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Settlement Performance of Piled Raft Foundations in Sand

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ABSTRACT- In the recent years, piled raft foundations have been utilized as a foundation system for many structures rested on different soil conditions. The combined effect of the piles and the raft improves the bearing capacity and reduces the settlement of the raft. This paper investigates the load–settlement behavior of piled raft foundation rested on sandy soil under uniform vertical load through three-dimensional finite element analyses using PLAXIS 3D. The effects of main influencing parameters including pile length, pile diameter, raft thickness and the internal friction angle of subsoil are considered in investigating the load–settlement behavior of piled raft foundation. The numerical results show that the settlement of the raft significantly decreased with increase in pile length, pile diameter, or the internal friction angle of subsoil. Also, the results indicate that the raft thickness has a slight effect on the raft settlement.

Index Terms - Piled raft; Load settlement behavior; Numerical analysis; PLAXIS 3D; Sand; Vertical load; Parametric study

1 INTRODUCTION

In many situations, raft foundation may have suitable factor of safety against shear failure, but its settlement may exceed the allowable levels. Therefore, piles should be installed under the raft to reduce the settlement of the raft to the allowable limits. This combined foundation system consisting of the piles and the raft is known as piled raft foundation.

In the recent years, piled raft foundations have been utilized to support different types of structures rested on different soil conditions. This type of foundation has been utilized to support a wide variety of structures, such as towers, buildings and industrial plants. Piled raft foundation offers some advantages such as increasing the bearing capacity and reducing settlement of the foundations in a very economical way comparing with traditional foundation concepts. Such advantages are due to the contribution of the raft to the load carrying capacity and to the efficient use of the piles to reduce settlement [1].

Some of the previous studies considered the most important factors that affect the load–settlement behavior of the piled raft foundation. Rajendra et al. [2] suggested that pile spacing has much effect on the maximum and differential settlement of the raft. OH et al. [3] carried out analysis on unpiled and piled raft foundation in sandy soil using PLAXIS software. They found that raft thickness does not affect significantly the load carrying capacity of the foundation. Luca and Alessandro [4] concluded that piled rafts provide an economical foundation option when the unpiled raft does not satisfy the design requirements. Hence, they suggested that addition of limited number of piles will improve the ultimate load capacity and settlement performance of the foundation. Poulos et al. [5] carried out 3D analysis of piled raft foundation of Incheon tower in South Korea subjected to horizontal and vertical loading using PLAXIS and the same is compared with pile group foundation system. They suggested that piled raft behaves safely in high raised buildings.

Therefore, it can be summarized that the settlement of piled raft foundation is a function of various parameters. The most important of these parameters are piles length, piles diameter, raft thickness, internal friction angle and vertical distributed load. In this paper, to study the effect of these parameters on the maximum settlement of piled raft foundation, numerical analyses have been carried out.

2 NUMERICAL MODELLING

Due to the complex interactions of piled raft foundations embedded in sandy soil, 3D finite element analyses are performed with finite element program "PLAXIS 3D" to investigate the load–settlement behavior of the foundation system. PLAXIS 3D is well suited finite element software which is specifically used for geotechnical applications. It is adapted perfectly to model the problems in several phases, like a sequence excavation, construction and loading. The soil behavior can be simulated accurately with advanced constitutive models. All the numerical analyses have been performed using "PLAXIS 3D CONNECT Edition V20". In this section, the main features of the finite element model employed are briefly summarized.

The first step of the modeling process is to define the model boundaries. Fig. 1 shows a typical section of the geometry for the finite element model used in this study to analyze the behavior of piled raft. Pile, raft, and soil are the main components of piled raft which should be modeled. The model boundaries are selected to avoid any influence of the outer boundaries. To eliminate boundaries effect, the lateral boundaries of the model are set at a distance equal to two

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times the raft width measured from the edge of the raft. The depth of the model is approximately two times the pile length.

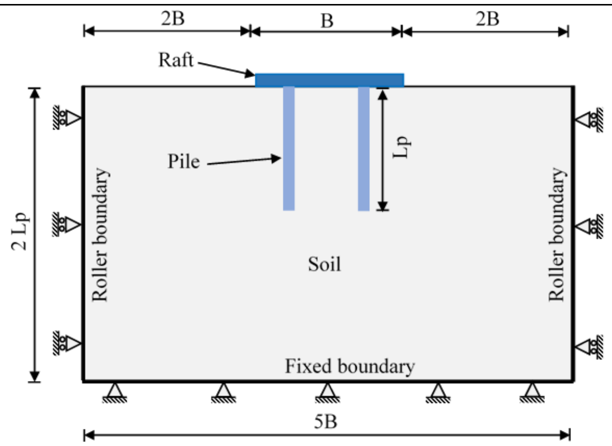

Fig. 1. A typical section of the geometry for the finite element model used in this study

The mechanical behavior of soil may be modeled at various degrees of accuracy. PLAXIS includes various types of constitutive models to simulate the behavior of materials. The elastic-perfectly plastic Mohr-Coulomb (MC) model is used to simulate the behavior of the soil. The structural elements including raft and piles are considered as isotropic elastic materials, so they are modeled by the linear elastic (LE) model in the analyses.

In this study, volume piles are used to model and simulate the behavior of piles. Volume pile comprises three-dimensional volume element, which interact with the surrounding soil by interface elements. Volume pile material properties are determined as a soil material with concrete properties. On the other hand, plate element is used to simulate the structure behavior of the raft.

Interfaces are used to modeling soil structure interaction. To simulate relative displacements between the soil and the structural elements, interface elements are used. The strength of the interface is related to the strength of the surrounding soil. The strength of the interaction is modeled by choosing a suitable value for the strength reduction factor (R_{inter}). For real soil-structure interaction the interface is weaker and more flexible than the surrounding soil, which means that the value of (R_{inter}) should be less than 1.0 [6].

The geometry must be divided into elements to perform finite element calculations. A composition of finite elements is called a mesh. The mesh should be sufficiently fine to obtain accurate numerical results. On the other hand, the increase in mesh density leads to excessive calculation times. PLAXIS 3D uses fully automatic generation of finite element meshes. Medium meshing is selected for the present numerical model.

3 Validation of Numerical Modelling

Validation is the only way to justify the predictions of a numerical model results to ensure that the problem is accurately modelled. The geotechnical centrifuge testing has the ability to simulate complicated soil-structure interaction for piled raft foundation. Centrifuge modelling is used as an effective physical modeling tool to replicate field conditions.

Several works such as Horikoshi et al. [7] used centrifuge modelling to evaluate the performance of piled raft foundations. PLAXIS 3D is validated by comparing the predicted load-settlement curve with observed data from centrifuge test.

The centrifuge test is conducted under 50 g centrifugal acceleration. Fig. 2 shows schematic the test setup used to evaluate the performance of the piled raft

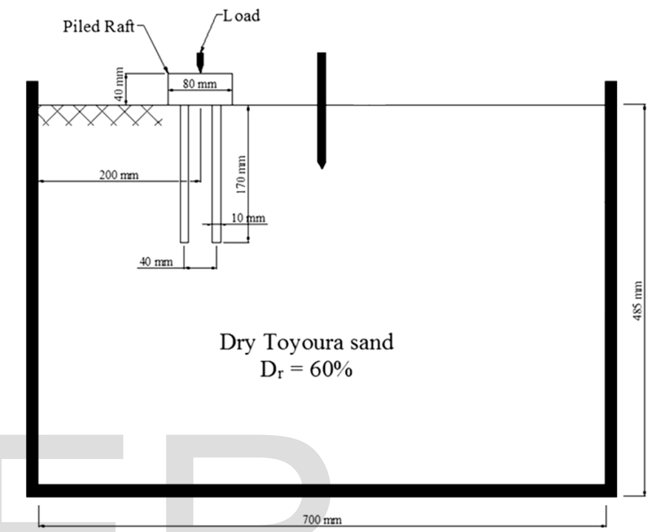

Fig. 2. Centrifuge test set up and the layout of piled raft [7]

The model consisted of four piles rigidly connected to the raft. The raft and the piles are made of aluminum. Toyoura sand with 60% relative density is used as the model ground. Table 1 shows the dimensions of the model in both model and prototype scales. The material of the piled raft model is different from the material for the prototype, which may affect the overall behavior. The axial stiffness is scaled correctly to satisfy the scaling laws for the centrifuge testing using the following scaling law:

$$\frac{(EA)_p}{(EA)_m} = n^2 \qquad (1)$$

where $(EA)_p$ and $(EA)_m$ are the axial rigidity for the prototype and the model, respectively, (n) is the scaling factor. The Load-settlement curve for the piled raft under vertical loading obtained from the centrifuge test is shown in Fig. 2.

A finite element analysis (FEA) is conducted using Plaxis 3D with the same geometry and dimensions as mentioned in Table 1. Only a quarter of the piled raft foundation is modeled taking advantage of the symmetry about the x and y-axes to reduce the size of model and the computation time. The boundaries of the model are set at a distance equal to two times the raft width measured from the edge of the raft. The depth of the model is approximately two times the pile length. The relatively small element size leads to high accuracy in results, so medium mesh is selected for the entire soil.

TABLE 1
THE DIMENSIONS OF THE MODEL IN BOTH MODEL AND PROTOTYPE SCALES [7]

	Symbols	Scaling laws	Prototype (n = 50)	Model
Diameter (mm)	D	1/n	500	10
Wall thickness (mm)	t_w	–	Solid	1
Materials	–	–	Concrete	Aluminum
Pile length	L_p	1/n	8.5 m	170 mm
Raft thickness	t	1/n	2.0 m	40 mm
Raft width (square)	B	1/n	4 m	80 mm
Pile Spacing	s	1/n	2 m	40 mm
Number of piles	–	–	4	4
Axial rigidity	EA	$1/n^2$	5 GN	2 × 10−3 GN

The Toyoura sand is modeled with Mohr-Coulomb model. Matsumoto et al. [8] reported that the maximum friction angle for Toyoura sand is about 45^0 and the reduction factor (R_{inter}) at the interaction surface between piles and Toyoura sand is 0.43 [7]. The raft and the piles are modeled with linear elastic model. The material properties used in the FEA for validation of centrifuge test conducted by Horikoshi are mentioned in Table 2.

TABLE 2
MATERIAL PROPERTIES USED IN VALIDATION

Parameter	Symbol	Toyoyra Sand	Raft and piles	Units
Material Model	-	Mohr-Coulomb	Linear Elastic	-
Drainage type	-	Drained	Drained	-
Unit weight	$\gamma_{sat}, \gamma_{unsat}$	14.9	25	kN/m^3
Poisson's ratio	ν	0.3	0.2	-
Young's modulus	E	4500	$25\ e^6$	kN/m^2
Increase in stiffness	E_{inc}	6500	-	$kN/m^2/m$
Reference level	z_{ref}	1	-	m
Effective cohesion	c	0.1	-	kN/m^2
Angle of internal friction	φ	38	-	Degrees
Angle of dilatancy	ψ	8	-	Degrees
Interface strength reduction	R_{inter}	0.43	-	-

A concentrated prescribed displacement of 20 cm is applied at the top center of the raft. This means that the piled raft is subjected to a certain displacement and the analysis is performed and the corresponding load is evaluated by the solver. The analysis of piled raft involved three phases; the first phase involved only the soil volume. The structural components and the interface elements are activated in the second phase. In the third phase, the prescribed displacement is applied.

Fig. 3 shows the comparison between the load-settlement curve obtained from the centrifuge test for piled raft supported by 4 piles carried out by Horikoshi et al. and predicted settlement using PLAXIS 3D model. Predictions of PLAXIS 3D model are in a reasonable agreement with measured results in the centrifuge test with minimum errors, so that this program can be used to analyze performance piled raft foundation.

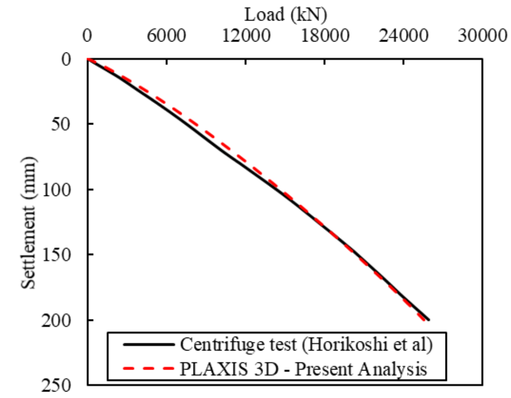

Fig. 3. Load-settlement curve obtained from the centrifuge test (Horikoshi et al. 2003b) and numerical analysis (PLAXIS 3D)

4 PARAMETRIC STUDY

A parametric study has been performed to investigate the effect of the most important parameters on the load–settlement behavior of piled raft foundation rested on sandy soil.

The studied subsoil is a homogeneous dry medium sand (Dr = 65 %), the properties of the subsoil as reported by Elwakil and Azzam [9] are shown in Table 3. The raft and piles are made of concrete. The elastic-perfectly plastic Mohr-Coulomb model is used to simulate the behavior of the soil, while the behavior of the structure elements, raft and piles, are modeled with linear elastic model. The material properties used in the finite element are summarized in Table 3.

TABLE 3
MATERIAL PROPERTIES CONSIDERED IN THE PARAMETRIC STUDY

Parameter	Symbol	Sand	Raft and piles	Units
Material Model	-	Mohr-Coulomb	Linear Elastic	-
Drainage type	-	Drained	Drained	-
Unit weight	$\gamma_{sat}, \gamma_{unsat}$	18.0	25	kN/m^3
Poisson's ratio	ν	0.3	0.15	-
Young's modulus	E	5000	$22\ e^6$	kN/m^2
Effective cohesion	c	0.1	-	kN/m^2
angle of internal friction	φ	35	-	Degrees
Angle of dilatancy	ψ	5	-	Degrees
Interface strength reduction	R_{inter}	0.67	-	-

The considered parameters in this study are the length of the pile (L_p), the diameter of the pile (d_p), the thickness of the raft (t_r) and the internal friction angle of the sand soil (ϕ). The studied parameters and their typical range values considered in this analysis are presented in Table 4.

To investigate the effect of these parameters on the load–settlement behavior of piled raft foundation, several models are carried out. These models consist of a square raft of plan dimensions 4.0 m × 4.0 m supported on 4 piles with pile spacing of 5 dp. The numerical analyses are performed on different piled raft models under a vertical uniformly distributed load of 200 kPa.

Due to the symmetry of the problem in both directions, only quarter of the geometry is modeled to reduce the size of the model and in turn to save computational time.

The analysis of piled raft foundations involved three stages, namely initial stage, construction stage and loading stage. In the initial stage, the soil domain is activated. Raft and piles are activated in the construction stage. In the loading stage, the applied load is activated.

TABLE 4

THE MAIN INFLUENCING PARAMETERS CONSIDERED IN THE PARAMETRIC STUDY

Parametric study	Raft dimensions		Pile group geometry				Internal friction angle (φ)
	$B \times L$ (m)	t_r (m)	S/d_p	n_p	d_p (m)	L_p (m)	
Pile length	4×4	0.6	5	2×2	0.4	B 2B 2.5B	35
Pile diameter	4×4	0.6	5	2×2	0.3 0.4 0.5	2B	35
Raft thickness	4×4	0.1 0.6 1.0	5	2×2	0.4	2B	35
Internal friction angle	4×4	0.6	5	2×2	0.4	2B	32 35 40

B: raft width, L: raft length, t_r: raft thickness,
S: pile spacing, d_p: pile diameter, n_p: number of piles,
L_p: pile length, φ: Internal friction angle

5 Results and Discussions

The effect of various parameters such as pile length (L_p), pile diameter (d_p), raft thickness (t_r) and the internal friction angle of subsoil (ϕ) on the behavior of piled raft foundation is described in detail in the following sections.

5.1 Effect of Pile Length

Analysis is performed on a square rigid raft of dimensions 4.0 m × 4.0 m × 0.6 m supported on 4 piles with pile spacing of 5 dp. All the piles have a diameter of 0.4 m. The pile length is varied by the following values 4.0 m (i.e., B), 8.0 m (i.e., 2B) and 10.0 m (i.e., 2.5B).

The settlement performance of piled raft foundation can be evaluated using a non-dimensional parameter, called the settlement efficiency ratio, which is defined according to Equation (2):

$$\eta = \frac{w_r - w_{pr}}{w_r} \quad (2)$$

where w_r and w_{pr} are the settlements of the unpiled raft and piled raft, respectively. Increasing the number of piles improves the settlement of the raft so that the values of w_{pr} are always smaller than w_r. Therefore, larger values for the settlement efficiency ratio means more efficient in reducing raft settlement.

It can be seen that, increasing the pile length leads to decrease in the maximum settlement of the piled raft as shown in Fig. 4. As pile length increases from B to 2.5B, the settlement efficiency increases by 34.7 % compared to the case of raft without piles as shown in Fig. 5.

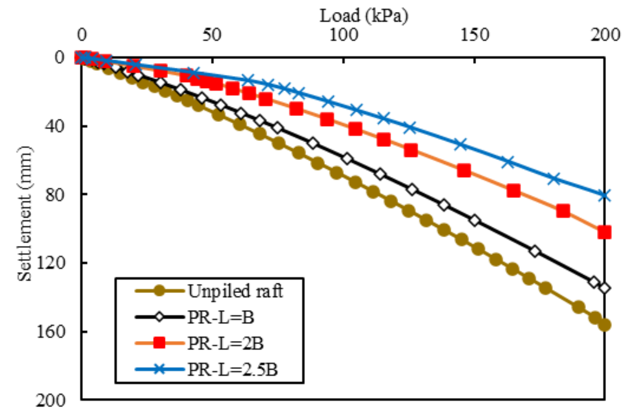

Fig. 4. Effect of pile length on load–settlement curve

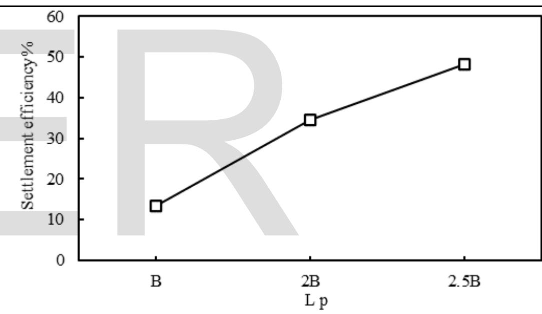

Fig. 5. Effect of pile length on settlement efficiency

5.2 Effect of Pile Diameter

Analysis is performed on square rigid raft of dimensions 4.0 m × 4.0 m × 0.6 m supported on 4 piles with pile spacing of 5 dp. The pile diameter (dp) is varied from 0.3 m to 0.5 m and the pile length is 8.0 m (i.e., 2B).

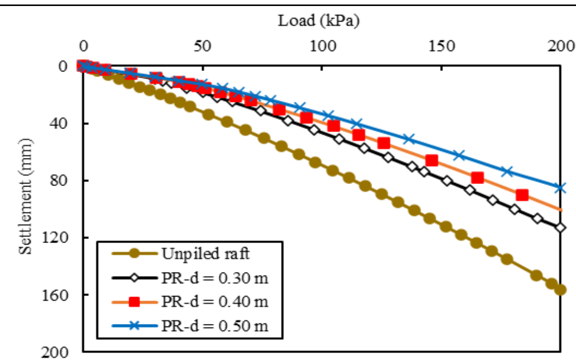

Fig. 6 Effect of pile diameter on load–settlement curve

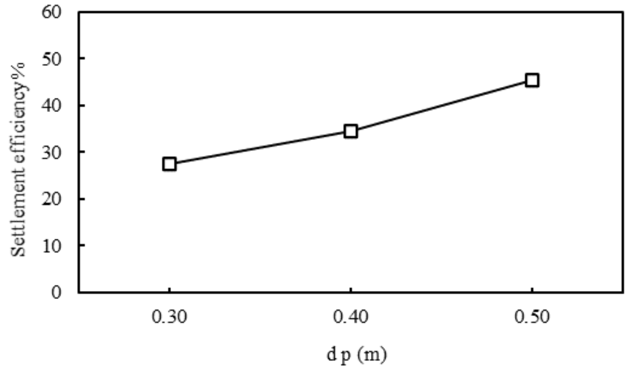

Fig. 7. Effect of pile diameter on settlement efficiency

It is noticed that, increasing the pile diameter causes decrease in the maximum settlement of the piled raft as shown in Fig. 6. By increasing pile diameter from 0.3 m to 0.5 m, the settlement efficiency increases by 17.9 % as shown in Fig. 7.

5.3 Effect of Raft Thickness

Analysis is performed on a square raft of plan dimensions 4.0 m × 4.0 m supported on 4 piles with pile spacing of 5 dp. All the piles have a diameter of 0.4 m and the pile length is 8.0 m (i.e., 2B). The thickness of the raft is varied from 0.1 m (i.e., representing fully flexible raft) to 1.0 m (i.e., representing fully rigid raft) as shown in table 5. The raft–soil stiffness (k_{rs}) can be estimated according to the following equation which proposed by Horikoshi and Randolph [10].

$$K_{rs} = 5.57 \frac{E_r}{E_s} \left(\frac{1 - \nu_s^2}{1 - \nu_r^2} \right) \left(\frac{B}{L} \right)^{0.5} \left(\frac{t_r}{L} \right)^3 \quad (3)$$

where E_r and E_s are Young's moduli of the raft and the soil, respectively, v_r and v_s are Poisson's ratio of the raft and the soil, respectively, t_r is the thickness of the raft, B and L are the width and the length of the rectangular raft, respectively. According to (Horikoshi & Randolph 1997) [10], the raft is fully flexible when k_{rs} is smaller than 1.0, and the raft is fully rigid when k_{rs} is greater than 10.

TABLE 5

THICKNESS OF RAFT MODELS AND THE CORRESPONDING RAFT–SOIL STIFFNESS

Raft models	Thickness value (m)	Raft–soil stiffness (K_{rs})
Fully flexible	0.10	0.37
Rigid	0.60	77.0
Fully rigid	1.00	616

It is noticed that, increasing the raft thickness has almost no effect on the maximum settlement of the piled raft and on the settlement efficiency as shown in Figs. 8 and 9.

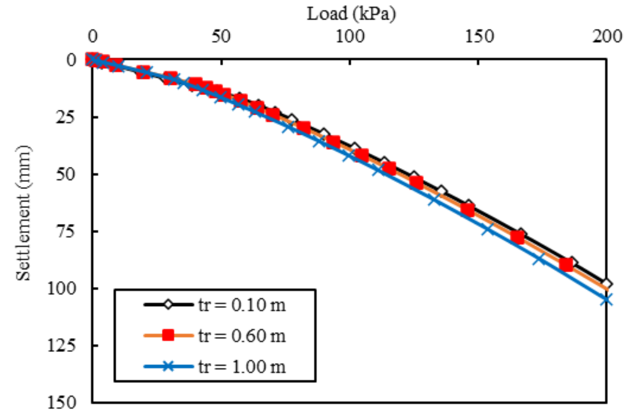

Fig. 8 Effect of raft thickness on load–settlement curve

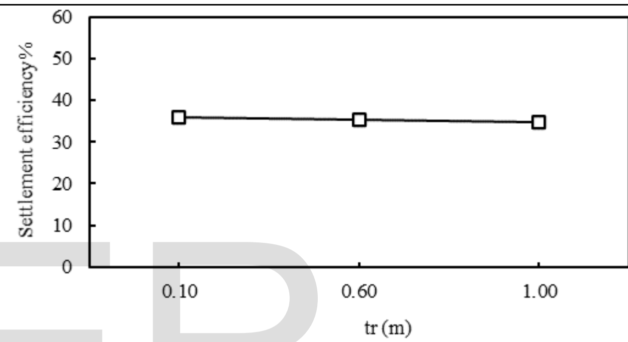

Fig. 9 Effect of raft thickness on settlement efficiency

5.4 Effect of Internal Friction Angle of Subsoil

Analysis is performed on a square rigid raft of dimensions 4.0 m × 4.0 m × 0.6 m supported on 4 piles with pile spacing of 5 dp. All the piles have a diameter of 0.4 m and the pile length is 8.0 m (i.e., 2B). The effect of soil internal friction angle of the subsoil on the settlement of piled raft foundation is shown in Fig. 10. This analysis is carried out by considering amounts of 32^o (i.e., representing loose sand), 35^o and 40^o (i.e., representing dense sand) for internal friction angle of subsoil.

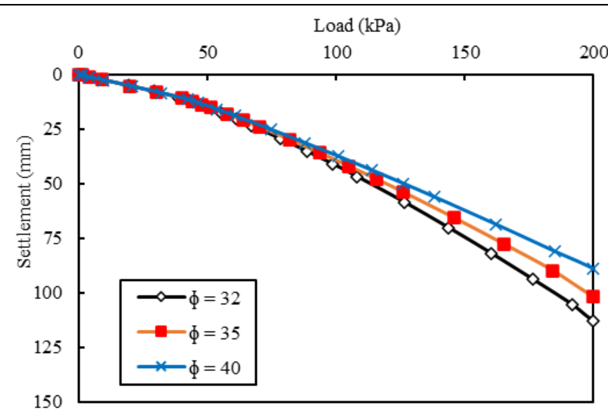

Fig. 10 Effect of internal friction angle of subsoil on load–settlement curve

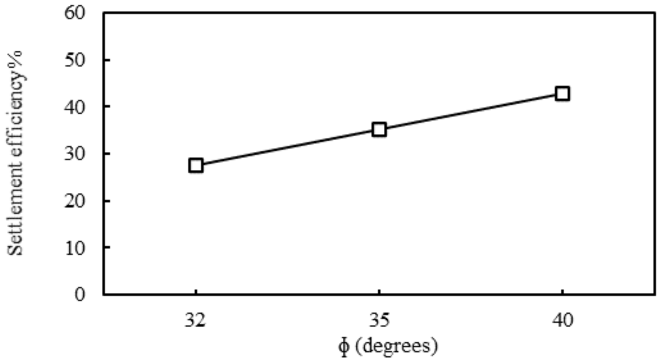

Fig. 11 Effect of internal friction angle of subsoil on settlement efficiency

As shown in Fig. 10, increasing soil internal friction angle leads to decrease in maximum the settlement of piled raft foundation. By increasing internal friction angle of subsoil from 32º m to 40º m, the settlement efficiency increases by 15.4 % as shown in Fig. 11.

6 Conclusion

A series of 3-D numerical analysis is performed to investigate the effect of pile length, pile diameter, the thickness of the raft and the internal friction angle of the sand soil on the load–settlement behavior of piled raft foundation rested on sandy soil under uniform vertical load. The main conclusions can be summarized as follows:

- The pile length has a marked effect on the load–settlement behavior of piled raft foundation. The settlement of the raft decreases with increase in pile length.
- The pile diameter also plays an important role in reduction of the raft settlement. Increase in pile diameter shows a decrease in maximum settlement.
- The raft thickness almost has no effect on the settlement of the raft.
- Increasing the internal friction angle of subsoil leads to significant reduction in the settlement of raft.

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