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ALTERNATIVE FOUNDATION SYSTEM FOR PILES WITH SOFT TOE CONDITION

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Abstract: This paper presents an alternative foundation system implemented for a 17 storied mixed development building at Kollupitiya. Initially, the foundation system of above building was designed to contain bored cast insitu piles driven to hard basement rock. During pile dynamic testing, the tested piles were found to undergo excessive settlements and failed to mobilize the expected design capacity due to soft toe condition. As an alternative for this problem, piled raft system was proposed and its feasibility was examined. Finite element modelling and analysis was carried out using SAFE v12 representing the raft as shell element and piles as springs. The simulation design and process is discussed in detail in this paper. The 'conventional approach' was highlighted in the design of raft with a load apportionment of 60:40 to piles and raft. While replacement of failed piles and rectification of piles incur significant time, cost and resources, the proposed piled raft system was found to be a sustainable and economical solution with least disturbance to the ground.

Keywords: piled raft; finite element modelling; pile dynamic test; settlement

1. Introduction

Foundations play a key role in the safe transfer of superstructure loads to the ground. Weak ground creates the requirement to go for deep foundations which enables transferring loads to either good bearing soil by skin friction or to stable rock by end bearing or a combination of both. The common practice in Sri Lanka is to socket bored cast- insitu piles into hard rock wherever transferring loads from tall structure to the ground is required. Eventually, it is the integrity of the pile that comes into play when considering the safe load transfer from the superstructure. Poor workmanship, non-availability of appropriate equipment and poor construction practices can result in piles with lower carrying capacity which can put the whole structure at risk. As remedial actions for pile failures may cause significant implications on time, cost and resources, it is very important to find an appropriate solution which is safe and economical.

This paper presents a solution proposed for pile foundation of a 17 storied mixed development building located at Kollupitiya which was found to undergo excessive settlements during pile dynamic testing (PDA). Initially, the foundation system of above building was designed to contain bored cast insitu piles driven to hard basement rock. Pile Integrity Test (PIT) and Pile Dynamic test (PDA) were conducted to check the quality and probable carrying capacity of piles. Three piles out of 65 were subjected to Pile Dynamic Test and one of them was found to undergo excessive settlement of 37 mm and the rest were found to have mobilized lower end bearing resistance. Hence, soft toe condition due to presence of bentonite or fine sand layer underneath the toe of pile was suspected. Due to the fact that main contractor had been already awarded and the client was insisting to proceed with no further delay, a quick decision had to be made on course of action. Three solutions were possible.

1. Test some more piles (contractor was under obligation to test at no cost for the failed ones) and to drive compensate piles.
2. Rectification of piles by core drilling up to thetoe and grouting the base area after cleaning to remove entrapped sand or bentonite.

3. Adopt a piled raft utilizing a certain percentage of the available skin friction of piles also.

Based on the fact that a similar type of pile failure was observed in a previous contract with the same piling contractor, it was felt that further testing of piles would be a futile exercise and wastage of time. Furthermore, driving additional piles will also take long time and cause delay for the main contractor. In view of the fact that core drilling of a pile is a very skilled job where high precision is required and only very limited specialized contractors were available to carry out the work within the stipulated time frame, method (2) had to be discarded.

Therefore, it was agreed by all parties concerned to adopt a piled raft system. The method of analysis performed is discussed in detail in the following chapters.

2. Literature Review

For the foundation design of a tall structure, it is a common practise to consider the use of shallow foundations, such as raft first, to support a structure. Designing a pile foundation where entire design loads are resisted by piles is considered only when the first option is not workable. Despite of this, it is common for a raft to be part of the foundation system. The foundation which makes use of both raft and piles is referred to as a piled raft foundation. The piles play an important role in controlling differential settlement, and therefore can lead to an economical design without compromising the structural safety. In several cases, piles are allowed to yield under design loads. Although the load capacity of the pile is exceeded, raft can hold additional loads with controllable settlement [1, 2].

The behaviour of piled raft foundation is governed by interaction between the piles, soil and raft. There are two basic interaction factors, namely, pile- soil- pile interaction and pile- soil- raft interaction. The interaction factors are dependent on the density of soil, the ratio between pile length and diameter of pile (L/d) and the ratio between the pile spacing and pile diameter (S/d). When pile spacing to diameter ratio increases, the interaction factor decreases. It implies whenever the spacing is large, the behaviour of a pile can be closely approximated to the behaviour of a single pile [2]. Additional settlement of piles caused by adjacent piles is usually taken into consideration while calculating the pile spring stiffness. Hence, the stiffness of pile spring $k_{s'}$ is given by

$$k_{s'} = P_s / W \tag{1}$$

Where P_s is the load carried by pile shaft considering the pile- soil- raft interaction. This has been taken into consideration by assuming there is no any contribution by soil friction component up to 17m of pile and W is the vertical displacement of pile.

$$k_s = k_{s'} . \eta \tag{2}$$

2.1 Alternative design principles

Randolph has defined clearly three different design philosophies with respect to piled rafts [1]:

1. A conventional approach, where piles are designed to carry the major part of the load while making some allowance for raft.
2. 'Creep piling', where piles are designed to operate at their working loads, sufficient piles are included to reduce the contact pressure between the raft and the soil. Raft carries more load than in case 1.
3. Differential settlement control, where the piles are positioned strategically to reduce the differential settlement instead of substantially reducing the overall average settlement.

3. Method of analysis

The underlying challenges identified in this project are predominantly related to the piles those are unable to carry expected design loads and intrusion of organic clay layer at a depth of 11 m which limits the maximum load transferable to shallow bearing strata. The function of raft in this case is reducing differential settlement of piles and distributing the additional loads on weak piles to adjacent piles and subsequently to the soil. Simultaneously, it is vital to ensure that the earth pressure does not exceed allowable value. The analysis and design of pile raft system involves iterative procedure. The main concern in modelling of piled raft is assigning appropriate spring stiffness for piles. In this particular case, pile dynamic test results were utilized to calculate the relevant pile stiffness values. The high strain dynamic testing was performed on selected piles. Several blows with increasing drop heights were applied on the tested piles and dynamic measurements and permanent pile top settlements were measured. The field results were further analysed with CAPWAP software, a signal matching program that uses force and velocity data measured by the Pile Driving Analyzer (PDA) system to calculate static soil resistance, static end bearing and stresses at any point along the shaft. Preliminary values of pile spring stiffness were calculated from CAPWAP results assuming linear force- displacement relationship. The technical feasibility analysis of piled raft involved 4 main steps as follows.

Step 1 : Calculating initial value for pile spring stiffness from PDA and CAPWAP results

Step 2 : Assessing the quality of piles based on soft toe conditions

Step 3 : Determining the allowable capacity of piles

Step 4 : Finite element modelling of piled raft and performing the iteration

3.1 Design criteria

Conventional approach was used in design of piled rafts since the foundation system of proposed building had been designed as end bearing piles and PDA test results revealed that more than 50% of the design capacity mobilized in the tested piles. Initially the piled raft was analysed based on the two criteria listed below. These were also optimized in the final design stage.

a. Apportionment of loads to piles and raft is 50:50

$$\alpha = \frac{\sum n_i k_i}{(A k_r + \sum n_i k_i)} \quad (3)$$

$$A = A_r - \sum n_i A_i \quad (4)$$

b. Piles take 100% of their allowable load and any additional load is distributed to soil by raft

3.2 Calculation of preliminary spring stiffness of piles

PDA test results allowed calculating a reasonably closer value of pile spring stiffness to start with. The iteration process of bringing pile reactions within the tolerance may become time consuming depending on the number of piles and range of diameters. The proposed building has 65 piles in total with diameters ranging from 750 mm to 1200 mm as shown in Figure 1. Soil model parameters extracted from PDA and CAPWAP results are tabulated in Table 1.

For modelling purposes, soil skin friction and toe resistance were idealized as springs. Equivalent pile spring stiffness is expressed as,

$$\frac{1}{k} = \left(\frac{1}{k_t} - \frac{1}{\eta k_s}\right)\frac{P_t}{P} + \frac{1}{\eta k_s} \quad (5)$$

for single pile. Based on this, spring stiffness of pile was calculated as presented in Table 2.

A_r - Area covered by raft
k_r - Bulk Modulus of soil up to highly weathered rock layer (kN/m^3)
A - Effective area of the Raft
k_i - Stiffness of pile type i
n_i - Type i number of piles
A_i - Area of Type i, piles
k_t - Stiffness Contribution by pile toe
k_s - Stiffness Contribution by pile shaft with sound rock and fractured rock layers (single pile)
k - effective pile stiffness
η - Pile group efficiency

α - Fraction of load transmitted to piles
P_t - Allowable end bearing capacity
P - Allowable capacity of pile

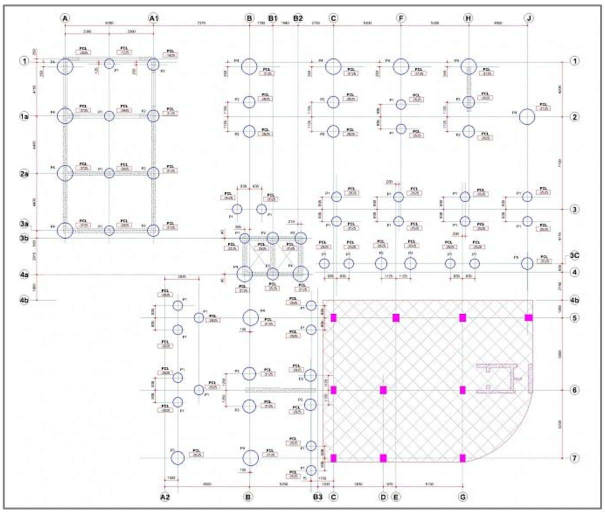

Figure 1: Pile layout

Table 1: Summary of CAPWAP results

Pile No	60	49	2
Pile diameter (mm)	1200	1200	750
Mobilized capacity (kN)	7277	4280	2341
Average shaft resistance (kN)	5527	3826	1226
Shaft quake (mm)	2.0	2.0	2.0
Mobilized toe resistance (kN)	1749	454	1115
Toe quake (mm)	8.1	1.02	5.3
End bearing resistance (Nmm^{-2})	1.55	0.4	2.52

A lower value of 3000 kN/m3 was used for the subgrade modulus in view of the presence of a soft soil layer at an average depth of 11 m.

3.3 Identification of quality of pile

There are several factors that affect the quality of piles such as quality of drilling machines and drilling tools, quality of rock socketing, quality of maintaining the borehole, quality of cleaning the borehole, quality of concreting and the integrity of pile. Integrity of pile is really depends on all other factors given above. Pile integrity test provides quick and inexpensive means of assessing the integrity of cast in- situ piles. The soft toe condition can be identified by studying the wave propagation diagram from PIT test [3].

Table 2: Spring stiffness of piles

Pile No	60	49	2
Shaft stiffness , k_s (kN/m)	208500	172200	52500
Toe stiffness , k_t (kN/m)	216000	151600	210396
Equivalent pile stiffness, k (kN/m)	195897	154367	93076

In this case, PIT test results were used to identify 'good' and 'weak' piles in terms of existence of soft toe condition. From the study, 32 piles out of 65 were suspected as weak. Figure 2 shows the layout of good and weak piles.

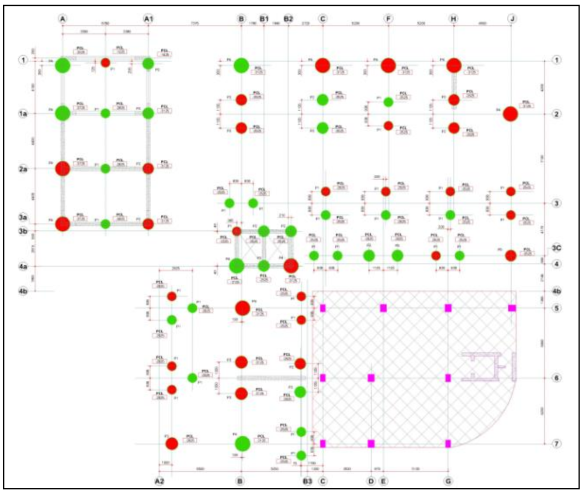

Figure 2: Layout of piles based on soft toe condition

3.4 Determination of allowable bearing capacity of piles

Allowable load bearing capacity of pile (P_{all}) is given by division of mobilized bearing capacity (P_m) by an appropriate safety factor.

$$P_{all} = P_m / FOS \qquad (6)$$

From the PDA and CAPWAP results presented in Table 1, pile number 60 was found to have mobilized an end bearing resistance of 1.55 Nmm^{-2}. Pile number 49 and 2 had mobilized end bearing resistance of 0.4 Nmm^{-2} and 2.52 Nmm^{-2} respectively. Comparing to the net allowable end bearing capacity of 5 Nmm^{-2} specified for the basement rock, it was concluded as these three piles were terminated on soft material. For analysis purposes, it was assumed that the good pile had mobilized its design capacity fully whereas weak pile had attained 50% of the design capacity. A safety factor of 1.2 was taken to be reasonably enough for deriving allowable capacity of good piles. Table 3 tabulates the capacities of piles of various diameters.

Table 3: Capacity of piles

Pile diameter (mm)	Design capacity (kN)	Allowable bearing capacity (kN)	
		Good	Weak
750	2700	2250	1350
900	3900	3250	1950
1000	4800	4000	2400
1200	7000	5800	3500

3.5 Finite element modelling of piled raft and iteration

The proposed method was used to estimate the settlement and bending moment induced in the raft. Finite element modelling of foundation was carried out with SAFE v12. Raft was modelled as thick shell element with a maximum element size of 0.75 m so as to maintain the aspect ratio of mesh elements close to 1. The bearing soil medium and piles were modelled as springs with soil subgrade properties and point spring properties respectively. Initially, pile supported suspended raft (case 1) was modelled using elastic modulus of piles and the reactions on piles were obtained for comparison. The analysis procedure of piled raft system (case 2) using SAFE v12 was as follows:

1. Modelled the piled raft foundation, where the raft is modelled as a thick shell element, piles were modelled as point springs and soil stiffness was assigned as area spring using subgrade modulus.
2. Pile point springs were assigned initially using the values given in Table 2.
3. Obtained the reactions in every pile and compared with allowable values tabulated in Table 3.
4. Changed the point spring stiffness iteratively till obtaining reactions close to allowable bearing capacities given in Table 3. If it exceeded, replaced the pile spring with allowable load in Table 3 and repeated the analysis.
5. Finally, the settlement of raft, soil pressure contour and bending moment were obtained.

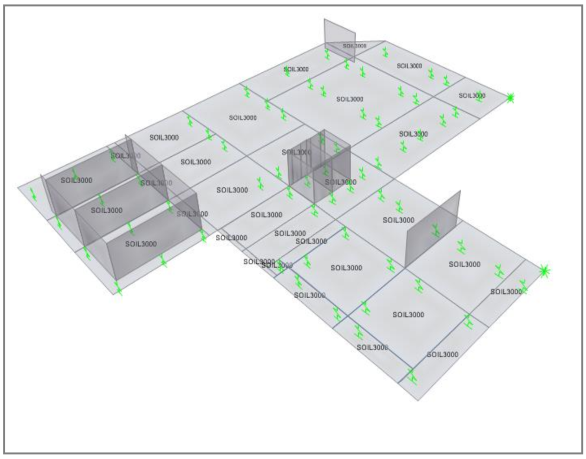

Figure 3: Piled raft model

4. Results and discussion

The feasibility of piled raft in this scenario was assessed by settlement of raft and soil pressure below the raft. The sum of serviceability loads including the weight of raft obtained from case 1 was 204 MN. With the tolerance of 0- 20% between allowable capacity and actual load allowed, sum of loads transferred to piles was 122 MN.

Hence, the load sharing percentage between piles and raft was 60:40. If the tolerance was brought up to 5-10 %, the load transferred to soil can be reduced to 20%. Also, it is transparent from Figures 4 and 5 that the maximum settlement and maximum soil pressure generated for Serviceability Limit State was 37 mm and 113 kN/m2 respectively. Average settlement of the raft was 32 mm. For the given soil conditions and the total working load, it was found that the raft alone will undergo a settlement of 240 mm which is more than the allowable settlement. In this scenario, by taking part in the load carrying system, piles act as settlement reducers to the raft. Consequently, it was noted that the maximum soil pressure is less than the allowable bearing pressure recommended for a raft foundation.

4.1 Selection of raft thickness

Neither the maximum settlement nor the percentage of load carried by piles is very sensitive to raft thickness. However, increasing the raft thickness reduces the differential settlement [1]. Hence, the.

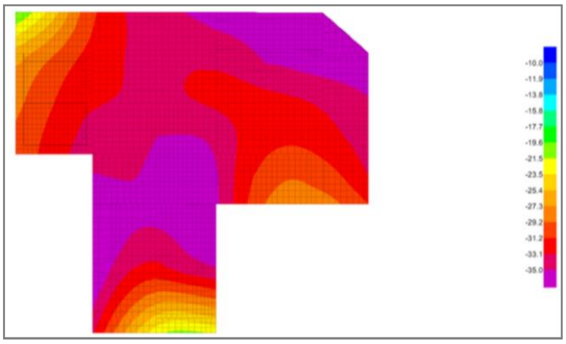

Figure 4: Deformation diagram of raft (in millimetres)

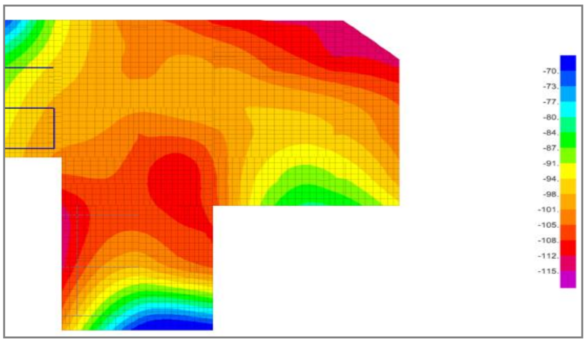

Figure 5: Soil pressure diagram of raft (in kN/m²)

maximum bending moment and punching shear governs the selection of raft thickness In this case, considering the highest bending moments at lift core and underneath the columns, raft thickness was chosen as 1000 mm.

5. Conclusion

This paper presented the method of analysis of piled raft system implemented for a 17 storied building as an alternative to pile foundation which failed to carry intended working load due to soft toe condition. The analysis was carried out using commercial finite element modelling software SAFE v12 in which the raft was modelled as thick shell and piles and soil as springs of appropriate stiffness. The challenge of choosing the initial spring stiffness values for piles was overcome by incorporating PDA and CAPWAP results which significantly reduced the time taken for iteration. Also, pile integrity test results, which assisted in identifying the quality of piles, eliminated the need of any additional pile dynamic tests.

In case of piles failing to mobilize enough carrying capacity due to soft toe condition, rectification can be done in several ways such as installing new piles to replace failed ones and strengthening suspected piles with core drilling beyond the toe, cleaning thoroughly and injection of grout to strengthen the area below and around the toe. While these solutions cause greater disturbance to the ground and surrounding in the form of noise and vibration, proposed piled raft system was found to be a sustainable and economical solution.

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