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Simplified Analysis of Three Dimensional Mega Foundations for High-Rise Buildings

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Abstract

In this study, an approximate computer-based method was developed to analyze the behavior of raft and piled raft foundations. Special attention is given to the improved analytical method proposed by considering raft flexibility and soil nonlinearity. The overall objective of this study is to focus on the application of a simplified analysis method for predicting the behavior of sub-structures. Through the comparative studies, it is found that the computer programs (YS-MAT and YSPR), developed in this study, is in agreement with the general trends observed by field measurements. Therefore, YS-MAT (Yonsei-Mat) and YSPR (Yonsei Piled Raft) can be effectively used for the preliminary design of a raft or a piled raft foundation for high-rise buildings.

Keywords: Piled raft, Raft, High-rise buildings, Approximate computer-based method

1. Introduction

In recent years, a number of huge construction projects, such as high-rise buildings and long span bridges, are being undertaken. In the design of foundation, firstly, a raft is considered to be the foundation to support a structure. If the raft foundation is not sufficient for a bearing capacity and a settlement criterion, secondly, a fully piled foundation can be applied. In this design concept, although the foundation consists of piles and raft (or pile cap) on the top of the piles which are in contact with the soil, mostly, a contribution of raft is ignored and the total structural load is only transferred through piles. So the piles are usually designed to address a bearing capacity using end-bearing piles and those do not permit the settlement of foundation. This design concept (Capacity Based Design) is conservative and too expensive. With increase in height, the super tall buildings have enormous load of superstructure which is transmitted to the foundation. Therefore, the foundation structures of super tall buildings have also been built more massively to ensure that the buildings are supported with maximum stability. Optimized design strategy is a major importance for an economic construction to be achieved. The piled raft is a composite foundation system consisting of three bearing elements: raft, piles and subsoil. Therefore, the behavior of a piled raft is affected by the 3D interaction between the soil, piles and raft, thus, a simple and convenient analytical method is needed to evaluate these interactions.

In general, for the accurate analysis, a complete three-dimensional analysis of a foundation system can be carried out by a finite element analysis. However, a finite element analysis is more suitable for obtaining benchmark solutions against which to compare simpler analysis methods, or for obtaining solutions of a detailed analysis for the final design of a foundation, rather than as a preliminary routine design tool.

In this study, a numerical method is used to combine the pile stiffness with the stiffness of the raft, in which the flexible raft is modeled as flat shell element and the piles as beam-column element, and the soil is treated as linear and nonlinear springs. Based on the proposed analysis methods, e.g., YS-MAT (Yonsei-MAT) for mat and YSPR (Yonsei Piled Raft) for piled raft are developed respectively. In order to examine the validity of the proposed method, the analysis results are compared with the available solutions from previous researches and field measurement data.

2. Approximate Computer-based Methods for Mega Foundation

2.1. Modeling of flexible raft

Typically, a plate element was used for modeling a raft or a pile cap in several analysis methods (Clancy et al., 1993; Zhang et al., 2000; Kitiyodom et al., 2003). The primary limitation of these methods is that the membrane behavior of the flexible raft cannot be considered because the nodal displacements (in the x- and y-direction) for the membrane action are not included. This limitation can be

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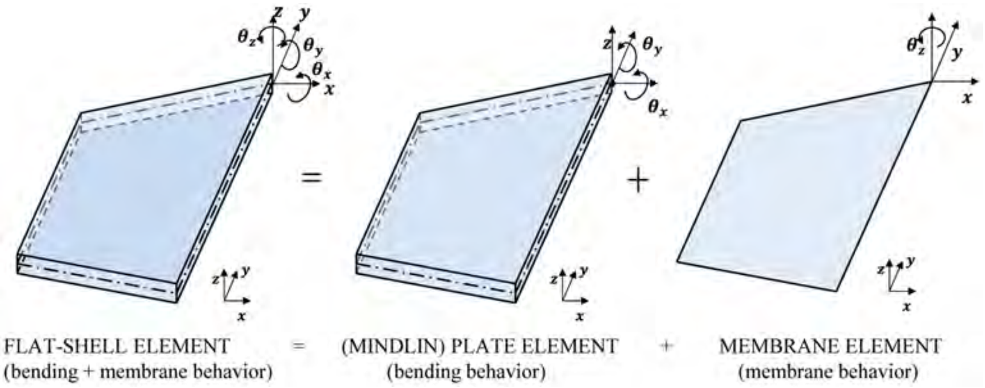
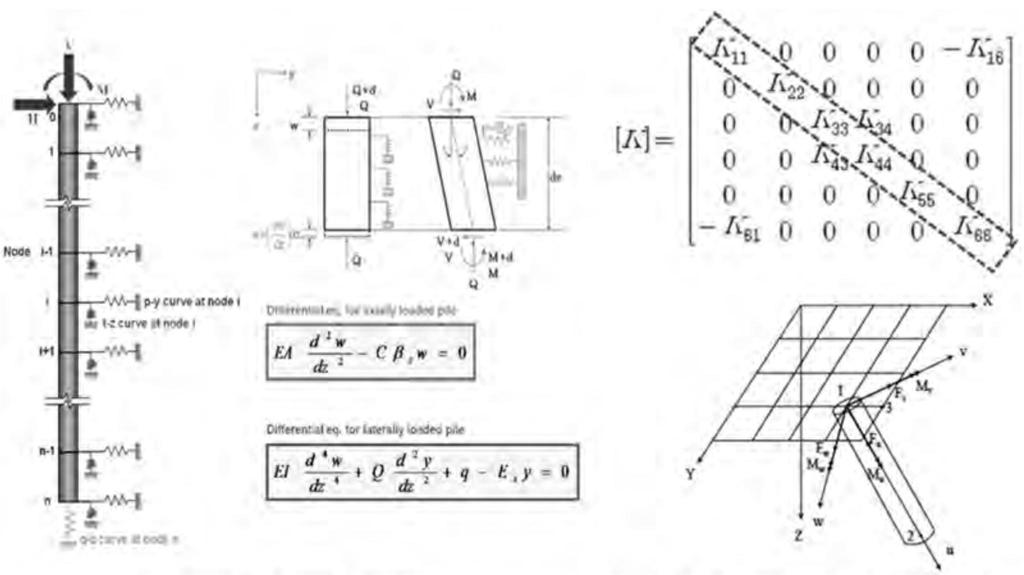


Figure 1. Modeling of flexible raft.

overcome by using a flat shell element. An improved four-node flat shell element (Choi et al., 1996), which combines a Mindlin's plate element and a membrane element with torsional degrees of freedom as shown in Fig. 1, is adopted in this study. The flat-shell element can be subjected to the membrane and bending actions. The displacement due to the membrane action is considered independent of the displacement due to the bending action, therefore it can be considered separately. For the bending action, the displacement field for an individual element can be described in terms of the vertical nodal displacement and the rotations about the x and y axes. For the membrane action, the displacement field can be described in terms of the nodal displacements in the x and y directions. This element having six degrees of freedom per node permits an easy connection with other elements such as beams or folded elements.

2.2. Modeling of piles and stiffness matrix

In the numerical approach, piles are treated as beam-column elements. The behavior of soil surrounding the individual piles is represented by load-transfer curves (t-z, q-z, and p-y curves), and the interaction between piles is represented by p-multiplier and group efficiency factor. The load-deformation relationship of individual pile heads may be derived by a single pile analysis based on beam-column method. In this method, a pile member is described as a series of beam column elements with discrete springs to represent the soil support condition as shown in Fig. 2. The governing differential equations for the axially loaded and laterally loaded pile (Fig. 2(a)) were considered. In the next step, finite difference technique is used to solve the differential equations governing the compatibility between the pile displacement and the load transfer along a pile.



(a) Beam-column elements (b) Stiffness matrix & pile coordinates

Figure 2. Modeling of pile.

The stiffness of piles is incorporated through structure analysis as a form of the pile head stiffness matrix, which is derived by the load-displacement curves obtained from single pile analyses. The pile head stiffness matrix (K_p) is of order 6×6, representing three spring constants, three rotational constraints, and four coupling between spring and rotational constraints (Fig. 2(b)).

2.3. Modeling of soil-structure interaction

The load-bearing behavior of a piled raft is characterized by complex soil-structure interaction between the piles, raft and the subsoil. The present method makes use of pile-soil-pile and raft-soil-pile interaction to simulate the real piled raft-soil response under lateral and vertical loadings. Additionally, for the raft-soil interaction, this study uses a semi-empirical parameters as the modulus of soil reaction below the raft. The use of these parameters as assumed in the derivation procedure, may be a limitation. However, these interactions are incorporated in a calculation procedure that is computationally very efficient.

Piles in such groups interact with one another through the surrounding soil, resulting in the pile-soil-pile interactions. In this study, a set of nonlinear p-y curves which can be modified by reducing all of the p-values on each curve by a p-multiplier are used as input to study the behavior of the laterally loaded piles.

In a group of closely-spaced piles, the axial capacity of group is also dominated by variation in settlement behavior of individual piles due to pile-soil-pile interaction. In this study, load-transfer curves in side resistance (t-z curve) and in end bearing resistance (q-w curve) which can be modified by reducing all of the t- and q-values on each curve by a group efficiency factor are used as input to study the behavior of the vertically loaded piles.

In classical solution, the Winkler model is used for analyzing raft foundation. However, the Winkler model could not predict accurately the displacement of some solids, e.g., soil. The Winkler model ignores the important interaction existing between adjacent points in the soil continuum. In order to overcome a limitation, in this study, Pasternak's shear layer model (1954) was incorporated to involve the soil spring-coupling effects. This system can provide a mechanical interaction between the individual soil spring and pile elements by using the flat-shell element. As shown in Fig. 3, the present method proposes an improved raft-soil-pile system by connecting the top ends of soil springs and pile elements with a flat-shell element including membrane action. As a result, the proposed numerical method can be represented the coupled soil-structure interactions, and thus it shows a more realistic behavior of the soil reaction.

2.4. Method of analysis

As a final outcome, a numerical method was developed to analyze the response of a raft and a piled raft considering pile-soil-pile and raft-soil interactions. In the present method, the raft was simulated with four-node flat shell elements, the piles with beam-column elements, and the soil with nonlinear load transfer curves. A nonlinear analysis algorithm was proposed using a mixed incremental and iterative technique in this study. The stiffness matrix of piles, soil and that of a flat shell element are combined and a coupled analysis method of a raft and a piled raft is developed including a nonlinear analysis algorithm. Fig. 4 shows the flow chart of the present method (YS-MAT and YSPR).

3. Comparison with Field Case Histories

3.1. Piled raft foundation

The load sharing behavior of large piled raft installed in stiff clay was compared with the predicted values of the

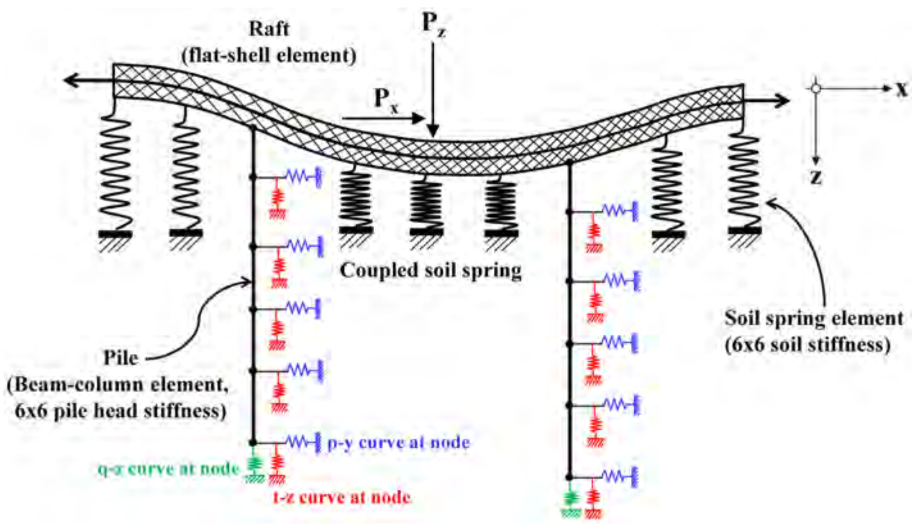


Figure 3. Interactions between raft, piles, and subsoil in present method.

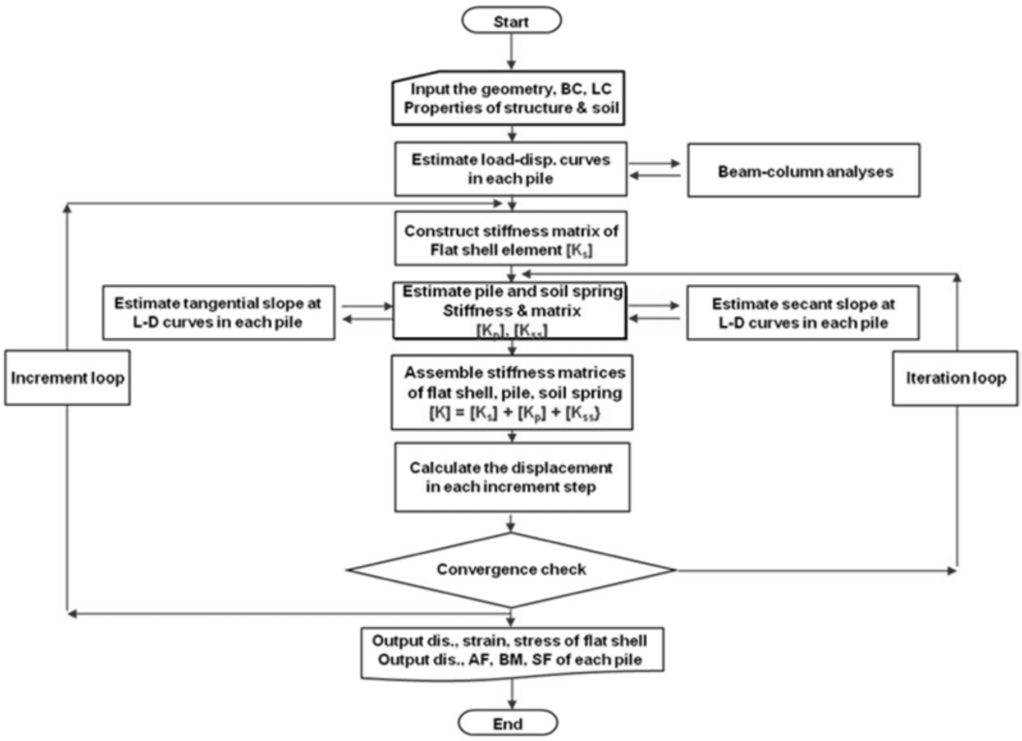
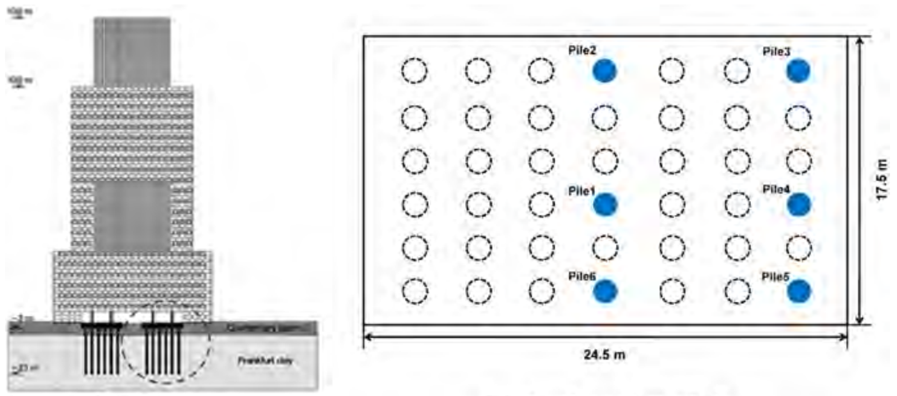


Figure 4. Flowchart of the present method.

proposed and the FE analyses. Constructed between 1983 and 1986, the 130 m high Torhaus was the first building in Germany with a foundation designed as a piled raft. A total number of 84 bored piles with a length of 20 m and diameter of 0.9 m are located under two 17.5×24.5 m large raft. The bottom of the 2.5 m thick raft lies just 3 m below ground level (Fig. 5(a)). The subsoil comprises quaternary sand and gravel up to 2.5 m below the bottom of the rafts, followed by the Frankfurt clay (Reul et al., 2003). And a schematic diagram of 7×6 piled raft structure is shown in Fig. 5(b). Fig. 6 shows the one quarter of the 3D FE mesh used in this analysis. At the left- and right-hand vertical boundaries, lateral displacements were restrained, whereas fixed supports were applied to the bottom boundaries (Fig. 6(b)). The specified initial stress distributions should match with a calculation based on the self-weight of the material. After the initial step, the applied loading was simulated by a vertical load at the raft. Modeling the construction process is so complicated that the effect of construction is omitted in the analysis. The structure was modeled as an isotropic elastic material, and constant values for each material parameter were used for the soil layer for simple analyses.

The material behavior of subsoil was modeled with a



(a) Profile view (b) Configuration of pile

Figure 5. Torhaus Der Messe.

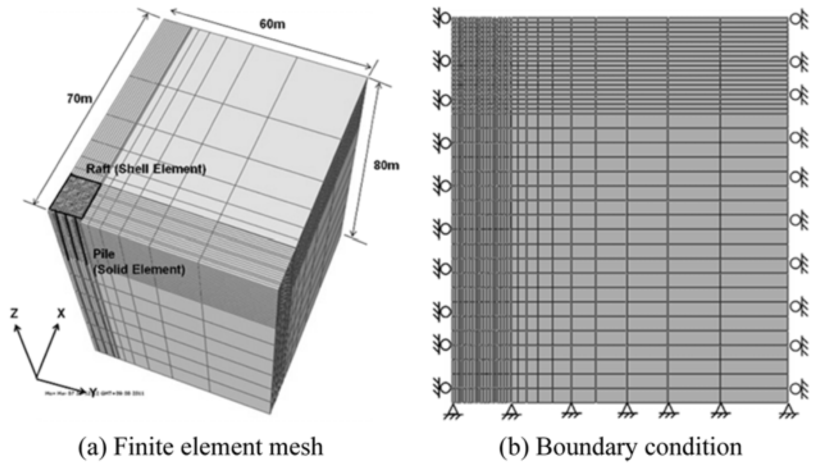


Figure 6. Finite element mesh and boundary condition.

Table 1. Material parameters used for this study

Case	Material Properties							
	Type		E (MPa)	ν	γ (kN/m^3)	ϕ (deg.)	c (kPa)	Model*
Germany case	Pile	Concrete	23,500	0.2	25	-	-	L.E.
	Raft	Concrete	34,000	0.2	25	-	-	L.E.
	Soil	Sand	75	0.25	18	32.5	0	M.C.
		Frankfurt clay	47*	0.15	19	20	20	M.C.

*Note: M.C. is Mohr Coulomb elasto-plastic model, L.E. is linear elastic model used in PLAXIS 3D Foundation.
Frankfurt clay: $E = 45 + [\tanh((z-30)/15) + 1] \times 0.7z$

Mohr-Coulomb model. In order to simplify the analysis process, constant (average) values of material parameters were adopted for the soil layer. The raft and piles were modeled with a linear elastic model. Material properties used in this FE simulation are summarized in Table 1. All loads from the super-structure were assumed to be equally transferred to the raft. The maximum load of P=200MN for each raft (Sommer, 1991) minus the weight of the raft is successively applied by means of a uniform load over the whole raft area.

Figs. 7(a) and 7(b) show a comparison of the measured and calculated pile loads. The prediction of the present method is much more conservative than that of 3D FE analyses and the measured one. However, the proposed

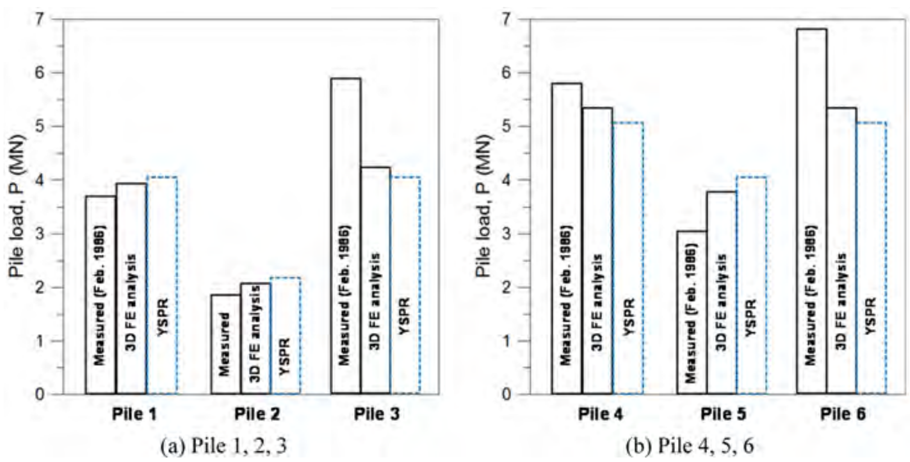


Figure 7. Pile load.

method YSPR is in good agreement with general trend of FE analysis and the measurement data for the same load level. The computed results for the center, side, and corner piles show that the load distribution of the individual piles in a group is highly influenced by the flexibility of the raft. This finding was similar to what Won et al. (2006) discussed about correlation between the pile member force and the flexibility of pile cap for a pile groups.

The time taken for the computer to run this case saves 115 min of computer time, and is about 24 times faster than the 3D FE analysis. For large problems this computational saving can be very significant.

3.2. Raft foundation

A preliminary design case of raft foundation at a high-rise building construction site in Korea was representatively selected for the design application. The tower consists of 123 storeys with height of about 491 m over a footprint of approximately 70×70 m. The construction site is mainly comprised of normally banded gneiss, brecciated gneiss, shear zone, and fault core zones. A schematic diagram of a raft foundation is shown in Fig. 8. A large raft size 71.7×71.7 m with a thickness of 6.0 m is resting on banded gneiss. The raft, with Young's modulus of 30.5 GPa, are subjected to a vertical load (P_{total}=6,701 MN). Each soil spring stiffness for different location on the r foundation was used, according to the preliminary design report.

Fig. 9 shows the raft settlement distribution predicted by GSRaft (Arup in-house program) and YS-MAT at different section. The rock conditions at the site are highly variable, and the presence of faults, shear zones or highly foliated soft to hard rock would have a significant influence to the differential settlement of the raft. As shown in these results, the agreement between the GSRaft and YS-MAT settlement predictions is generally good. Although there are no measured profiles of the raft settlement, the proposed analysis method showed reasonably good fit with

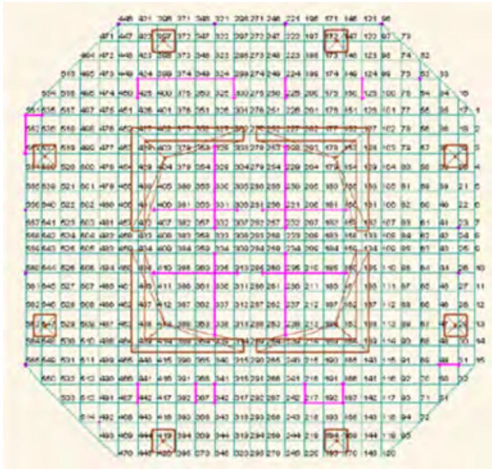


Figure 8. Preliminary design case of large raft.

the well-known in-house program. Therefore, it is concluded that proposed method YS-MAT can be used in the design of large raft foundations.

4. Conclusions

An analytical methods have been developed for the analysis of the raft and piled raft foundations. The conceptual methodology of the proposed method are completely different from that of general method. Through comparisons with case histories, the proposed method was found to be in good agreement with measurement data. The following conclusions are noted:

1. Approximate computer-based analytical methods have been developed for analysis of raft and piled raft. By taking into account the raft flexibility and soil nonlinearity, Program YS-MAT and YSPR are capable of predicting reasonably well the settlement and load sharing behavior of mega foundations for high-rise buildings. This analytical

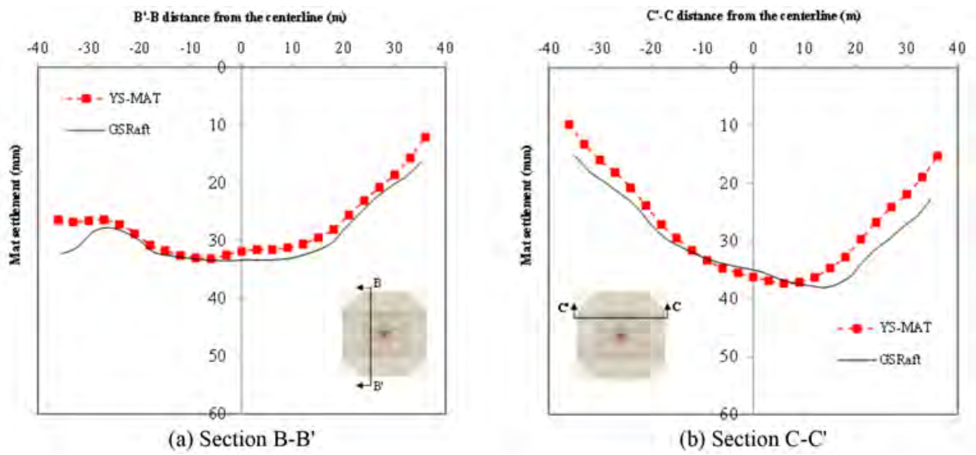


Figure 9. Raft settlement profile.

method is intermediate in theoretical accuracy between general three-dimensional FE analysis and the linear elastic numerical method.

2. From the example case histories, the proposed method is shown to be capable of predicting the behavior of a large raft and piled raft. Nonlinear load-transfer curve and flat-shell element can overcome the limitations of existing numerical methods by considering the realistic nonlinear behavior of soil and membrane action of flexible raft.

3. Additionally, the comparative studies showed that the present method is useful for computational saving and improving performance in engineering practice.

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