4 m below ground level was considered. Detailed soil-structure interaction analysis was performed using a 3D finite element model developed in Midas GTS NX.

3.4 Pile-Raft Analysis for the Proposed Tower Foundation

A 3D finite element model was developed for the proposed pile raft system using Midas GTS NX commercially available software as shown in Fig. 5. The line to solid interface model (embedded pile) was utilized in the modeling of piled raft system. The material properties used for FEM modeling are presented in Table 4.

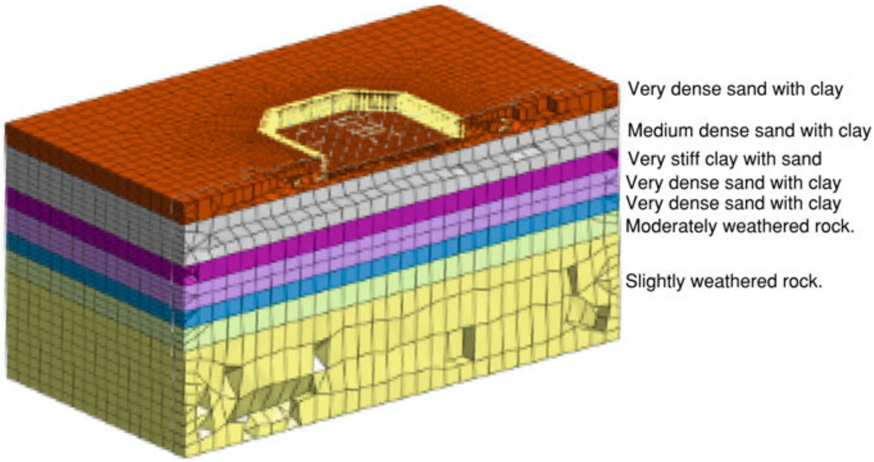


Fig. 5 Midas GTX pile raft model

Table 4 Material models used in FE modeling

Element	Material	Element type	Material behaviour type
Piles	Concrete	2D beam	Isotropic material with elastic behavior
Walls	Concrete	2D shell	Isotropic material with elastic behavior
RAFT	Concrete	3D solid	Isotropic material with elastic behavior
Soil strata	Soil	3D solid	Isotropic material with Mohr-Coulomb behavior
Rock strata	Rock	3D solid	Isotropic material with Hoek Brown behavior

More often in 3D finite element analysis soil is modeled in Mohr-Coulomb behavior. As the rock is more hard and rigid than soil, behaviour cannot be predicted by deriving the stiffness changes due to applied stress. Therefore, Hoek and Brown proposed a concept of equivalent continuum to define the reduction of stress phenomenon in jointed rock masses. This method accommodates to consider unconfined compressive strength of rock which is not considered in Mohr-Coulomb behaviour which leads to simple and accurate representation of rock behaviour.

Raft, soil and the rock were modeled using solid elements while the pile was modeled by a line element as described in an embedded pile approach. The interface between piles and soil was modelled by interface element available in the software which accommodates to simulate the boundary behaviour between same or different materials. Interface parameters are given in Table 6.

The material properties used in the analysis according to the geotechnical report used are summarized below in Table 5.

When modeling the soil boundary, a minimum length equal to the pile cap width was maintained from the edge of the Pile cap to the X-Y plane boundary. The boundary of the rock layer was kept one pile length from the pile base level.

The hybrid meshing method in the programmed was adopted in the analysis. These hybrid elements are formed by combining pyramid and tetrahedron on a hexahedron base which leads to more accurate results that were used for the meshing of elements. The size of the mesh was reduced near pile cap and pile surface. Control points were added in locations of the columns and walls to apply the loads from the supper structure as shown in Fig. 6. At the boundary of soil and rock element points were pinned.

The analysis was carried out under four construction stages. Pile loads for the analysis are given in Fig. 7 and the expected settlement contours are in Fig. 8.

According to Figs. 7 and 8 it was observed pile loads have distributed between all the piles due to the settlement of heavily loaded piles under the core of the building. Table 7 illustrate the final loads share by piles group and raft for each analysis method.

Based on this detailed soil-structure interaction analysis it was observed approximately 11% of the total load is shared by the raft. Further, a nearly uniform distribution of pile loads was observed due to the stiffness contribution of the raft. The effective raft area is 2051 m^2 and average bearing pressure was 110 kN/m^2. Consequently, results from this analysis assisted to minimize the pile loads and rock socketing required. A more economical, safe and constructible foundation design using the piled raft system was obtained.

Around 25% of the total load from the superstructure was shared by the raft in most of the pile rafts designs around the world where the piles are friction piles. In this case study piles were end-bearing piles, and this leads to a higher stiffness ratio of pile group. Therefore only 11% of the total load was shared by the raft.

Table 5 Material properties used for FE modeling

Category	Depth of Layer (m)	Depth from Ground (m)	Elastic Modulus (MPa)	Poisson Ratio	C′ (KPa)	Cu (KPa)	Friction Angel (φ)	Ultimate Skin Friction (kPa)	UCS (MPa)
Very dense sand with clay	6.3	6.3	2	0.3	10		38	15	–
Medium dense sand with clay	7.5	13.8	25	0.28	–	–	32	25	–
Very stiff clay with sand	4.5	18.3	14	0.3	–	190	–	50	–
Very dense sand with clay and mica	6	24.3	40	0.25	40	–	10	70	–
Moderately weathered rock	9.2	33.5	350	0.25	–	–	–	200	12.00
Slightly weathered rock	5.5	39	600	0.2	–	–	–	200	26.00
Concrete	–	–	25,000	0.2					

Table 6 Interface properties used for FE modeling

Category	Ultimate shear force (kN/m^2)	Normal stiffness modulus (kN/mm)
Pile to soil interface	50	30,000
Pile rock interface	200	500,000

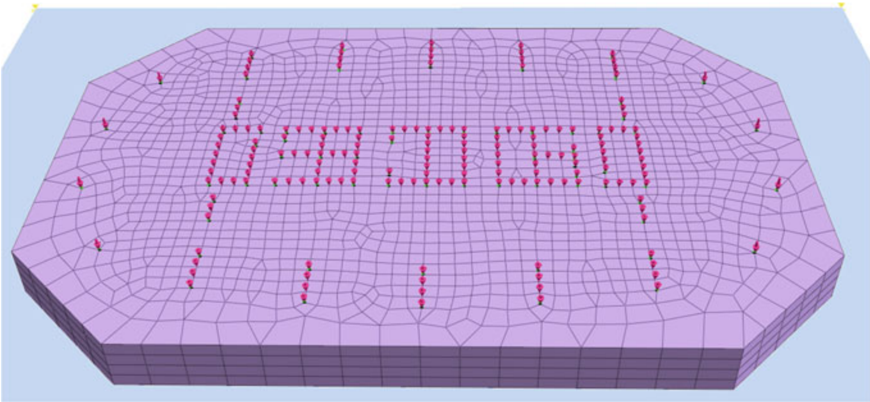


Fig. 6 Loads applied at the controlled points

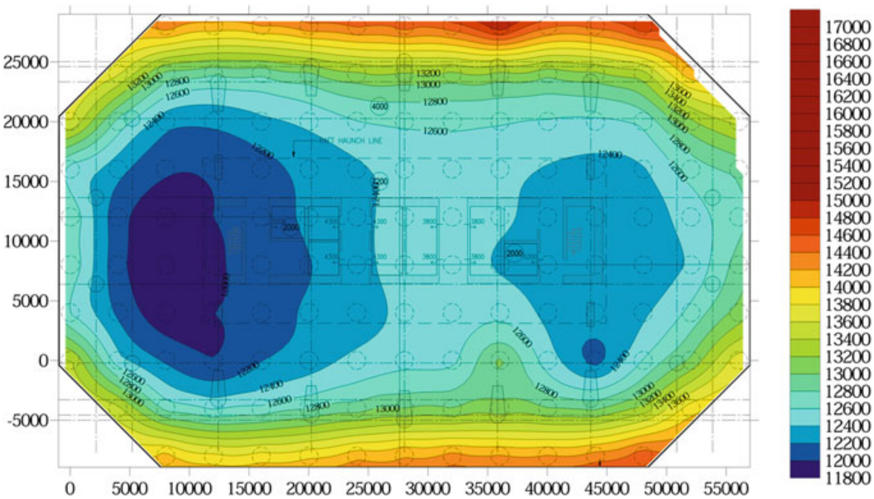


Fig. 7 Pile load contour from pile raft analysis

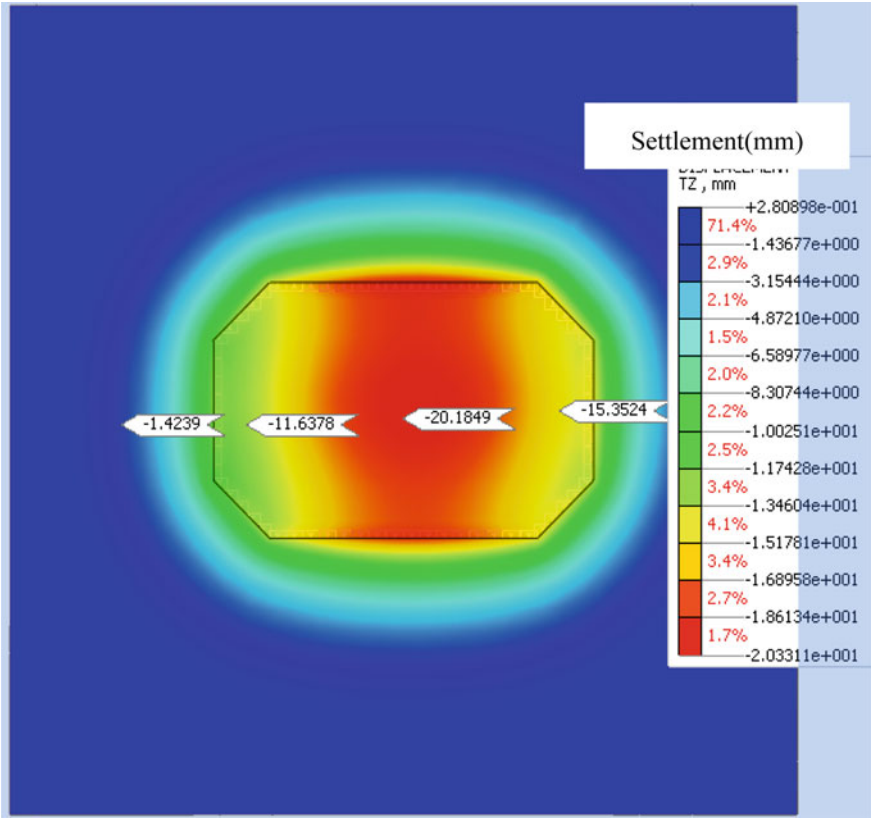


Fig. 8 Settlement contour from pile raft analysis

Table 7 Load carried by pile and raft for different models

	Load carried by pile (MN)	Load carried by raft (MN)
Etabs model	1994.63	–
Midas GTS NX model	1771.27	223.36

4 Conclusion

The concept of the piled raft foundation system and its advantages for tall buildings is discussed in this paper. Background of the piled raft foundation system, behaviour and various analysis methods including finite element methods were outlined. Important considerations to be made in the Finite element modeling and analysis of piled raft foundation were discussed. Significance of adopting piled raft foundation for tall buildings located in fractured rock sites over conventional pile foundation was explained through a case study. Obtaining a sustainable foundation design for a tall building considering geotechnical pile capacities, pile settlements, cost, and constructability, etc. were highlighted.

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