The significance of raft flexibility in pile group and piled raft design

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ABSTRACT

An important aspect of the design of pile groups and piled rafts is the checking of axial loads, lateral loads and bending moments in each of the piles to ensure that they are structurally sound, but most commercially available pile analysis programs assume that the raft or pile cap is rigid. This paper explores the importance of taking the flexibility of the pile cap into account in making assessments of the load and moment distributions. The case of a hypothetical soil profile is considered first and then the case of a super tall building in Korea is considered. The differences between the computed axial loads for a rigid raft and for the actual raft thickness are presented, and it is shown that consideration of the actual thickness of the raft is essential to avoid having to design for unrealistically large loads in the outer piles within the group.

Keywords: pile group, piled rafts, rigid raft, raft flexibility, high-rise structures, axial load distributions

1 INTRODUCTION

In the design of pile group and piled raft foundations, the pile caps or rafts are designed to distribute the loads from the structure to the piles which then transfer load to the soil. To ensure the foundations are structurally sustainable, it is required to assess the loads and moments in the piles and provide this information to the structural engineers for the structural checks.

A number of commercially available software packages can be used for the assessment of loads and moments in piles, including the programs PIGLET, REPUTE and DEFPIG in which the pile cap or raft is assumed to be rigid. With this assumption, the flexibility of the pile cap or raft is not taken into account. Basically, the rigid pile cap shows less deformation, resulting in higher computed loads and moments than for a flexible pile cap. Considering the axial load in the pile, the piles near the outer parts of the foundation tend to carry higher loads than those in the interior parts of the foundation, especially for large foundations, which may lead to difficulties in the structural design of the piles.

In general, the flexibility of the pile cap or raft influences the distribution of pile loads, bending moments and shear forces in individual piles (Won et al, 2006). The flexibility of the pile cap or raft is governed by several factors including the raft thickness and spacing between piles.

This paper demonstrates the importance of considering the flexibility of the pile cap/raft in the design of a pile group and piled raft foundation by examining first a case with a hypothetical soil profile. Numerical analyses are undertaken for pile groups of different sizes and comparisons are made of computed axial loads and bending moments in the piles for a rigid pile cap where flexibility is not considered and for a flexible cap where thickness and flexibility are considered.

The case of a super tall building in Korea is then examined, and the differences between the computed axial loads on the piles, vertical pile stiffness and foundation settlement for a rigid raft and for a flexible raft (where the actual raft thickness was considered) are presented.

2 EXAMPLE OF RIGID RAFT VS FLEXIBILE RAFT IN PILED RAFT FOUNDATION

To demonstrate the importance of considering the flexibility of the cap/raft in the foundation design, a simple example is considered in which pile groups of different sizes are embedded in a two layered soil model, as shown in Figure 1. The assumed geotechnical parameters are summarised in Table 1. The cap/raft is assumed to be in contact with the underlying soil. The piles have a diameter of 0.6m with a length of 10m and a Young's modulus of 30,000MPa. The centre-to-centre spacing (s) between the piles is taken as three times the pile diameter, d (i.e. s = 3xd).

Three cases have been analysed, with varying numbers of piles and size of raft as summarised in Table 2. For each case, both a rigid raft and a flexible raft are taken into account. To model a "rigid raft", a thickness of 3m is considered while for modelling of a "flexible raft", a thickness of 0.5m is considered. Analyses have been carried out for the pile groups subjected to (a) a uniform axial load and (b) a uniform horizontal load equal to 10% of the uniform vertical load. The magnitude of the axial load (Pv) is taken as the total ultimate capacity (Pu) of the pile group divided by an overall factor of safety (FOS) of 2.5 (i.e Pv = Pu/2.5).

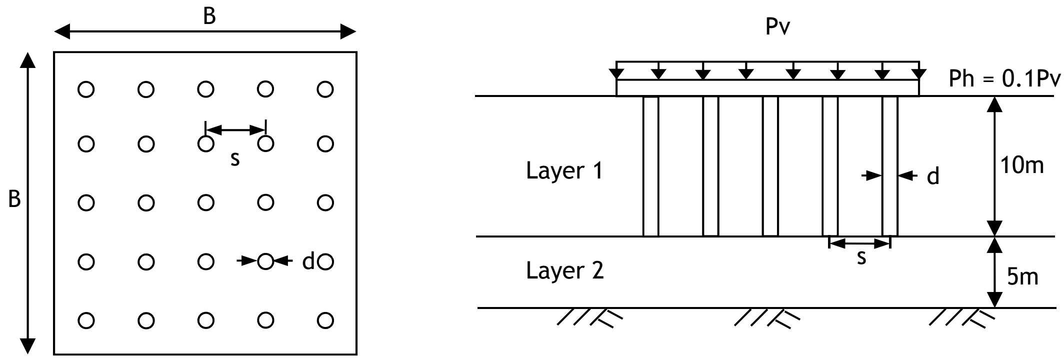

Figure 1. Typical Foundation Layout Embedded in Two Layered Soil Model

Table 1: Properties of soil material

Material	Thickness (m)	Young's Modulus, Es (MPa)	Skin friction, fs (kPa)	End bearing, fb (MPa)
Layer 1	10	20	25	-
Layer 2	5	100	120	6

Table 2: Summary of cases considered

Cases	No. of piles	Raft Dimension, B (m)
1	3x3	5.4
2	5x5	9.0
3	7x7	12.6

2.1 Pile groups subjected to uniform axial loads

For a uniformly axial loaded pile group, the computer program GARP (General Analysis of Raft with Piles) has been used for the analysis. GARP employs a simplified boundary element approach to model the piles and soil, and a finite element approach to model the raft (Small and Poulos, 2007).

2.1.1 Effect of pile group size

The effect of the size of the pile group on the axial load distribution in the piles is illustrated by the three cases presented in Table 2 with rigid and flexible rafts.

Figures 2 and 3 show plots of normalised axial load (P/Pav) versus number of piles in the foundation with rigid and flexible rafts where P = load on pile and Pav = average load on pile (Total applied load/no. of piles) for the centre and corner piles.

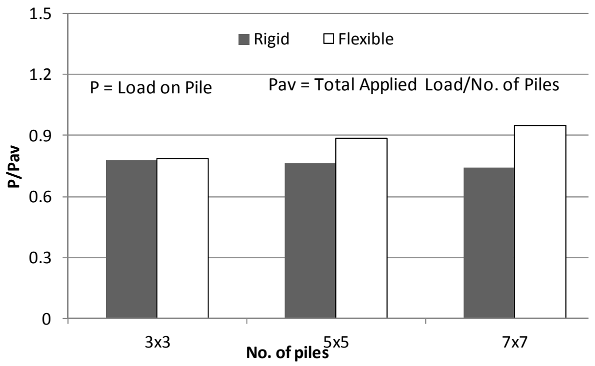

Figure 2. Axial load distribution in centre pile

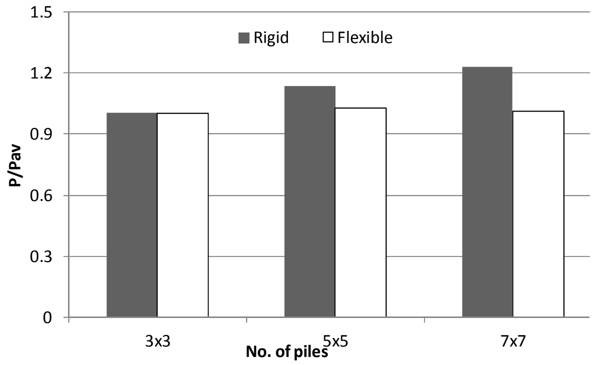

Figure 3. Axial load distribution in corner pile

For a 3x3 pile group with a rigid raft, the axial loads in the centre and corner piles are similar to those with a flexible raft. However, as the size of the pile group increases, the centre piles with the flexible raft tend to carry higher loads than the case with the rigid raft while the corner piles with a flexible raft are carrying lower loads than the case with a rigid raft.

As shown in the Figures 2 and 3, the axial loads in the pile group with a flexible raft are relatively uniformly distributed, however, with a rigid raft, the corner piles are carrying loads higher than the centre piles. As the size of pile group with a rigid raft increases, the difference between the loads carried by the centre and corner piles increases.

Based on the three cases considered, for a small pile group, the assumption of a rigid raft will generally be adequate for assessing the axial loads in the pile. However, as the size of pile group increases, a flexible raft assumption will be more suitable for the pile axial load assessment.

In most cases involving tall buildings, the loading will not be uniformly distributed, but will involve concentrated column loads. In such cases, proper modelling of the raft flexibility may be even more important than with a uniformly distributed loading.

2.1.2 Effect of raft thickness

The effect of raft thickness on the axial load distribution is illustrated by considering raft thicknesses of 0.5m, 1m and 3m for Case 2 – a 5x5 pile group with a centre-to-centre spacing of 3 times the pile diameter, as shown in Table 2. Figure 4 presents the variation of normalised axial load (P/Pav) with different thicknesses of cap/raft.

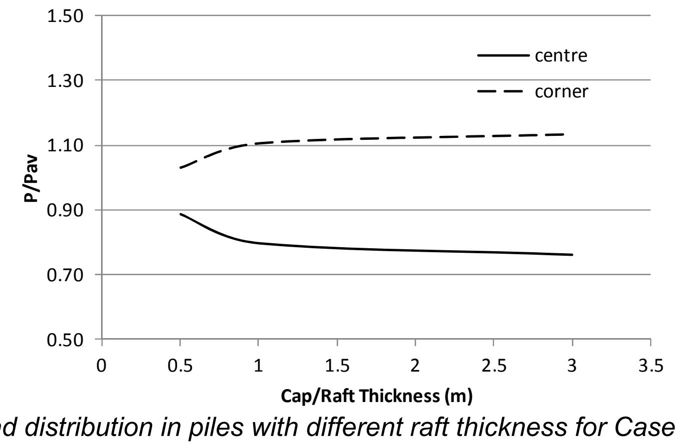

Figure 4. Axial load distribution in piles with different raft thickness for Case 2 – 5x5 pile group

For a 5x5 pile group, the following points are observed from Figure 4:

- For corner piles, as the raft thickness increases from 0.5m to 1m, the P/Pav ratios tend to increase and reach a relatively constant ratio with further increase in the thickness.
- For centre piles, the P/Pav ratio decreases with increasing raft thickness from 0.5m to 1.0m and reaches a relatively constant ratio on further increase in the raft thickness.
- For raft thicknesses of less than 1m, flexible raft behaviour is observed in which axial loads acting on the piles are fairly uniform.

This example illustrates that the flexibility of the raft decreases as the raft thickness increases. Considering the ratio of raft thickness to pile spacing (t/s) of 0.28 and 0.56 with a raft thickness of 0.5m and 1m, the raft can be assumed to be flexible in the design. However, as the t/s ratios increase, rigid raft behaviour can be assumed.

2.2 Pile groups subjected to uniform horizontal loads

For a uniformly horizontal loaded pile group, the computer program ARPILS (Analysis of Raft with Piles in Layered Soil) has been used for the analysis. APRILS employs a finite element approach to model the raft and piles and a finite layered approach to model the soil (Chow, 2007).

The three cases summarised in Table 2 with rigid and flexible rafts have again been analysed. A uniform horizontal load of 10% of vertical load is applied to the foundations. Figures 5 and 6 present comparisons of normalised pile head bending moment versus number of piles in the foundation, for the centre and corner piles of systems with both flexible and rigid rafts. It can be seen that the bending moment in the piles decreases with increasing sizes of pile group. The bending moment in the corner piles are higher than the centre piles.

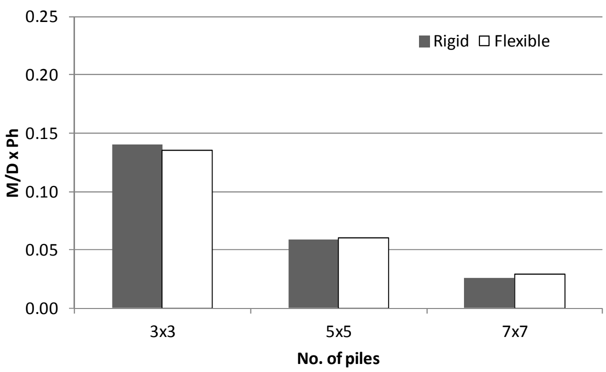

Figure 5.Bending moment distribution in centre pile

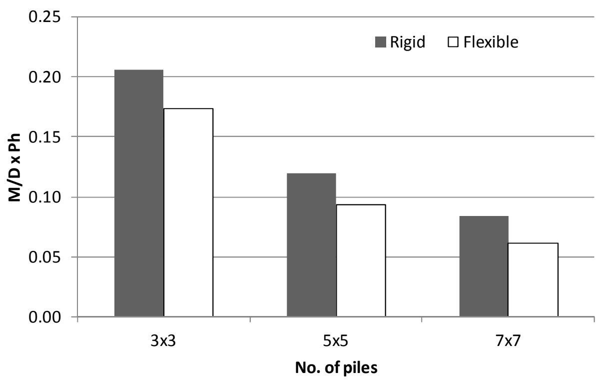

Figure 6. Bending moment distribution in corner pile

As shown in Figure 5, the bending moment in the centre pile for a 3x3 pile group with a rigid raft is slightly higher than that of with a flexible raft. As the pile group size increases, the centre pile with a flexible raft tends to carry a slightly higher bending moment. Figure 6 shows that the bending moments in the corner piles with a rigid raft are higher than those in the case with a flexible raft.

In summary, there is no significant difference in bending moments in the centre piles for pile groups with rigid and flexible rafts. However, the modelling of a rigid raft tends to give higher bending moments in the corner piles. Therefore, for foundations subjected to horizontal loads and moments, the assumption of a flexible raft is more appropriate for the bending moment assessment.

In most cases involving tall buildings, horizontal loads and moments due to wind and earthquake loads are often applied at locations of cores and shear walls, and therefore, modelling of raft flexibility is important in the assessment of foundation performance.

3 APPLICATION TO A TALL TOWER FOUNDATION – INCHEON TOWER, SOUTH KOREA

The Incheon 151 Tower is a super high rise twin tower, where each tower consists of 151 storeys with a height of 601m located in reclaimed land constructed on soft marine clay in Songdo, Korea. The foundation system considered comprises 172 x 2.5m diameter bored piles, socketed into the soft rock layer and connected to a 5.5m thick raft. This building is illustrated in Figure 7 and is described in detail by Badelow et al. (2009); thus, only a brief summary is presented here.

3.1 Ground conditions and geotechnical model

The Incheon area has extensive sand/mud flats and near shore intertidal areas. The site lies entirely within an area of reclamation, which comprises 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 50 metres 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 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.

Figure 7. Incheon 151 Tower (artist's impression)

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 and it was found that there was a potential variation in level of the top of the soft rock (the pile founding stratum) of up to 40m across the foundation.

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 UMD under lateral and vertical loading, hence careful consideration was given to the selection of parameters for this stratum. Typical parameters adopted for the foundation design are presented in Table 3. The parameters for the weathered/soft rock layer were estimated on the basis of the pile test results in the adjacent site and the ground investigation data such as pressuremeter tests and rock core strength tests.

Table 3: Summary of adopted geotechnical parameters

Material	Vertical Modulus, Ev (MPa)	Young's Modulus, Eh (MPa)	Ultimate Skin friction, fs (kPa)	UltimateEnd bearing, fb (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

3.2 Foundation layout and load components

The foundation comprises a 5.5 m thick concrete mat and piles supporting columns and core walls. The number and layout of piles and the pile size were obtained from a series of trial analyses through collaboration between the geotechnical engineer and the structural designer. The pile depth was determined by considering the performance and capacity of piles of various diameters and length. The pile depths required to control settlement of the tower foundation were greater than those required to provide the geotechnical capacity required.

The final design employed 172 piles of 2.5m diameter, with lengths below the base of the raft varying from about 36m to 66 m, depending on the depth to the desired founding level. The base of the raft was about 14.6m below ground surface level. The pile layout was selected from the various options considered, and is presented in Figure 8. Load components applied to the foundation are shown in Table 4. Various combinations of these loads were applied to the structure in design.

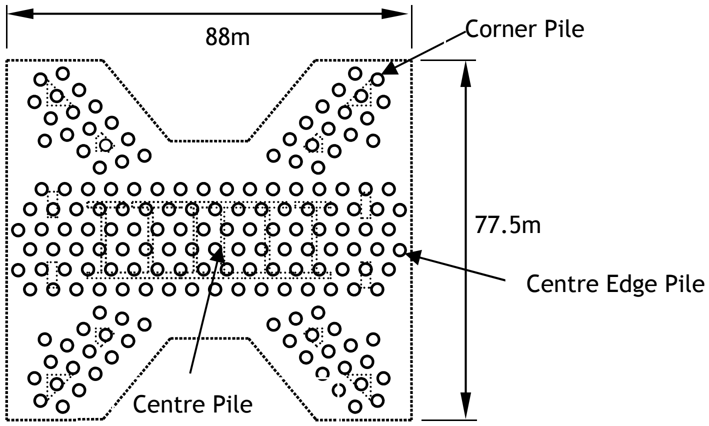

Figure 8. Foundation layout

Table 4: Load components for Incheon Tower

Load Component	Value
Dead Load	6036MN
Live Load	651MN
Horizontal load x-direction	149MN
Horizontal load z-direction	115MN
Earthquake load x-direction	110MN
Earthquake load z-direction	110MN
Moment in x-direction	21,600MN-m
Moment in z-direction	12,710MN-m

3.3 Assessed Foundation Performance

The foundation performance was assessed taking the flexibility of the raft into account. The serviceability load case (i.e dead and live loads) was considered and the loads were applied at column and core locations.

Table 5 presents a summary of foundation settlement, axial loads and stiffness on the corner, centre edge and centre piles of the foundation (see Figure 8). The maximum predicted settlement occurs within the heavily loaded core area, while the computed pile stiffness values are greatest for the outer piles. As the analysis considered non-linear pile behaviour, therefore the higher stiffness (and hence larger loads) for the outer piles degrade more rapidly under loading than the central piles.

Considering a rigid raft for the foundation, the total and differential settlement was predicted to be smaller, with higher pile head loads for corner and centre edge piles, thus resulting in higher vertical pile stiffness values, especially on the outer piles when compared with those for a flexible raft.

For a flexible raft for the foundation, the pile load distribution is fairly uniform, with slightly higher pile loads being predicted at the centre of the foundation where the heavily loaded core is located. The loads on piles for a rigid raft case are approximately two times the loads for a flexible raft, except for the centre piles.

As the thickness of the raft (t) is 5.5m and the average centre-to–centre pile spacing (s) is approximately 5m, the ratio of t/s is greater than one, and the raft would be expected to behave as a semi-flexible raft (i.e. behaviour in-between a flexible and rigid raft) with the loads on the outer piles then being significantly less than those for a perfectly rigid raft.

Based on the assessment, we conclude that it is important to model the flexibility of the raft to avoid having to design for unrealistically large loads in the outer piles within the group.

Table 5: Summary of foundation performance

		Rigid Raft	Flexible Raft
Pile Load (MN)	Centre Pile	24	49
	Centre Edge Pile	65	33
	Corner Pile	85	43
Pile Stiffness (MN/m)	Centre Pile	511	726
	Centre Edge Pile	1418	932
	Corner Pile	1604	1292
Raft Settlement (mm)	Maximum	52	67
	Minimum	26	28

4 CONCLUSIONS

This paper investigates the importance of modelling the flexibility of a raft in the foundation design. An illustrative example with pile groups of different sizes, connecting to either a rigid or flexible raft embedded in a hypothetical soil profile, is presented. The following conclusions can be drawn from the analysis of the cases considered:

- Uniformly axial loaded foundation:
  - For small pile groups, the computed axial loads on piles with a rigid raft are similar to those with a flexible raft, and so the assumption of a rigid raft will be adequate.
  - For large pile groups, the axial loads on piles with a flexible raft are relatively uniformly distributed; however, with a rigid raft, the corner piles carry loads significantly higher than the centre piles.
  - An assumption of a flexible raft for large pile groups will be more appropriate in the axial pile load assessment.
  - With increasing ratio of raft thickness to pile spacing, the flexibility of the raft decreases and it tends to behave as a rigid raft.
- Uniformly horizontal loaded foundation:
  - For centre piles, there is no significant difference in pile head bending moments for pile groups with rigid and flexible rafts.
  - For corner piles, the bending moments in piles with a rigid raft are higher than for the case with a flexible raft.

Therefore, modelling of the raft flexibility is likely to be of importance in the assessment of foundation performance for large pile groups or piled rafts.

A case study of a supertall tower – the Incheon 151 Tower, is also presented. This case demonstrates the importance of modelling raft flexibility in the assessment of foundation performance. Based on the analysis with a “flexible” raft, (considering the actual raft thickness of 5.5m), the pile load distribution is fairly uniform. The foundation settlement is a maximum under the heavily loaded core and maximum pile stiffness is observed at the outer piles in which relatively high axial loads with small settlements are predicted for those piles. Despite the significant thickness of the raft, the raft behaviour is still semi-flexible, and the axial loads on the outer piles are significantly less than those computed on the basis of a perfectly rigid raft. As a consequence, the reinforcement requirements for structural design are less when the flexibility of the raft is taken into account.

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