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Research Note

Centrifuge modeling of pile-soil-pile interaction considering relative density and toe condition

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Abstract. In a group of installed piles, the stresses applied from one pile to soil may have overlaps with another pile which leads to the changes in bearing capacity and settlement of each individual pile. In order to predict the performance of those piles, interaction coefficients, based on elasticity theory proposed by Mindlin, are widely applied. In this paper, the effect of soil relative density and also toe condition on the interaction between two similar piles in sandy soil is presented using centrifuge modeling. To achieve this objective, 22 tests have been conducted to investigate the effect of soil relative density and another 11 tests were performed to study the contribution of pile toe and shaft in the interactions. The results showed that the value of soil relative density has an important role in the coefficient of interaction which has not been considered in previously reported correlations. For this reason a modification has been proposed for the Randolph and Wroth equation to consider soil relative density. Accuracy prediction of the new model was compared with the Randolph and Wroth equation with the aid of different statistical parameters. This comparison indicated the superiority of the proposed model over previous methods.

1. Introduction

In recent decades, advances in analytical and experimental methods have provided a better understanding of the deformation of piles group under loading. Advances in numerical techniques, in particular the integral equations and the numerical boundary element methods [1], have made the analysis of piles group more feasible. The introduction of interaction coefficients, resulted from analytical studies, was one of the most advantageous concepts. These coefficients, represented by α_{ij}, have been defined as the displacement at the top of the pile i due to the load applied to the adjacent pile, j, divided by the displacement of the pile j under its own load:

$$\alpha_{ij} = \frac{\begin{array}{c}\text{Displacement of } i \text{ pile due to}\\ \text{applying unit load at } j \text{ pile}\end{array}}{\begin{array}{c}\text{Displacement of } j \text{ pile due to}\\ \text{applying unit load}\end{array}}. \tag{1}$$

Using the elastic interaction coefficients has provided a practical method for estimating the settlement of a piles group as well as distribution of the loads among individual piles. However, the value of predicted settlement can sometimes be greater than the observed settlement value, and there is an overall consistency between the theoretical settlements and those measured in the laboratory and field. The studies conducted so far on this topic and the reported equations are mostly

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based on the theory of elasticity. This means that soils and piles are assumed to remain in elastic condition with no sliding along the pile-soil interface, which may not occur in real case.

Factors influencing interaction coefficients are included pile (L/d ratio), pile roughness, installation method, relative density, S/d and etc. However, in this study the effects of relative density of sandy soil and the pile toe on the interaction coefficients are investigated.

For this purpose, 22 centrifuge tests have been conducted to investigate the effect of soil relative density and another 11 tests have been performed to study the contribution of pile toe and shaft on the interaction coefficient. Then, a new model for the prediction of pile-soil-pile interaction is proposed.

Similar methods representing raft as a thin plate, soil and piles as springs were also proposed by other researchers, Russo [2], and Klar et al. [3]. In all the methods, the interaction factor of pile to pile was one of the most important factors. Kitiyodom and Matsumoto [4], Liang et al. [5] and Kitiyodom et al. [6] analyzed the piled raft foundation system using this factor. Their proposed methods could analyze the large piled raft system in a reasonable time using a personal computer. In those methods, the pile behavior is assumed linear or nonlinear springs and the pile to pile interaction factors have been calculated based on elastic theory [7].

2. Methods to determine the pile-soil-pile interaction

The methods which are developed based on the theory of elasticity, owing to the handy available charts and tables which can be easily used, are currently one of the most popular methods for estimating the settlement of a piles group. In these methods, piles are applying vertical loads to the soil and, following the Mindlin equations, soil is assumed to be homogeneous, linear, elastic, isotropic half-space with the Young's modulus (E_s) and the Poissson's ratio (ν_s).

Poulos and Davis [8], for the first time, introduced the concept of interaction between two piles using Mindlin equations. In order to calculate the interaction between two piles in this method, a group of two piles is considered and each pile is divided into n elements. Assuming that the soil and the pile remain in elastic condition with no sliding in the interface of soil and pile, the resulted displacement in each element of pile is equal to that of the adjacent soil. The obtained results from a group of two piles were introduced as the interaction coefficients. They presented some charts to determine the coefficients based on the ratio of the distance of piles from each other to the diameter of pile (s/d).

O'Neil et al. [9] suggested that when the interaction between piles is considered, it is better to use the small strain Young's modulus for soil, i.e. the modulus between the piles, instead of the modulus for the soil surrounding the piles which represents much larger strains. The old method for analysis of interaction coefficients for a group of piles [8] uses a uniform soil modulus for calculating the settlement of a single pile and interaction coefficients.

Poulos [10] considered the effect of difference between the soil modulus around pile and the modulus of soil mass in calculation of the interaction coefficients and settlement of a pile group.

A comparison between the results and the real data indicated that the new analysis was able to estimate the settlements more realistically compared to the old analysis which only considered the modulus of the soil surrounding the pile [10]. Assuming linear elastic behavior for the soil causes to overestimate the interaction coefficients of the piles.

Assuming that the displacement of the pile shaft completely follows the surrounding soil, Randolph and Wroth [11] proposed separate equations for determining the interaction of the toe and shaft, using the shape of deformations of the soil around the single pile due to shaft and toe of the pile. They proposed the interaction coefficient of the pile shaft and the interaction coefficient of the pile toe, respectively, by:

$$\alpha = \frac{\mathrm{Ln}(\frac{r_m}{s})}{\mathrm{Ln}(\frac{r_m}{r_0})}, \tag{2}$$

$$\alpha_b = \left(\frac{d_b}{\pi.S}\right), \tag{3}$$

$$r_m = 2.5L(1-0.5\nu), \tag{4}$$

where S is the distance between the piles, r_0 is the radius of the pile, d_b is the diameter of the toe of the pile, and r_m is the effective radius of the pile which is calculated by Eq. (4). Base on the above equation, Wong and Poulos [12] have proposed other equations for pile-to-pile interaction factors between two dissimilar piles.

Jardine et al. [13] showed the importance of the nonlinear assumption for the settlement of a piles group and load distribution using the finite element analysis.

Using finite element modeling of a hollow pile in homogeneous linear elastic semi-infinite isotropic soil, Polo and Clemente [14] proposed charts for determining the interaction coefficients based on the Poisson's ratio of soil, length, diameter and distance of piles from each other. One of the important characteristics of this method is its ability for considering the effects of the pile shaft and toe separately in the analyses.

Mandolini and Viggiani [15] considered the nonlinear performance of a single pile in determining the interaction coefficients. They used boundary element method for calibrating the soil model against the load-settlement behavior of a single pile and then determined the interaction coefficients between two piles with different distances. They also suggested that after a certain distance, the interactions became very small and almost disappeared. They proposed a simple equation for determining the interaction in one of the forms:

$$\alpha = A\left(\frac{s}{d}\right)^{B}, \tag{5}$$

$$\alpha = \left\{C + D\ln(\frac{s}{d})\right\}. \tag{6}$$

Mandolini and Viggiani [15] reported the values of A, B, C and D based on four field studies as $A = 0.57 \backsim 0.98$, $B = -0.60 \backsim -1.20$, $C = 1.0$ and $D = -0.26$.

Milonakis and Gazetas [16] suggested that the displacement of pile shaft does not follow the surrounding soil completely and thus they proposed equations considering the stiffness of piles and interaction of pile with adjacent soil. On the other hand, the effect of soil mass reinforced by the piles was not considered in their equations and interaction coefficients. They considered this effect in their model by introducing diffraction factors. Considering the above factors generally decreased the interaction coefficients.

A number of centrifuge tests have been conducted in the present study to investigate the effect of relative density on pile-soil-pile interaction and thus to verify the accuracy of Randolph and Wroth equations.

Russo [2] proposed an equation for calculation of interaction factor that piles located at several of spacing (usually between $3d$ - $60d$) by implementing numerical boundary element analysis, given by:

$$\alpha = \frac{1}{1 + A(S/d)^{B}} + C\log\left(S/d + 10\right), \tag{7}$$

where $A = 0.2795$, $B = 0.8991$ and $C = -0.0474$.

3. Experimental methodology

3.1. Acceleration and scaling in centrifuge tests

An specimen, having a $1/N$ scale of the real dimensions in the centrifuge apparatus, under the acceleration, N times the gravitational acceleration, is able to simulate the stress levels of the real condition in a minimized model. Therefore, the results of such model can be used for interpretation of the pile performance in prototype. The observations made in the model can be correlated to the prototype behavior by the similarity equations noted in Table 1. All the models have been tested under 100 g acceleration and hence the scaling coefficient was $N = 100$.

Table 1. Similarity relationships.

Property	Prototype	Model
Acceleration	1	N
Area	N	1
Length	N^2	1
Volume	N^3	1
Velocity (projectile)	1	1
Velocity (undrained conditions)	1	N
Mass	N^3	1
Force	N^2	1
Energy	N^3	1
Stress	1	1
Strain	1	1
Mass density	1	1
Energy density	1	1
Time (dynamic)	N	1
Time (diffusion)	N^2	1
Time (creep)	1	1
Frequency	1	N

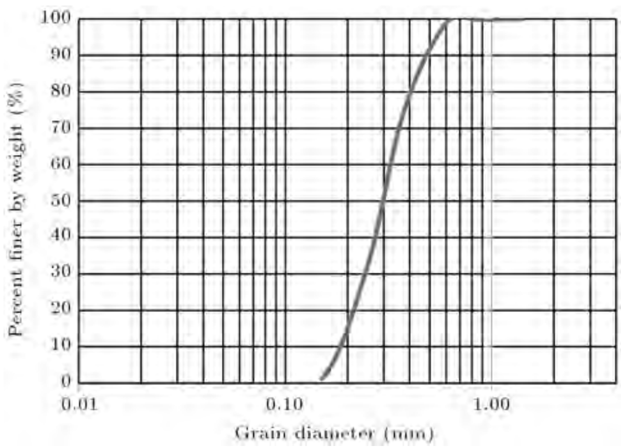

Figure 1. Grain-size distribution of the test sands.

3.2. Model preparation

The broken Firouzkouh sand known as 161-Firouzkouh sand with a uniform grading has been used in the experiments (Figure 1). This is clean sand with 1% fine grains with the gradation curve similar to the Toyoura standard sand.

In Table 2, the physical and mechanical properties of the mentioned sands have been compared with Toyoura standard sands, and in Figure 2, microscopic photos show the angular broken structure of the Firouzkouh sand.

In order to model the hollow piles, an aluminum pipe with 90 mm total length and 80 mm embedment length has been used. The external and internal diameters were 10 and 9 mm, respectively. The prototype model of the pile is a steel pile with 1 m

Table 2. Characteristics of Firouzkouh sand.

Sand	Gs	e_{max}	e_{min}	$D_{50(mm)}$	**F.C %**	ϕ	**Cu**	**Cc**	**K**
161-Firouzkouh sand	2.658	0.97	0.55	0.27	0.2	32	2.58	0.97	0.0 125
Toyoura	2.65	0.977	0.597	0.17	0	-	-	-	-

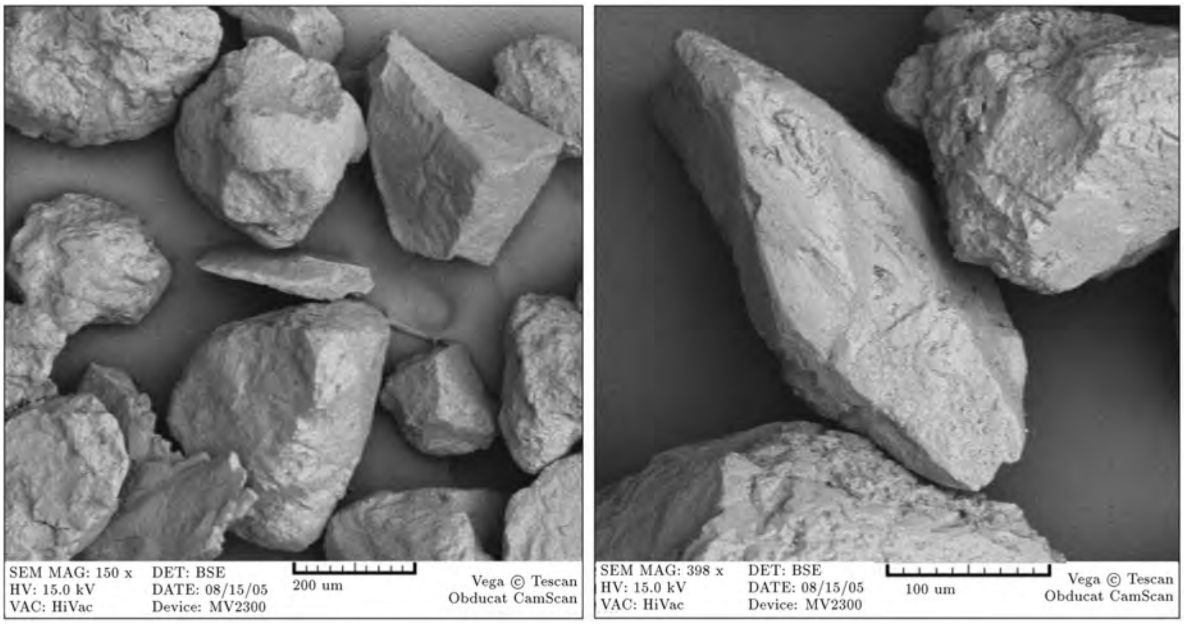

Figure 2. Electro-microscopic photo taken from the Firouzkouh sand.

diameter and 3.2 cm thickness with 8 m length. In order to model a close-ended pile, the ends of pipes, penetrated to the soil, were designed to be closed.

The effect of the grain size on the pile diameter has been studied by Bolton et al. [17].

They concluded that if the ratio of pile diameter to the average particle size is greater than 20, the scale effect would be very small. Bolton et al. [17] also suggested the ratio of pile diameter to the average particle size to be greater than 20. In the present study, this ratio was 37.04 and thus the effect of particle size was neglected.

In order to measure the displacement of piles and soil, three Linearly Variable Differential Transformer (LVDT) sensors have been employed. Figure 3 shows the boundary conditions location of the piles and LVDT sensors in the centrifuge box.

The interactions are determined using the flowing equation:

$$\alpha = \frac{A-B}{C-D}, \tag{8}$$

where A is the displacement of the non-loaded pile, B is the displacement of the non-loaded pile under the weight of LVDT sensor, C is the displacement of the loaded pile, and D is the displacement of the loaded pile under the weight of LVDT sensor.

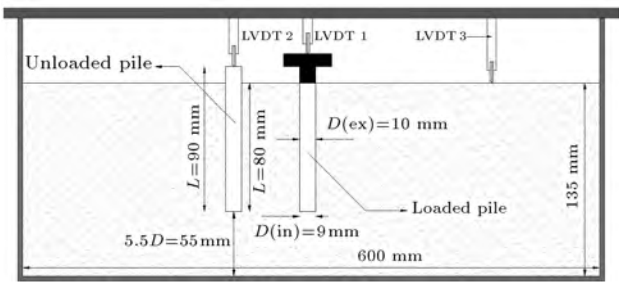

Figure 3. Boundary conditions and test model set-up for loading tests on the pile.

The size of test box is selected such that the boundary effect is minimized. However in all tests, the boundary condition was similar and therefore comparison of the centrifuge tests results is acceptable. Loading condition was also, similar for all tests. The pile was loaded by a weight mass resting on the top of pile. The loading level was in the range of 60% of ultimate bearing capacity of the pile.

4. Test results and observations

4.1. Test program

In order to study the effect of relative density, four sets of experiments with various relative density ratios have been performed. In order to investigate the effect

Table 3. Test program.

Pile model	**Open-ended**	**Open-ended**	**Open-ended**	**Open-ended**	**Close-ended**	**Close-ended**
Dr (%) / S/d	**23**	**40**	**56**	**78**	**56**	**23**
3	√	√	√	√	√	√
5	√	√	√	√	√	√
7	√	√	√	√	√	√
9	√	√	√	√	√	√
12	√	√	√	√	√	√
16	—	√	—	√	√	—

of the pile toe, two sets of tests with close-ended pile have also been conducted. The tests specifications are summarized in Table 3. For each set of experiments, the pile settlement in 100 g acceleration under the weight of the LVDT sensor has been measured. The distances mentioned in Table 3 refer to the distance between center to center of the piles.

4.2. Test procedure

Pluvial deposition technique has been used to prepare the specimens. The specimens have been prepared layer by layer to obtain a uniform compaction profile. This process is continued until the desired depth was obtained. In order to prevent possible errors in measuring displacements and achieving a better interlock between the pile shaft and soil, the specimen was flight to 100 g acceleration once and was reduced to 1 g prior to installation of LVDT sensor. Then three LVDT sensors have been placed; one instrument on the soil, one instrument on the loaded pile and the last one on the non-loaded pile (Figure 3). After installing the instrumentations, the model has been given 100 g acceleration and the LVDT data have been recorded for further analysis.

The LVDT sensor, installed on the soil, shows settlements of the soil in 100 g acceleration which also causes changes in the soil relative density. The loading on the pile has been in the range of 60% of ultimate bearing capacity of the pile.

5. Test results

The tests results are presented in two groups, one for investigating the effect of relative density and the other group for studying the effect of the pile toe. Table 4 shows the results of the interaction coefficient of hollow piles in 4 different relative densities.

Figure 4 shows the interaction coefficient of the open-ended piles for the ratio of the pile distance to the pile diameter (s/d). As can be observed, by increasing the distance of piles from each other, the interaction coefficient decreases. It is also indicated that the soil

Table 4. The obtained interaction coefficient of the open-ended piles in the current study.

Spacing/diameter	**Soil-pile-soil interaction factor**			
	Relative density			
	23	**40**	**56**	**78**
3	0.485	0.495	0.5004	0.513
5	0.114	0.214	0.320	0.338
7	0.083	0.166	0.290	0.326
9	0.046	0.135	0.206	0.210
12	0.015	0.095	0.141	0.142
16	—	0.020	0.048	—

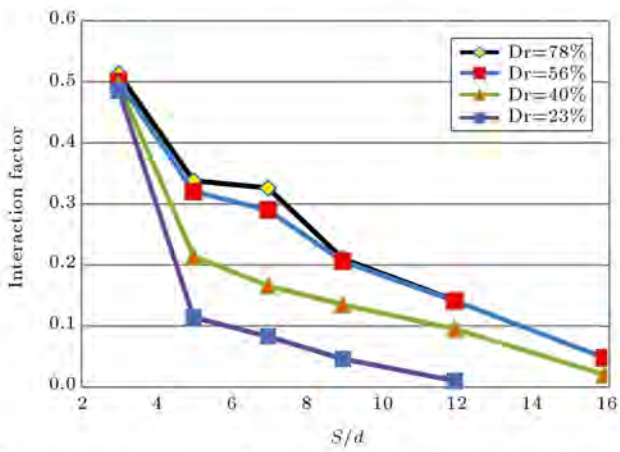

Figure 4. Settlement interaction between two piles with open-ended piles for different relative density.

relative density plays an important role in determining the value of interaction coefficient such that by decreasing the compaction of soil, the interaction coefficient significantly decreases.

The reason for reduction in pile-soil-pile interaction in low value of relative density can be explained by the occurrence of relative displacement between the surface of pile and soil which causes a decrease in pile-soil interaction and consequently decreasing the interaction coefficient of pile-soil-pile interaction.

As observed in Figure 4, when two piles are placed

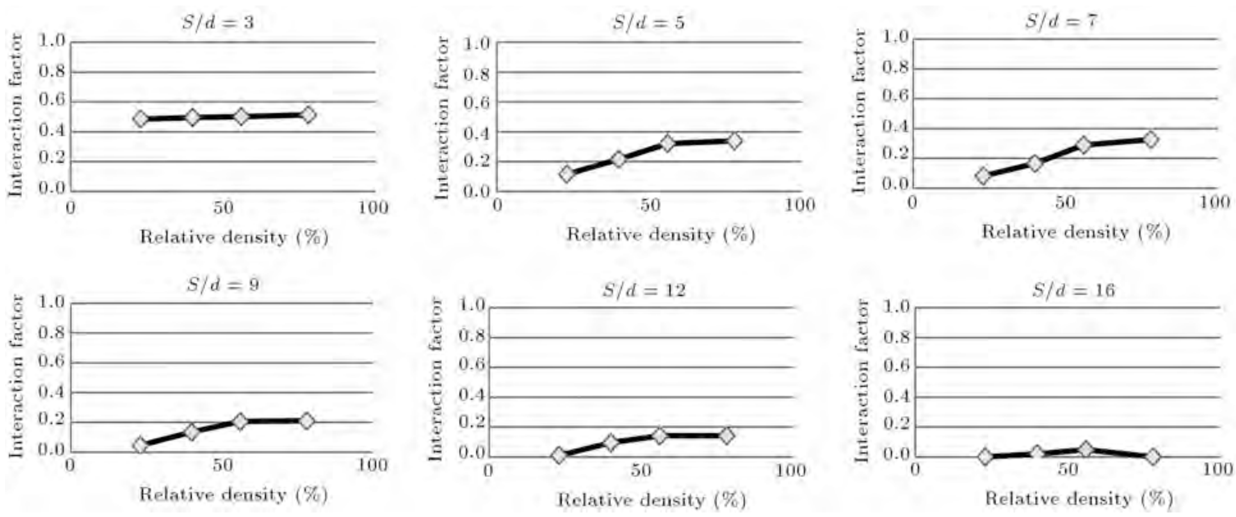

Figure 5. Settlement interaction between two piles with different relative density for open-ended pile.

in near distance ($S/d = 3$), interaction coefficient is approximately equal for all of the relative densities because during the piles installation, the soil between them is compressed so much that the relative density of soil does not affect the interaction coefficient.

Figure 5 shows the interaction coefficients of open-ended piles with regard to the relative density of soil for the tested s/d values. As can be observed for $\frac{S}{d} < 3$ and $\frac{S}{d} > 16$ the variations of the interaction coefficient compared to the changes in relative density ratio is very small (almost zero). However for $3 < \frac{S}{d} < 16$ the value of variations are about 0.2 which is a large number and shows that the relative density is an important factor in determining the interaction coefficient of pile-soil-pile. Also, it can be concluded that for relative density more than about 55%, no significant effect of relative density on the interaction coefficient existed and all the curves tend to become horizontal in this range.

Figure 6 and Table 5 show the interaction coefficients calculated for close-ended piles versus the ratio of the piles distance to the piles diameter (s/d) compared to the open-ended piles for 56% and 23% relative density. It can be concluded that the effect of pile toe in interactions is negligible compared to the effect of shaft. Also, most of the interaction occurs due to the pile shaft. With regard to the obtained results, it can be concluded that the average contribution of the pile toe in interactions is about 15% and 19.5% of the total interaction value for 56% and 23% relative density, respectively.

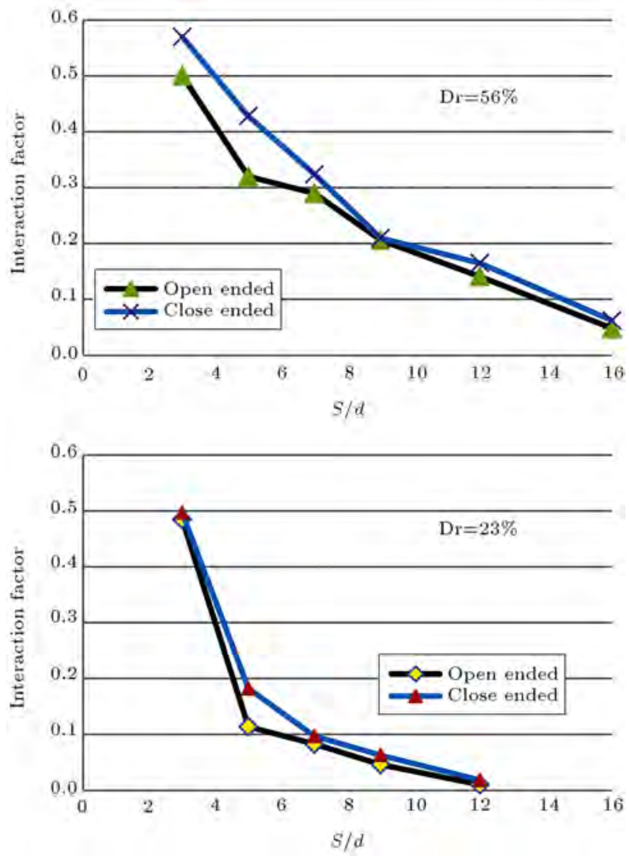

Figure 6. Influence of toe condition on the settlement interaction.

6. Comparing the results with previous method

6.1. Randolph and Wroth approach

Figure 7 compares the interaction coefficient of the pile shaft proposed by Randolph and Wroth [11] for sandy soil with Poisson's ratio of 0.25 and the ones obtained in this study. The coefficients proposed by Randolph and Wroth are in good agreement with the experimental results for relative density ratios greater than 50%. However, in low relative density ratios the coefficients proposed by Randolph and Wroth overestimate the real values and are very conservative.

In the equations proposed by Randolph and

Table 5. The obtained interaction coefficient of the close-ended piles in the current study.

Spacing/diameter	Soil-pile-soil interaction factor			
	Pile model (for Dr=56%)		Pile model (for Dr=23%)	
	Open-ended	Close-ended	Open-ended	Close-ended
3	0.500	0.570	0.485	0.497
5	0.320	0.428	0.114	0.182
7	0.290	0.324	0.083	0.097
9	0.206	0.210	0.046	0.063
12	0.141	0.165	0.015	0.018
16	0.048	0.062	—	—

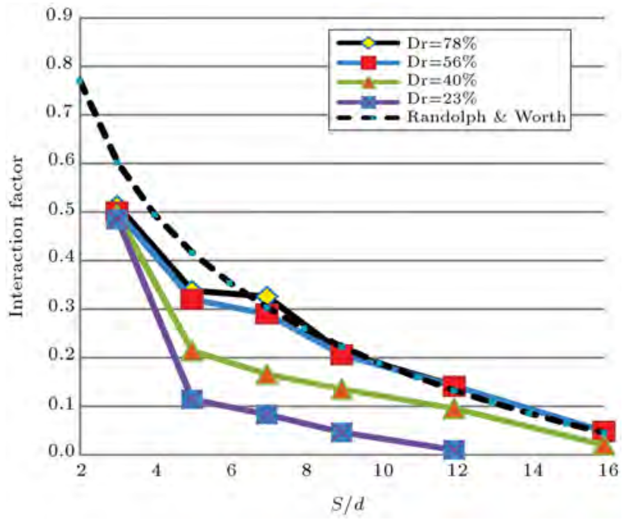

Figure 7. Comparing the centrifuge results with Randolph and Worth equation for open-ended pile.

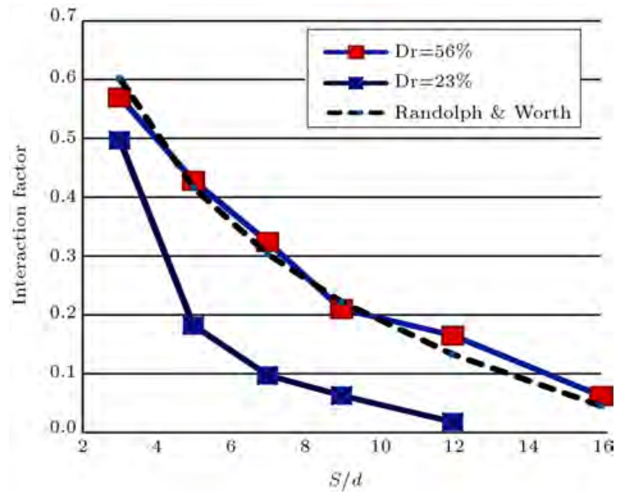

Figure 8. Comparing the centrifuge results with Randolph and Worth equation for close-ended pile for 56% and 23% relative density.

Wroth [11], it has been assumed that no sliding occurs between the pile and adjacent soil and the displacements of soil and pile shaft are equal. But as mentioned by Milonakis and Gazetas [16], the displacement of pile shaft does not completely follow the displacement of surrounding soil and it depends on the stiffness of pile and the interaction of pile with surrounding soil.

Figure 8 compares the obtained coefficients from the close-ended piles with equations proposed by Randolph and Wroth [11]. As can be observed, the experimental results of interaction for 56% relative density and close-ended pile are in good agreement with the results reported by Randolph and Wroth [11].

Generally, it can be concluded that for the soils with high relative density, the equations proposed by Randolph and Wroth [11] give a good estimate of the interactions, but in low relative density ratios, these coefficients are conservative and results in overestimating the settlements.

6.2. Mandolini and Viggiani approach

Mandolini and Viggiani [15] proposed two equations for the calculation of interaction coefficients based on the field analysis. One of their proposed equation does not give a certain value and thus for the purpose of comparison with the centrifuge results, its reported range is illustrated in Figure 9.

It can be observed that the maximum and minimum of Eq. (1), due to selecting the values of A and B, is almost consistent with the experimental results and Eq. (3) overestimates the interaction coefficients. It is worth to note that the exact values of A and B in Eq. (1) are not specified based on engineering application and the user needs to judge the values of A and B. According to Figure 9, centrifuge results are between the upper and lower boundary of Mandolini and Viggiani equation with moving toward maximum with increasing soil relative density. Therefore, it can be concluded that the selection of A and B values should be based on the relative density and the result of centrifuge modeling is perfectly matched with the results obtained from the field observation.

6.3. Polo et al. approach

Figure 10 shows the interaction coefficients of the pile shaft presented by Polo et al. [14] for a pile with the

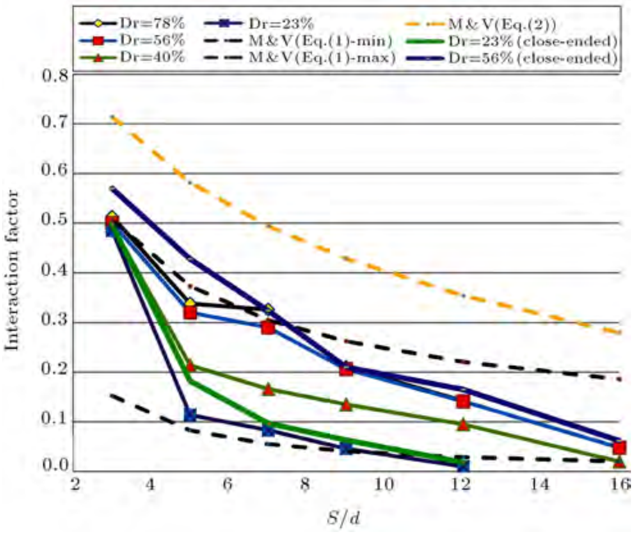

Figure 9. Comparing the centrifuge results with Mandolini and Viggiani equation.

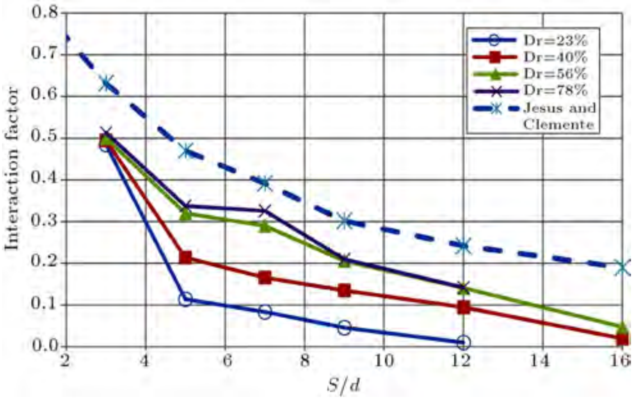

Figure 10. Comparing the centrifuge results with Jesus and Clemente equation for the open-ended pile.

length to diameter ratio of 8 in sandy soil with Poisson's ratio of 0.25 compared with the coefficients obtained in the centrifuge modeling. It can be observed that the charts presented by Polo et al. [14] overestimate the interactions and their proposed coefficients are very conservative.

Figure 11 compares the coefficients obtained from centrifuge modeling for close-ended piles with the charts proposed by Polo et al. [14]. As can be observed the results of centrifuge modeling for 56% relative density show a reasonably good agreement with the results presented by Polo et al. [14] for determining the interactions of the pile toe.

7. Modification of previous equations

The results from experimental tests clearly indicate the important effect of relative density on the interaction coefficient. Authors added a logarithmic function of relative density to the Randolph and Worth equation and provided a better correlation between the centrifuge results and the relative density. Thus, an equation for calculating the interaction was eventually obtained using the Randolph and Wroth equation and regression method, through adding only one term, given as:

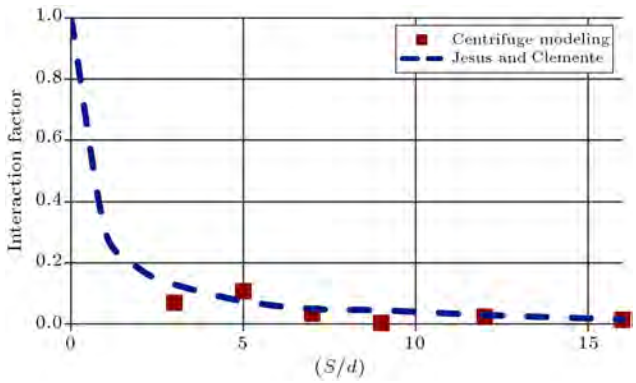

Figure 11. Comparing the centrifuge results with Jesus and Clemente equation for pile toe interaction and 56% relative density.

$$\alpha = \frac{\mathrm{Ln}(\frac{r_m}{s})}{\mathrm{Ln}(\frac{r_m}{r_0})} + \left(\frac{d_b}{\pi.S}\right) + 0.211\mathrm{Ln}(\mathrm{Dr}) + 0.128. \quad (9)$$

In order to assess the quality and accuracy of the proposed equation compared with previous relations, we also define the statistical parameters as:

$$R^2 = \left(1 - \frac{\sum\limits_{(i=1)}^{n}(M_i - P_i)^2}{\sum\limits_{(i=1)}^{n}(P_i - \bar{P})^2} \times 100\right)\%, \quad (10)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(M_i - P_i)^2}{n}}. \quad (11)$$

The determination coefficient (R^2) is a measure of the relative correlation between two sets of variables. The RSME is the most popular error measure, as it gives more weight to the large errors than the smaller ones.

The predicted interaction $(\alpha)_p$ of the original Randolph and Worth equation with the same equation modified for the effect of relative density are plotted against the measured $(\alpha)_m$ values in Figure 12.

The proposed equation has better performance than the original Randolph and Wroth equation, with $R^2 = 92\%$ and RMSE $= 0.05$ compared with $R^2 = 63\%$ and RMSE $= 0.1$.

8. Conclusions

In this study, in order to study the effect of soil relative density ratio and the amount of interaction of the pile toe in determining the pile-soil-pile interaction

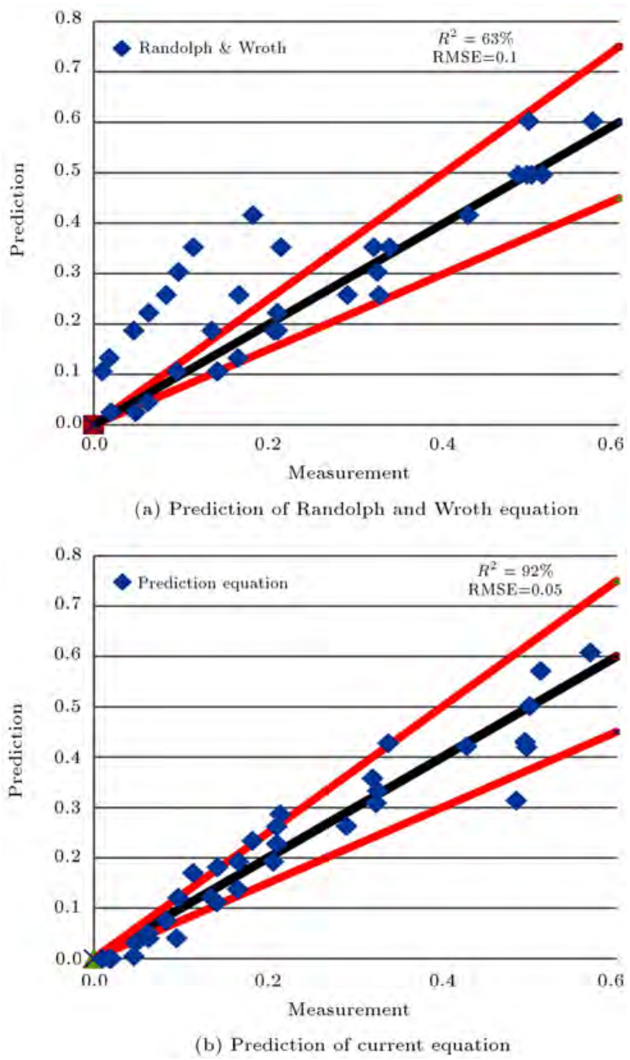

Figure 12. Measured versus predicted interaction coefficient.

coefficient, 33 centrifuge tests have been performed. These tests have been conducted using the uniform circular pile models under the vertical static load in sandy soil. The results showed that:

1. The relative density ratio of soil has an important role in determining the interaction coefficients. The reason for decrease of pile-soil-pile interaction in small value of relative density can be explained as the occurrence of relative displacement between the interface of soil and pile which causes, in turn, a decrease in the pile-soil interaction and consequently decreases the pile-soil-pile interaction coefficient.
2. The interaction coefficients proposed by Randolph and Wroth [11] are very consistent with the experimental results for relative density ratios greater than 50%, but in small value of relative density ratios their model overestimates the results and are very conservative.
3. Two equations proposed by Mandolini and Viggiani [15], which have been obtained from field cases, were compared with the experimental results and showd that the range of one of their equations is very consistent with the experimental results but the second equation overestimates the interaction coefficients.
4. The interaction due to the toe of the pile is negligible compared to the contribution of the shaft, and the average effect of the pile toe in this study was about 17% of the total interaction value.
5. The charts presented by Polo et al. [14] to calculate the interactions, due to considering the pile shaft, overestimates the interaction. However, their presented charts for estimating the interaction of the pile toe are almost consistent with the centrifuge tests results.

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