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Contribution of superstructure stiffness to building foundation design

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ABSTRACT: For many buildings, the geotechnical design of the foundation and the structural design of the superstructure are undertaken separately, without proper consideration of the interaction between the foundation and the superstructure. Previous research has shown that the stiffness of the superstructure (especially the main core) can have a significant beneficial contribution to the performance of the foundation. Much of the previous research has employed extensive three-dimensional numerical approaches to undertake the analysis in which foundation components and the superstructure are modelled simultaneously.This paper explores the effects of the stiffness of the building superstructure on the overall foundation behavior. A simplified approach is presented to approximate the foundation performance considering the effect of the superstructure core, and the interaction between the various foundation and superstructure components, including the main core and the floor slabs. This simplified approach can be used for preliminary design of the foundation and for the assessment of the overall performance of the foundation system, without the need for undertaking a full 3D numerical analysis. The results of the proposed simplified approach are presented, and some practical design implications are drawn from these results.

RÉSUMÉ : Pour de nombreux bâtiments, la conception géotechnique de la fondation et la conception structurelle de la superstructure sont souvent entreprises séparément, sans tenir dûment compte de l'interaction entre la fondation et la superstructure. Des recherches antérieures ont montré que la rigidité de la superstructure (en particulier le noyau principal) peut avoir une contribution bénéfique significative à la performance de la fondation. Une grande partie de la recherche précédente a utilisé des approches numériques tridimensionnelles approfondies pour entreprendre l'analyse dans laquelle les composants de fondation et les superstructures sont modélisés simultanément. Cet article explore les effets de la rigidité de la superstructure du bâtiment sur le comportement global de la fondation. Une approche simplifiée est présentée pour estimer la performance de la fondation en tenant compte de l'effet du noyau de la superstructure et de l'interaction entre les divers composants de la fondation et de la superstructure, y compris le noyau principal et les dalles de plancher. Cette approche simplifiée peut être utilisée pour la conception préliminaire de la fondation et pour l'évaluation de la performance globale du système de fondation, sans qu'il soit nécessaire d'entreprendre une analyse numérique 3D complète. Les résultats de l'approche simplifiée proposée sont présentés, avec des implications de conception pratiques tirées de ces résultats.

KEYWORDS: foundation system, superstructure stiffness, interaction, overall performance, simplified approach

1 INTRODUCTION

In the design of the foundation system for a building structure, it is ideal to consider the interaction effects of the soil, foundation and building superstructure (main core, basement walls and floor slabs). For an effective foundation design, collaboration between the structural and geotechnical engineers is essential. The behavior of both the superstructure and the foundation system should be captured in the structural design based on the foundation response provided by the geotechnical engineer (Poulos, 2017).

In many foundation designs, the geotechnical design and the structural design are carried out separately. The geotechnical engineers carry out the foundation design considering the soil profile and the foundation configuration in the geotechnical design and then provide the corresponding subgrade reaction moduli for the raft and the spring stiffness of the piles to the structural engineers for them to carry out the structural design of the foundation. This conventional approach takes into account the various interactions between the soil and foundation elements and the foundation system and superstructure. The stiffening effect of the superstructure is considered to some extent, but, the actual contribution of the stiffness of the superstructure to the foundation performance generally requires iterative analyses to be undertaken.

Three-dimensional (3D) numerical modelling is often used for the foundation design as each of the components (i.e. soil layers, foundation system and the superstructure) can be modelled simultaneously. Chow and Poulos (2019) explored the effects of basement resistance on the foundation behavior and simplified expressions were presented to approximate the effects without the need to undertake 3D numerical analysis. However, the effect of the superstructure stiffness (main core) was yet to be explored.

The prime objective of this paper is to explore the stiffening effects of the main core of the superstructure on the overall performance of the foundation, using a simplified approach. A numerical example, employing a three-dimensional (3D) finite element program PLAXIS 3D, is presented to illustrate the effects of the main core on the foundation performance, and to evaluate the applicability of the simplified approach.

2 NUMERICAL EXAMPLE

The example considered is a 20 storey building approximately 60 m in height. The building is supported by a square raft of 32 m x 32 m in plan with an 8 x 8 pile group having a centre-to-centre spacing of 4 m, embedded in a deep uniform stiff clay profile. The piles have a diameter of 1 m and a length of 24 m. A square main core is located at the central region of the raft with a wall thickness 0.3 m and length of 16 m, as shown in plan in Figure 1. The stiff clay layer is assumed to have an undrained shear strength (s_u) of 80 kPa. Based on the α-method, the ultimate shaft friction is estimated as $f_s = \alpha\ s_u$, and is estimated to be 56 ka. The ultimate end bearing capacity (f_b) is taken to be 720 kPa ($\approx 9\ s_u$). The parameters adopted for the analysis are summarized in Table 1.

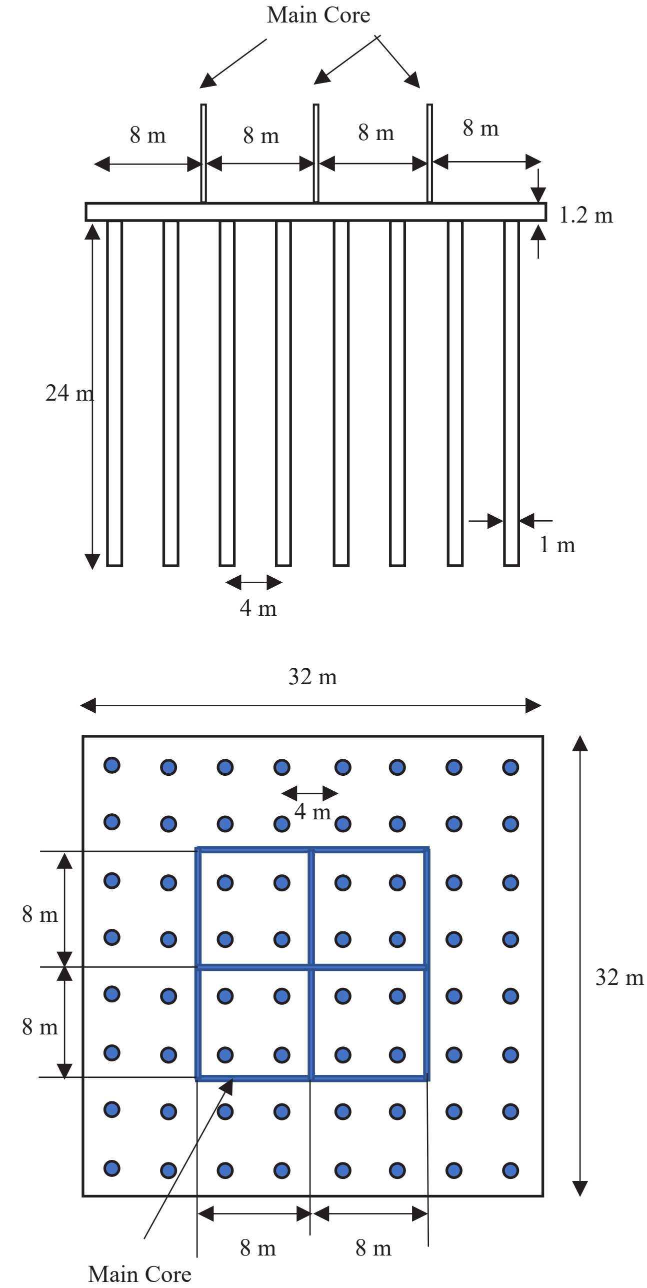

Figure 1. Arrangement of Foundation System and Main Core

Table 1. Parameters for example considered

Parameter	*Value*
Young's Modulus of Clay, E (MPa)	50
Undrained Shear Strength of Clay, s_u (kPa)	80
Ultimate Skin Friction, f_s (kPa)	56
Ultimate End Bearing, f_b (kPa)	720
Young's Modulus of Pile (Short Term), E_p (MPa)	30,000
Young's Modulus of Raft (Short Term), E_r (MPa)	30,000
Thickness of Raft (m)	1.2
Thickness of Core Wall (m)	0.3
Young's Modulus of Core Wall, E_c (MPa)	30,000

3 ANALYSIS METHODOLOGY

In the Plaxis 3D analysis, the soil is modelled as a homogeneous Mohr-Coulomb continuum. The piles are modelled by embedded beam elements with interface elements, and the raft is modelled by 6-noded triangular plate elements. The core walls and floor slabs, which form the main core of the superstructure, will be acting as a rectangular block on the foundation system which is similar to the approach adopted by Buttling and Zhong (2017). To incorporate the stiffness of the main core in the analysis, an equivalent solid square block of side equal to the length of the core walls is modelled such that the stiffness of the block is the same as the stiffness of the main core Thus,

$$E_{eq} A_{eq} = E_{core} A_{core} \quad (1)$$

where E_{eq} = Modulus of the equivalent solid block
A_{eq} = Area of the equivalent solid block (8 x 8 = 64 m^2)
E_{core} = Modulus of the main core
A_{core} = Area of the core walls within the main core (6 x 8 x 0.3 = 14.4 m^2)

Figures 2 and 3 show the piled raft foundation with the simplified main core, and the full 3D finite element mesh for the soil mass, respectively. The analysis considered a uniform vertical loading of 200 kPa acting on the foundation system. The analysis considered the main core having an equivalent height varying from 0 m (main core not modelled) to 10 m.

4 EFFECTS OF MAIN CORE ON FOUNDATION PERFORMANCE

4.1 *Total and differential settlement*

Figure 4 presents the computed maximum settlement at the centre of the foundation, as a function of the height of the equivalent core. Figure 5 presents the computed differential settlement between (i) the centre and corner and (ii) between the centre and edge of the raft. The maximum settlement and differential settlement decrease as the height of the main core increases. The rate of decrease in the both the total and differential settlement diminishes as the height of main core modelled exceeds 5 m (approximately 10 % of the total height of 60 m and 33% of the core wall length) and remains constant with further increase in the height modelled.

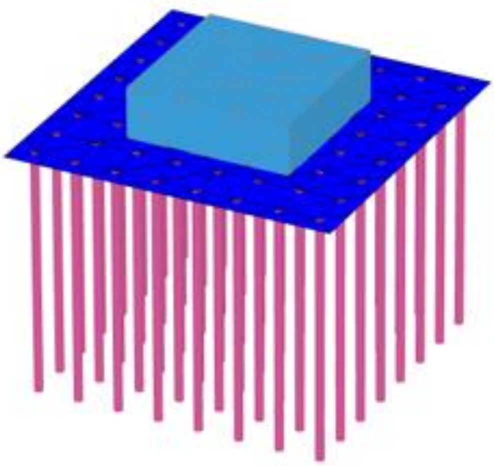

Figure 2. Piled Raft Foundation with Main Core

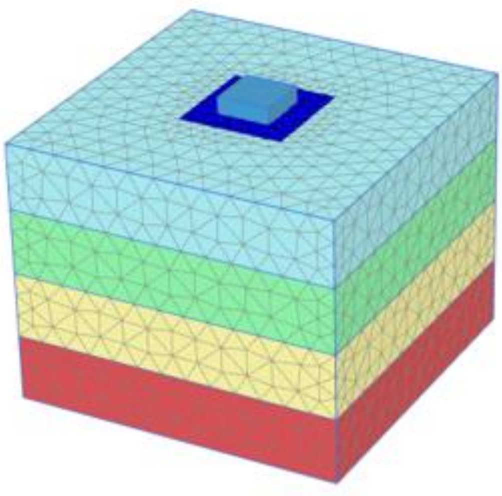

Figure 3. 3D Finite Element Mesh for Analysis

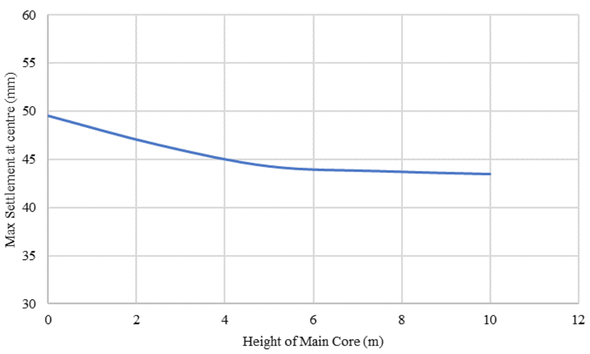

Figure 4. Maximum Settlement at centre of foundation versus equivalent height of main core

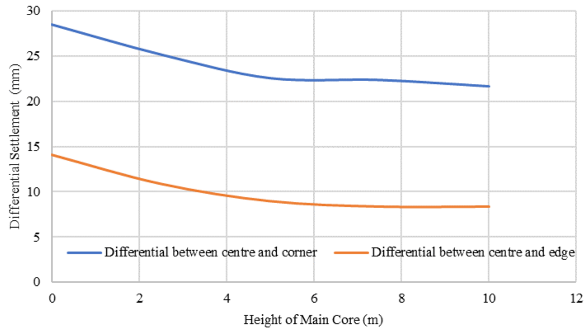

Figure 5. Differential settlement of the foundation

Figure 6 illustrates the percentage reduction in the differential settlement of the foundation as a function of the height of the equivalent core. This figure indicates that the main core of the superstructure has a significant stiffening effect on the foundation system. The differential settlement between the centre and edge of the raft, and between the centre and corner can be reduced by up to 40 % and over 20%, respectively, when the superstructure is incorporated into the model.

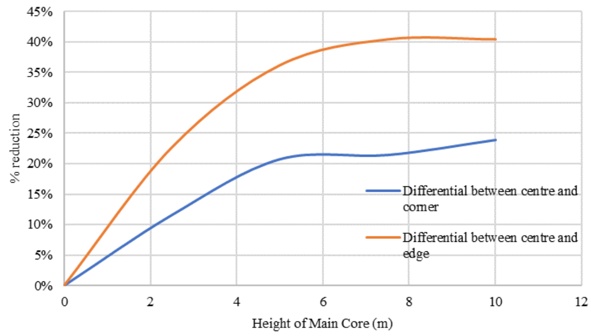

Figure 6. Percentage reduction in differential settlement with equivalent height of main core

The maximum differential settlement of the foundation (i.e. differential settlement between the centre and corner) is estimated using the settlement ratio approach by Mandolini et al (2005) in which the ratio R_{Dmax} of maximum differential settlement to average group settlement is expressed as

$$R_{Dmax} = 0.35\ R^{0.35} \quad (3)$$

in which

R = aspect ratio = $(ns/L)^{0.5}$ (Randolph and Clancy, 1993)
n = number of piles
s = centre-to-centre spacing of piles
L = pile length.

Table 2 summarises the estimation maximum differential settlement from the average settlement computed from Plaxis 3D based on the above settlement ratio approach.

Table 2. Estimation of maximum differential settlement using Mandolini et al settlement ratio approach

Height of main core modelled (m)	*0*	*2.5*	*5.0*	*7.5*	*10.0*
Average Settlement from Plaxis 3D (mm)	40	38	36.8	36.3	36.2
Differential Settlement between centre and corner (Plaxis 3D) (mm)	28	25	22.6	22.4	21.7
Maximum Differential Settlement - Mandolini et al (2005) - (mm)	21	20.2	19.5	19.3	19.2

The estimated maximum differential settlements from the settlement ratio approach are somewhat smaller than those computed from the Plaxis 3D analysis. Based on these results, there is a possibility that the settlement ratio approach may underestimate the maximum differential settlement of the raft by approximately 25% (maximum) as the approach estimates the settlement based on the load test for a single pile and does not take into account the presence of the raft-pile interaction.

4.2 *Pile load distribution*

Figure 7 presents the computed axial load distributions for piles at the centre, edge and corner of the raft and the percentage reduction in load carried by the centre piles. The loads on the centre piles decrease as the equivalent height of main core increases. However, there is only a small difference in the loads at the edge and corner piles for various heights of main core modelled. Similar to the settlement profile, the load on the centre piles approaches a constant value when the height of the main core modelled exceeds about 5 m, i.e. less than 10% of the building height or 33% of the core wall length. This figure also indicates the load carried by the centre piles could be reduced by a maximum of 40% when the stiffening effect of the main core is considered.

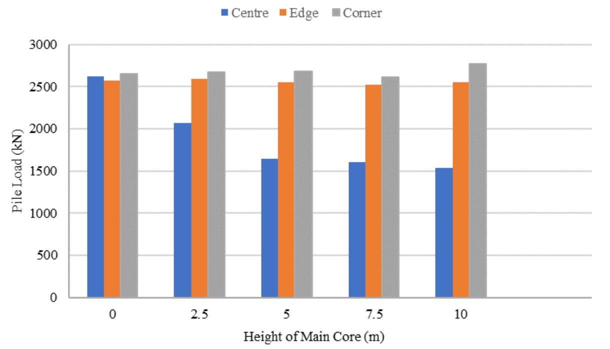

Figure 7. Axial pile load distribution underneath raft for various height of main core modelled.

4.3 *Vertical stiffness of foundation system*

In the estimation of foundation stiffness, the contribution of each component of the foundation system has to be considered. The overall vertical stiffness of the system can be taken as a combination of the stiffness of the piled raft and the superstructure, expressed as:

$$Kv = Kpr + Kst \quad (2)$$

where Kv = overall vertical stiffness of the system
Kpr = vertical stiffness of piled raft
Kst = vertical stiffness of superstructure

For preliminary analyses, the vertical stiffness of the piled raft, Kpr can be estimated in an approximate but simple manner from the "PDR" approach described by Poulos (2001). The average vertical stiffness of the superstructure can be estimated based on the vertical shear stiffness provided by the components of the main core. Table 2 summarizes the overall stiffness of the foundation system, considering various heights of the main core modelled. Figure 8 illustrates the percentage increase in vertical stiffness for different percentages of the main core height in the model. It indicates that the superstructure provides an approximate 10% increase in the vertical stiffness of the foundation system when the height modelled is about 10% of the total height of the superstructure. As with the settlement performance of the foundation, there is no further increase in the overall stiffness if a larger percentage of the total superstructure height is modelled.

Table 3. Overall vertical stiffness of foundation system

Height of main core modelled (m)	*0*	*2.5*	*5.0*	*7.5*	*10.0*
% of Total superstructure height = 60 m	*0%*	*4%*	*8%*	*13%*	*17%*
Vertical Stiffness (MN/m)	5120	5375	5570	5637	5647

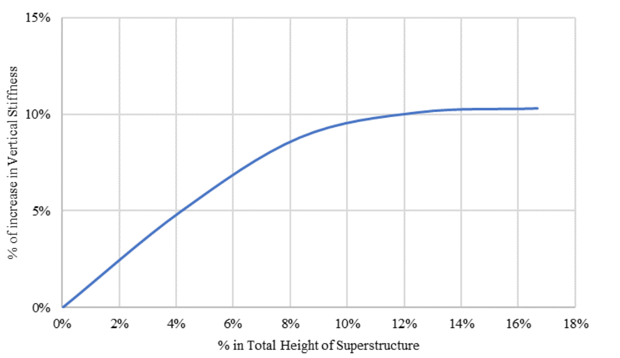

Figure 7. Variation of vertical stiffness with percentage of total height of superstructure modelled

The analysis results imply that the main core located within the central region of the raft provides additional bending stiffness to the foundation system, resulting in a reduction of differential settlement between the centre and the corners and edges, and also leads to a reduction in the loads carried by the centre piles. Such stiffening effects contribute to some percentage increase (up to approximately 10%) in the overall stiffness of the foundation system.

5 CONCLUSIONS

This paper describes a 3D finite element analysis of a piled raft foundation, taking into account the stiffening effects of the superstructure in a simplified manner. The core of the superstructure is modeled as an equivalent block, with a stiffness equal to that of the structural core.

Based on the analyses discussed above, the conclusions and practical implications are as follows:

1. The total and differential settlements of the foundation decrease as the modelled height of the superstructure (main core) increases.
2. The reduction in differential settlement between the centre and the edge is almost the same, resulting in the percentage reduction being higher between the centre and the edge.
3. The loads carried by the piles within the centre region of the raft, where the main core is modelled by an equivalent block, decrease as the modelled height of the main core increases.
4. The main core has little influence on loads carried by the piles around the edges and corners of the foundation.
5. The vertical stiffness of the foundation increases by approximately 10% when the main core is incorporated into the analysis.
6. In the example considered herein, the stiffening effects of the superstructure reach a maximum when the modelled equivalent height of the main core is about 10 % of the total height of the superstructure, or 33% of the core wall length, implying that any further increase in the modelled height of the main core in the analysis would have negligible additional contribution to the stiffness of the foundation.
7. The additional stiffness provided by the superstructure can contribute to a reduction of total and differential settlement, with a reduction in the loads carried by the interior piles within the system and a reduction in bending in the raft.
8. The use of settlement ratio approach may underestimate the differential settlement of the foundation as the estimate may be based on the results of load tests on a single pile and interaction of the raft and pile is not considered. However, it is still useful for preliminary design of foundation as it can provide an indication of the range of differential settlement of the foundation.

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