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Assessments of dimensionless pile stiffness for embedded piled raft foundations in soft clays under vertical loads

D.W. Chang & J.H. Lin
Tamkang University, New Taipei City, Taiwan

Y.K. Lin, F.C. Lu & C.J. Kuo
Ground Master Construction Co., Ltd., Taipei, Taiwan

A.Zh. Zhussupbekov
L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

ABSTRACT: Three-dimensional finite element analysis has been widely used in foundation design. For the efficiency of computations, simplified analysis treating the soils by series of springs were suggested in many design practice. For piled raft foundation, the coefficients of subgrade reactions and the pile stiffness are thus important to the design analysis. This paper intends to discuss the values of coefficients of pile reactions and/or pile stiffness for the embedded piled raft foundations in soft clays subjected to vertical uniform loads. Dimensionless pile displacements, pile reactions, and coefficient of pile reactions were suggested. Their correlations with the ratio of foundation embedment depth to raft size, the slenderness ratio of pile, and the ratio of pile-to-pile spacing distance to pile diameter were examined. Finally the optimized correlation diagrams were reported while a simple modelling was able to verify the suggestion.

1 INTRODUCTION

1.1 *Piled raft foundation analysis*

Piled raft foundation can provide economic and ecologic design solution to mega building structures. The load-response mechanism of such foundation can be deviated from those known for pile foundations. It has been noted that conventional pile foundation is usually designed assuming that the piles are connected to a rigid cap which can yield uniform settlements and rotations under the loads. Soil resistance underneath the cap is typically ignored. In the contrast, piled raft foundation relies heavily on the resistances of soils below the raft. To evaluate the foundation serviceability, the design of piled raft foundation requires computing the structural deformations. Overview of the available analysis methods have been suggested by Poulos (2001). The three-dimensional finite-element (FE) analysis has been known as the most powerful tool to estimate the behaviors of building foundations. The correspondent applications have been reported in numerous engineering projects on high-rise buildings (Katzenbach et al 2016). With the performance based design (PBD) guidelines, Katzenbach & Choudhury (2013) suggested that both the capacity and serviceability performances of the foundation should be taken into account in designing the piled raft foundation (or namely the combined pile raft foundation, CPRF). Figure 1 depicts the qualitative relationships of the settlement ratio (maximum settlement of CPRF to max. settlement of a single raft) versus the load ratio (the load supported by piles to the total foundation load) of the CPRF. It was suggested that both ratios at 50% should be aimed for an efficient design. Chang & Matsumoto (2017) suggested that the serviceability (*i.e.,* deformations) of the foundation is significantly important to modern design practice since the foundation load-response relations became more predictable with the advanced numerical methods, and the foundation deformations are commonly restraint first to avoid inelastic behaviors.

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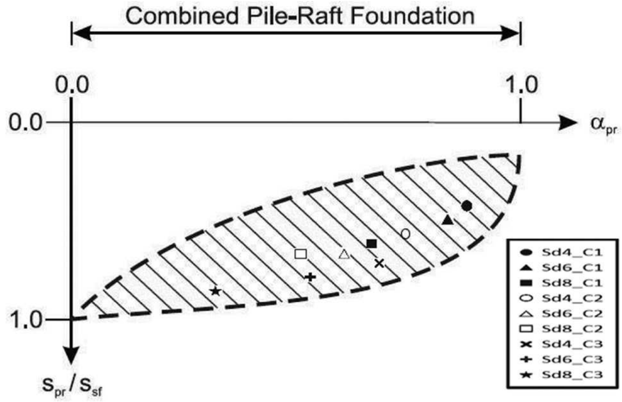

Figure 1. The qualitative relations between the settlements and the load of CPRF (after Katzenbach & Choudhury, 2013).

1.2 *Piled raft foundation analysis in Taiwan*

The current design of pile foundation in Taiwan follows the conventional methodologies. Vertical bearing capacity and uplift capacity of the single pile are analyzed first with presumed pile dimensions and bored-hole data from the field. The factors of safety at different design conditions are applied to ultimate loads in the predictions. In some cases, negative skin frictions are estimated to ensure that the piles are safe under such effects. The pile load test is required to ensure the design. Total capacity of the grouped pile is calculated using either analytical formulas suggested in the design code excluding the interferences of pile-to-pile interactions or the solutions from simplified computer-based analysis. Computer programs such as APILE, LPILE and GROUP (Ensoft, 1987-) are commonly adopted to examine the pile performance. The *t-z*, *Q-z* and *p-y* curves interpreted from the field test and/or available documents are often used for the measurements. The SAP2000 analysis is sometimes utilized by structural engineers to examine the foundation behaviors. Analytical equations suggested by Chang (1937) on single pile subjected to horizontal loads are sometimes used to check the corresponding pile performance. If the site had liquefaction induced problems, both vertical and lateral resistances of the pile will be analyzed with soil stiffness and strength reduced from the empirical liquefaction potential analysis. The soil parameter reduction coefficients suggested by JRA (1996) and AIJ (1988) are recommend for such deductions. According to the design code, lateral resistance of the pile is dominated by an allowable displacement at 10% of the pile diameter. One can refer to Chang et al (2016) for the general report.

Until now, the design of piled raft foundation (or CRPF) is rarely addressed in geotechnical engineering design code in Taiwan. The design of such foundation requires the third-party structure assessments. In order to ensure that the foundation performs safely under the loads, structural deformation analysis of the foundation became rather important. It is normally done by treating the raft as a beam or a plate attached to a series of soil and pile springs. The values of spring constants can be assumed using empirical formulas and/or engineering judgements. Therefore these springs require special attentions.

Chang et al (2022a) recently has reported the variations of the modulus of subgrade reactions for surface raft foundation subjected to short-term vertical loads. For the piled raft foundation at the ground surface, the loads carried out at the piles were found mainly dependent of the soil stiffness and the number of piles installed, however the size of the raft also would interactively affect the results (Chang et al 2022b). For mat foundations with the embedment, a technic paper on dimensionless modulus of subgrade reactions is shared at 17ARC (Chang et al 2023). This paper is aimed to discuss the similar studies for embedded piled raft foundation in clays under short-term vertical loads from three-dimensional finite element analysis. The long-term loading effects including the consolidation influences to the clays would dramatically increase the foundation settlements, therefore the pile stiffness should be further analyzed with cautions.

2 NUMERICAL MODELS

2.1 *Foundation modelling*

The numerical model of the embedded piled raft foundation is illustrated in Figure 2. A square raft with the width varying at 16, 26 and 36 meters was assumed. The thickness of the raft was 1m. Embedded depth of the raft was varying at 8 and 12m. For more realistic modelling, the concrete diaphragm wall was around the raft. The depth of the diaphragm wall was kept as 2 times of the depth for foundation embedment. Round concrete piles with 1m diameter were installed underneath the raft. The pile length was varying at 20m and 30m. The pile-to-pile spacing distance was kept at 3 and 5 times of the pile diameter. Homogeneous soft clay was assumed for the ground soil. The corresponding shear wave velocity, V_s of the soil was varying at 100, 120 and 140 m/s, respectively. Ground water table was temporarily excluded whereas the averaged Poisson's ratio of the soil was kept at 0.4.

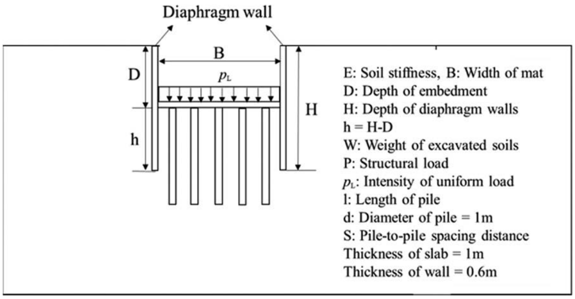

Figure 2. Foundation model of this study.

The Young's modulus of the soil, E_s were thus obtained from elasticity equations. Empirical relations suggested by Hsieh et al (2003) between the Young's modulus E_s and the undrained shear strength of the clays, S_u in Taipei was used to obtain the value of the undrained shear strength. The Mohr-Coulomb soil model was adopted. Note that the structural load, P was taken approximately as 1.5 times the weight of excavated soils. In some studies, the total load was fixed to be independent of embedment depth and size of the slab. The applied uniform load, p_L was decomposed into a series of incremental loads of 10kPa. Iterative procedure was carried out to ensure the equilibriums of the system. Table 1 summarizes the material properties and engineering parameters used in the analysis. Totally 72 numerical cases were analyzed.

Table 1. Foundation geometries, material properties and parameters of the study.

Foundation dimensions and load	FE zone: 350m×350m×150m, Mat width (B): 16m, 26m, 36m, Depth of embedment (D): 8m, 12m Depth of diaphragm (H): 2D Thickness of mat: 1m, Thickness of wall: 0.6m Pile diameter (d): 1m, Cross-section area of pile (*a*), Pile length (l): 20m, 30m Pile-to-pile spacing distance (S): 3m, 5m Structural load (P): 1.5W, Weight of soils excavated (W):$\gamma_s \times B^2 \times D$
Concrete	γ_c = 24 kN/m^3, E_c =30 GPa, v_c = 0.15
Soil	γ_s = 20 kN/m^3, v_s= 0.4, V_s = 100m/s, 120ms, 140m/s, E_s =57 MPa, 82Mpa, 112Mpa, S_u= 28.5kPa, 41kPa, 56kPa (E_s/S_u =2000) for soils denoted as E1, E2 and E3 soils

2.2 *Discrete mesh and boundaries*

The 3D FE analysis was made using Midas GTX NX package (Midas, 2014). Three dimensional 8-node solid elements were used to model the concrete structure and the soils. The interface elements were implemented between the concrete and the soils. Normal and tangent stiffness of the interface elements, k_n and k_t were assigned as $10E_s$ and E_s, respectively. Ultimate adhesion of the interface elements was assumed as 2/3 of the undrained shear strength of the clay. Stage-construction feature available in Midas analysis was used. The stability of the foundation displacements was ensured with the FE dimensions at 350m×350m×150m. Essential boundaries such as the rollers were placed. Two- and three-dimensional hinges were resulted at the interfaces of these boundaries. For computational efficiency, 1/4 FE mesh was analyzed based symmetry. The computation time required for the piled raft foundation analysis are around 6~24 hours using PC with Processor 11th Gen Intel® Core™ i7-11700 @2.5 GHz. The required time was mainly found in proportion to the resulted foundation settlement.

3 GENERAL PILE BEHAVIORS

3.1 *Pile displacements*

The largest displacements of the foundations were found appeared at the center in the range of 16~231mm. The pile displacements are the same. They were mainly reduced by the increase of soils stiffness, number of piles, and the length of pile. For similar structural loads, increasing the depth of embedment and the size of mat foundation will reduce the foundation settlements. Figure 3 presents the influences of soil stiffness, the number of piles and the pile length for piled raft foundation where the raft width is 26m. The maximum pile displacements occurred at different locations of the piled raft foundation can be found in Lin (2022).

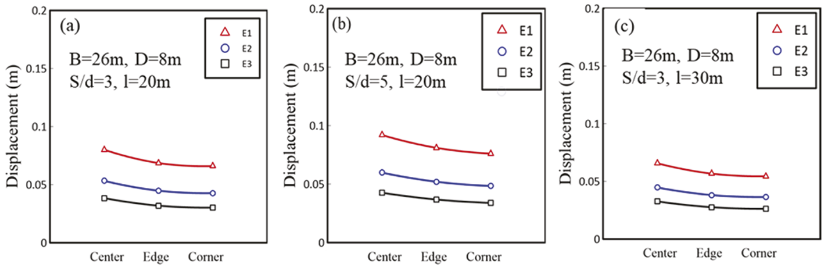

Figure 3. Foundation displacements affected by (a) soil stiffness (b) number of piles (c) pile length.

3.2 *Pile reactions*

The variations of pile reactions were found relatively insignificant in comparison with the pile displacements. The pile reactions (p) at the center pile or the pile near to the center of the foundation were found in between 989~4137kPa. The load sharing of the piles was found influenced by the soil stiffness, the raft dimension, embedment depth, number of piles, and the pile length. The influences of soil stiffness are rather smaller compared to those found at the pile displacements. Figure 4 indicates the influences of the pile reactions by soil stiffness, embedment depth, number of piles and pile length. More details of the discussions can be found in Lin (2022).

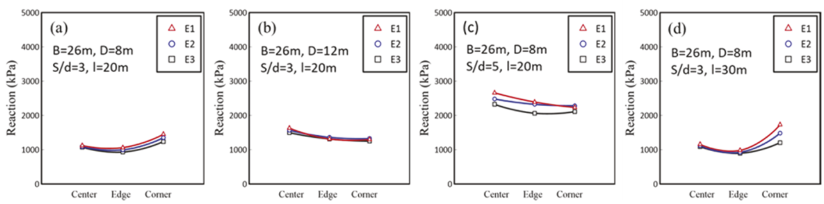

Figure 4. Pile reactions affected by (a) soil stiffness (b) depth of embedment (c) number of piles (d) pile length.

3.3 *Coefficient of pile reaction and corresponding pile stiffness*

The coefficient of pile reaction (k) is able to obtain subtracting pile reactions by pile displacement. The pile stiffness kp is calculated by multiplying k with the cross-section area of the pile. It was found that the coefficient of pile reaction (k) at the center were in the range of 8.7~136MN/m^3. Corresponding pile stiffness is about 6.8~106MN/m. It seems that the increase of soil stiffness, depth of the embedment, and the pile length will help to increase the pile stiffness. Figure 5 reveals the corresponding results. For more information, please see Lin (2022).

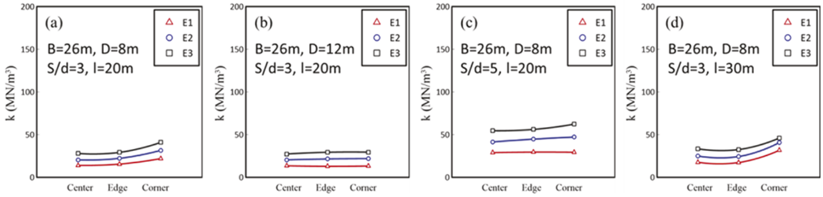

Figure 5. Coefficient of pile reaction affected by (a) soil stiffness (b) depth of embedment (c) number of piles (d) pile length.

4 DIMENSIONLESS MEASURES

4.1 *Pile displacements*

The dimensionless pile displacement in this study was defined as $\gamma_c s/E_c$ and s/B, where s is the real pile displacement. The values of 2D/B, S/d and l/d were taken as the dimensionless characters of the foundation geometry. It was found that the correlations between the dimensionless pile displacements and the dimensionless character of the foundation geometry are more scattered compared to those shown in mat foundation. Therefore the Box Plot was used to find the median values of the dimensionless pile displacements. For example, the dimensionless pile displacements ($\gamma_c s/E_c$) can be plotted against the shear wave velocities (V_s) of the soils considering the variations of raft dimensions and embedment depth. Figure 6 depicts the plots of $\gamma_c s/E_c$ versus V_s varying with the raft dimension (B) and depth of embedment (D). The corresponding plots of medians of $\gamma_c s/E_c$ versus the values of 2D/B are shown in Figure 7 separating the influences of raft dimension. Similarly, the plots for $\gamma_c s/E_c$ versus 2D/B separating the influences of the depth of embedment are shown in Figure 8.

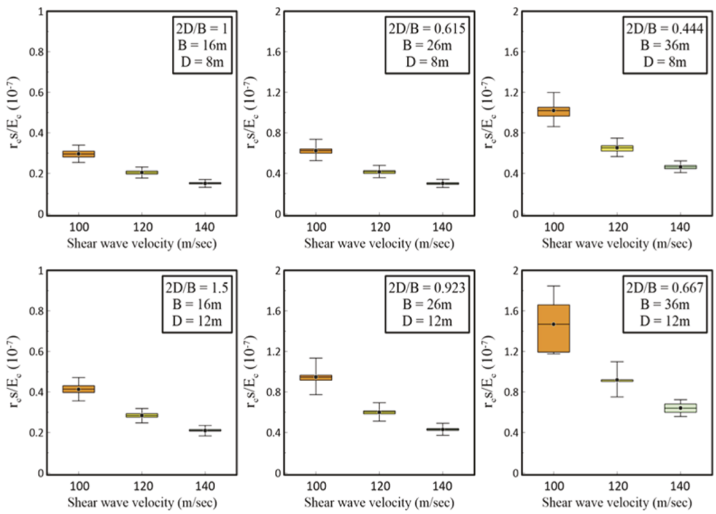

Figure 6. Box plots for dimensionless pile displacements ($\gamma_c s/E_c$) versus shear wave velocities (V_s).

For dimensionless pile displacement defined as s/B, the plots of s/B versus Vs varying with the raft dimension (B) and depth of embedment (D) can be shown in Figure 9. Again, the corresponding plots of s/B versus the values of 2D/B separating the influences of the raft dimension and the depth of embedment are depicted in Figure 10 and Figure 11, respectively. Correlations of the dimensionless pile displacements and the dimensionless character of foundation geometry (2D/B) based on different depths of the embedment were suggested owing to the number of data points presented.

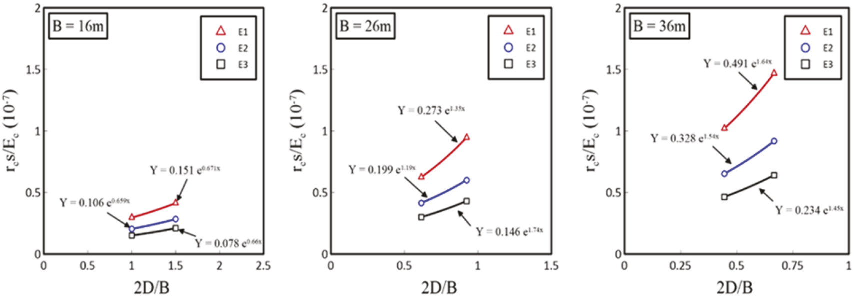

Figure 7. Correlations of dimensionless pile displacements (γ_cs/E_c) versus 2D/B for various raft dimensions.

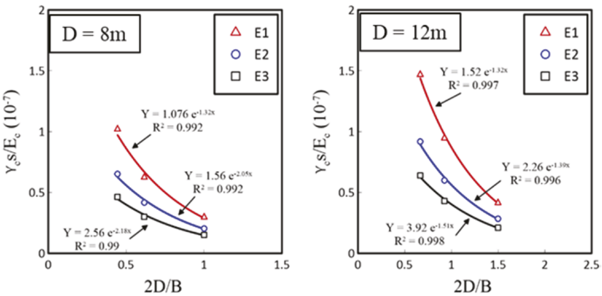

Figure 8. Correlations of dimensionless pile displacements (γ_cs/E_c) versus 2D/B for various depths of embedment.

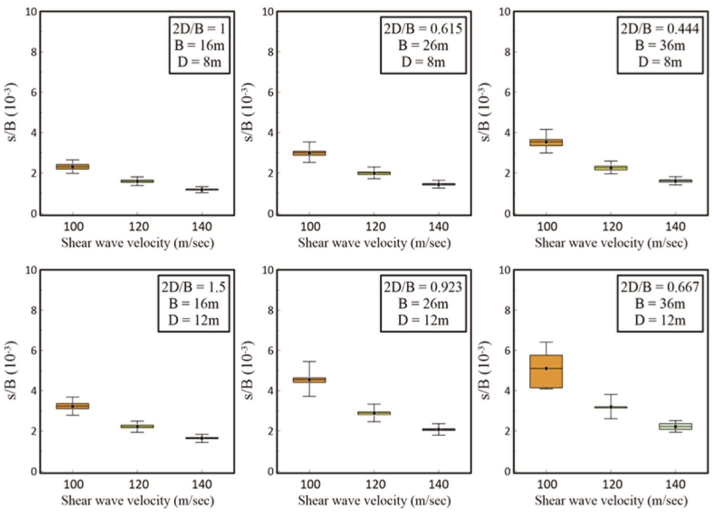

Figure 9. Box plots for dimensionless pile displacements (s/B) versus shear wave velocities (V_s).

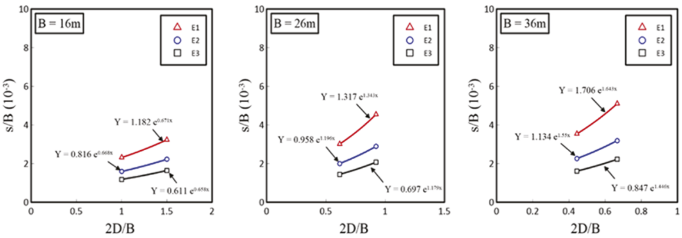

Figure 10. Correlations of dimensionless pile displacements (s/B) versus 2D/B for various raft dimensions.

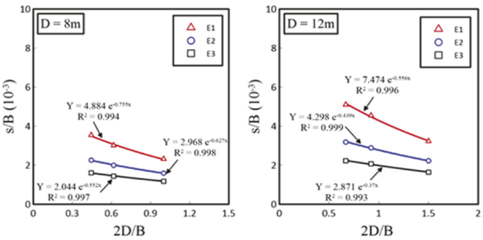

Figure 11. Correlations of dimensionless pile displacements (s/B) versus 2D/B for various depths of embedment.

The similar procedures to plot the dimensionless pile displacements $\gamma_c s/E_c$ and s/B with the dependence of shear wave velocity (V_s) of the ground soils, and subsequently obtain the correlations of the pile displacements versus other characters of the foundation geometry (e.g. S/d and l/d) can be found in Lin (2022). It was generally found that the Box plots made with the dependence of S/d and l/d would have larger deviations in terms of the height of the box and the height difference of the maximum and minimum values. Therefore they were not recommended.

4.2 *Pile reactions*

Following the above definitions of dimensionless pile displacement, the dimensionless pile reaction in this study was defined as p/E_c and $p/\gamma_c B$ respectively, where p is the pile reactions (Units in F/L^2). Figure 12-Figure 15 reveal the Box plots for p/E_c and $p/\gamma_c B$ versus the shear wave velocity of the ground soils with variations of embedment depth, and the correlations of the medians with respect to the dimensionless character 2D/B. The correlations of $p/\gamma_c B$ were not recommended owing to relatively higher deviations.

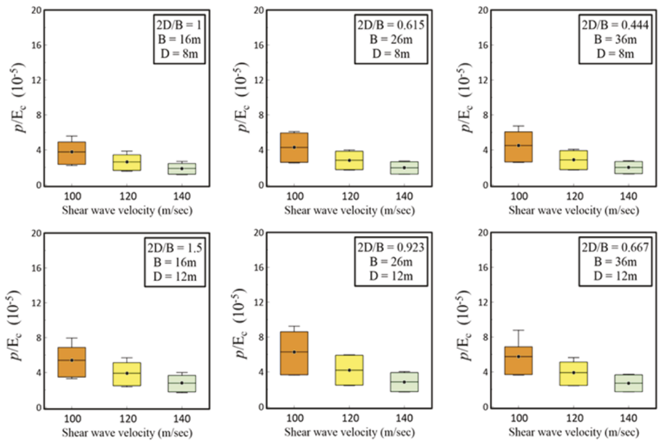

Figure 12. Box plots for dimensionless pile reactions (p/E_c) versus shear wave velocities (V_s).

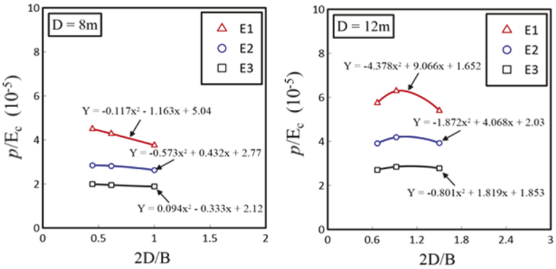

Figure 13. Correlations of dimensionless pile displacements (p/E$_c$) versus 2D/B for various depths of embedment.

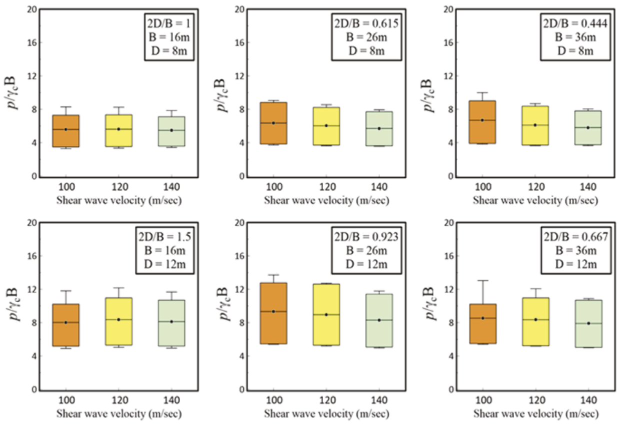

Figure 14. Box plots for dimensionless pile reactions (p/γ_cB) versus shear wave velocities (V_s).

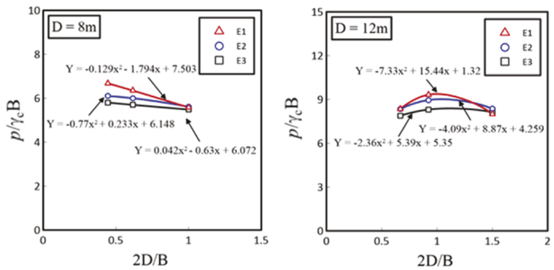

Figure 15. Correlations of dimensionless pile displacements (p/γ_cB) versus 2D/B for various depths of embedment.

4.3 *Coefficient of pile reactions*

The dimensionless coefficient of pile reactions was denoted as p/γ_cs following the above dimensionless quantities of pile displacement and pile reaction. Similarly, the Box plots of p/γ_cs versus V_s can be shown in Figure 16. The correlations between the dimensionless coefficient of pile reaction and the dimensionless character of foundation geometry (2D/B) at different depths of embedment are shown in Figure 17.

4.4 *Applications*

Notice that the maximum load pressure applied to the studied foundation is in the range of 240~360kPa. Therefore, if the loading condition can be approximated, engineers can use the regression curves shown in Figures 8, 13 and 17 to estimate the pile displacement, the pile reactions and the coefficient of pile reactions based on similar soil conditions. For soil stiffness different to the suggested quantities, interpolations should be used to obtain the approximated values. For example, the pile displacement, s can be found as the procedures shown in Figure 18 considering the depth of foundation embedment is in between 8~12m. The pile reactions and the coefficient of pile reaction (or multiplying with *a* to obtain the pile stiffness) can be found using the similar procedure. Once the pile settlement, s and pile reactions, *p* are obtained, the coefficient of pile reaction, k can be also calculated as *p*/s.

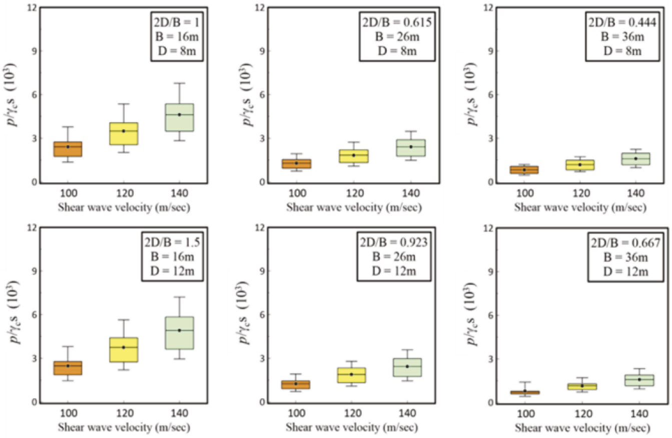

Figure 16. Box plots for dimensionless coefficient of pile reaction ($p/\gamma_c s$) vs. shear wave velocities (V_s).

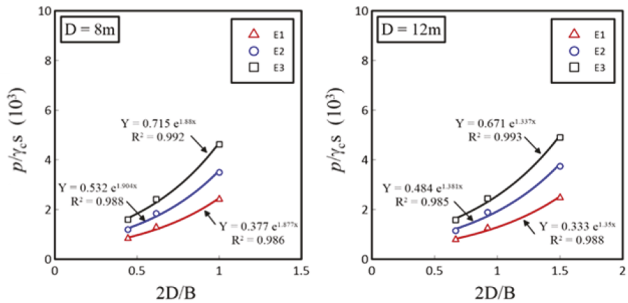

Figure 17. Correlations of dimensionless coefficient of pile reaction ($p/\gamma_c s$) vs. 2D/B for various depths of embedment.

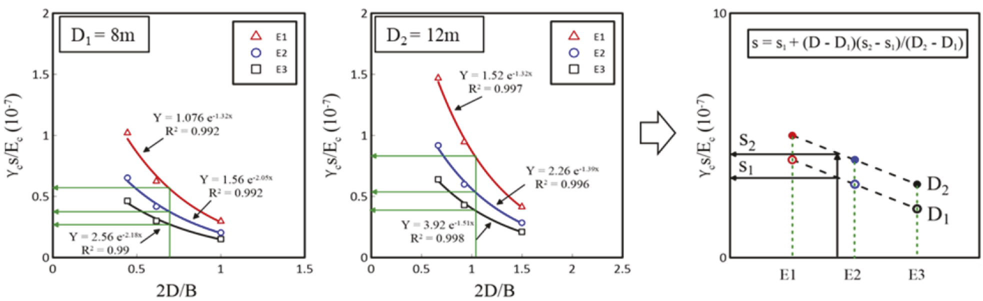

Figure 18. Interpolation procedure to find pile displacement of the piled raft foundation in clays for approximate soil and embedment depth conditions.

5 CONCLUDING REMARKS

The pile displacements, pile reactions, and the coefficient of pile reactions of the embedded piled raft foundation located in soft clays subjected to vertical loads have been analyzed by 3D FE analysis. The influences of soil stiffness, raft dimension, depth of embedment (which affects the applied load), the number of piles installed, and the pile length were studied by seventy-two numerical cases. Enable to use them in routine design, the dimensionless measures were proposed first and then analyzed using Box plot. With the medians, their correlations with the dimensionless characters of the foundation geometry were examined. The correlations of $\gamma_c s/E_c$, p/E_c, and $p/\gamma_c s$ versus 2D/B were finally recommended to design practice. They are suggested as a preliminary design tool for piled raft foundations in soft clays. Further examination with the field measurements is welcomed.

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