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3D Modeling of Piled Raft Foundation Subjected To Vertical Loading

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Abstract: In recent years large number of mega projects were constructed using the piled raft foundation system concept. hence a noticeable attention have been drawn toward better understanding of the performance of piled raft foundation systems subjected to vertical loading. Piled raft foundations have a complex soil-structure interaction scheme including the pile-soil interaction, pile-pile interaction, raft-soil interaction, and finally the pile-raft interaction. Consequently, there is a need for 3D numerical models that is capable of studying this complex interaction. In this paper, a 3D finite element model was verified using published geotechnical centrifuge test data. The study was performed on cohesionless soil with linearly increasing stiffness with depth. The developed 3D model was able to capture the behavior of the piled raft foundation system. In addition, an extended parametric study in which the effect of different parameters, such as pile spacing, piled diameter, raft width, and raft thickness on the overall behaviour of a piled raft was conducted.

Keywords: piled raft foundation, soil-structure interaction, 3D FEM, centrifuge, cohesionless soil

1 Introduction

A piled raft foundation is a composite structure with three components: subsoil, raft and pile. These components are related to each other through a complex soil-structure interaction scheme, including the pile-soil interaction, pile-pile interaction, raft-soil interaction, and finally the pile-raft interaction.

Generally, the construction of a piled raft foundation system is similar to the current practices used to construct a pile group foundation in which a cap is normally cast directly on the ground. Although this installation of a cap will allow a significant percentage of the load to be transmitted directly from the cap to the ground, the pile group is usually designed conservatively by ignoring the bearing capacity of the raft (in this case the pile cap). The raft alone can provide an adequate bearing capacity; however, it may induce excessive settlement. Therefore, the concept of settlement reducer piles was presented by Burland et al. (1977) in which the piles are used to limit the average and differential settlements.

The vertical load applied to a piled raft foundation is transmitted to the ground by both the raft and the pile in the pile raft foundation. This fact is the major difference between the piled raft and the pile group. The percentage of load each element carries depends on a number of factors, such as the spacing of piles, the number of piles, subsoil, and the thickness and stiffness of the raft.

A piled raft foundation has some advantages over the pile group in terms of the design and from a serviceability and economic point of view. They include the following: (i) a piled raft foundation will require fewer piles in comparison to a pile group to satisfy the same design requirements; this will lead to a more economical design; (ii) for a piled raft, the piles will provide sufficient stiffness to control the settlement and differential settlement at serviceability load; and the raft will provide additional capacity at ultimate load; (iii) in case any piles in the piled raft become defective, the raft allows re-distribution of the load from the damaged piles to the other piles (Poulos et al. 2011); (iv) a raft in the piled raft foundation can carry 30% to 50% of the applied load and transmit to the soil (Clancy and Randolph, 1993); and (v) the pressure applied from the raft to the subsoil may increase the lateral stress between underlying piles and the soil, which can increase the pile bearing capacity accordingly compared to the piles in a pile group (Katzenbach et al. 1998).

A number of methods were proposed using different analytical, numerical and physical modeling approaches to evaluate the performance of piled raft foundation , including the following: (i) a simplified PDR in which the Poulos and Davis (1980) method as well as Randolph (1994) are combined (Poulos 2001); (ii) a plates-on-spring method in which the raft is represented by plates and the piles by springs (Clancy and Randolph 1993); (iii) methods based on combining the finite element analysis for the raft and the boundary element analysis for the piles (Ta and Small 1996); (iv) methods based on a three-dimensional finite elements analysis (Katzenbach et al.1998); and (v) geotechnical centrifuge technology which has been used to evaluate the performance of piled raft loading under vertical, lateral and seismic loading (Horikoshi et al. 2002, 2003a, b, Matsumoto et al. 2004a, b).

A finite element model (FEM) was created as part of this study in order to simulate the centrifuge results of a piled raft foundation under vertical loading; this model will be used in future work to evaluate the performance of a piled raft foundation, and the load sharing in particular will be investigated using this calibrated, verified and rigorous 3D finite element model. Moreover, the effect of the raft thickness in load sharing between piled raft components was investigated.

2 Objectives

A geotechnical centrifuge test is capable of producing very accurate results that represent the real behaviour of a prototype in the field. This is due to the fact that vertical and horizontal stresses in geotechnical centrifuge are similar to the stresses in the field. Since soil parameters are influenced by the surrounding stress, matching the field stress will produce more realistic model behaviour compared to the prototype behaviour. Another great tool that is capable of modeling the behaviour of soil and structural elements accurately is a finite element analysis (FEA); however, in order to increase the confidence in FEM to accurately simulate the problem, it is very necessary to calibrate the FEM. Using a calibrated FEM is a great tool in performing an extended parametric study in the most accurate and economic way.

In this paper, the aim was to accurately simulate the behaviour of a piled raft foundation numerically using a 3D FEM. This objective was achieved by calibrating the FEM using centrifuge results for a piled raft model. It is very important for the calibrated model to be able to predict the stresses in the pile, raft and soil that are similar to the stresses in the field; by achieving this, the results obtained from a FEM will be representative of the field results. This calibrated model was used to conduct an extended parametric study in which the effect of different parameters, such as pile spacing, piled diameter, raft width, and raft thickness on the overall behaviour of a piled raft was investigated.

3 Centrifuge Testing

Geotechnical centrifuge testing has the ability to model very complicated problems such as the soil-structure interaction for a piled raft. Horikoshi et al. (2002, 2003a, b) used this technology to evaluate the performance of a piled raft under different types of loading: vertical; horizontal and dynamic loading. The results of the vertical loading test were used to calibrate the 3D finite element model for the current investigation. The tests were conducted under 50g centrifugal acceleration and all the model parts were made of aluminum. The model consisted of four piles rigidly connected to the raft. Toyoura sand was used as the model ground (Horikoshi et al. 2003a). Table 1 summarizes the dimensions of the model in both model and prototype scales. Although the material of piled raft model is different than the material for the prototype, the axial stiffness is scaled correctly which will satisfy the scaling laws for the centrifuge testing using the following scaling law:

[2] $\frac{EA_p}{EA_m} = n^2$

Horikoshi et al. (2003a) performed cone penetration tests (CPT) during the geotechnical centrifuge testing to evaluate the sand strength. The test was performed using an in-flight miniature cone penetration (see Figure 1). The strength was increased with depth which is normal for sand soil. These results are very important and were used to evaluate the FEM input parameters such as the initial modulus of elasticity and the incremental modulus of elasticity which took into account the increase in stiffness with depth. The piles were instrumented with foil strain gauges in order to estimate the load carried by the piles as well as the load carried by the raft. The load-displacement curve for the piled raft foundation under vertical loading obtained from the centrifuge test is shown in Figure 4 in the prototype scale. In addition, Figure 5 shows the percentage of the load carried by each component in the piled raft.

Table 1. The dimensions of the model in both model and prototype scales.

	Symbols	Model	Prototype (n=50)
Diameter (mm)	D	10	500
Wall thickness (mm)	t_w	1	Solid
Materials	-	Aluminum	Concrete
Pile length	L_p	170 mm	8.5 m
Modulus of Elasticity	E_o	71 GPa	41.7 GPa
Raft thickness	t	40 mm	2.0 m
Raft width (square)	B	80 mm	4 m
Pile Spacing	s	40 mm	2 m
Number of piles	-	4	4
Axial rigidity	EA	$2x10^{-3}$ GN	5 GN

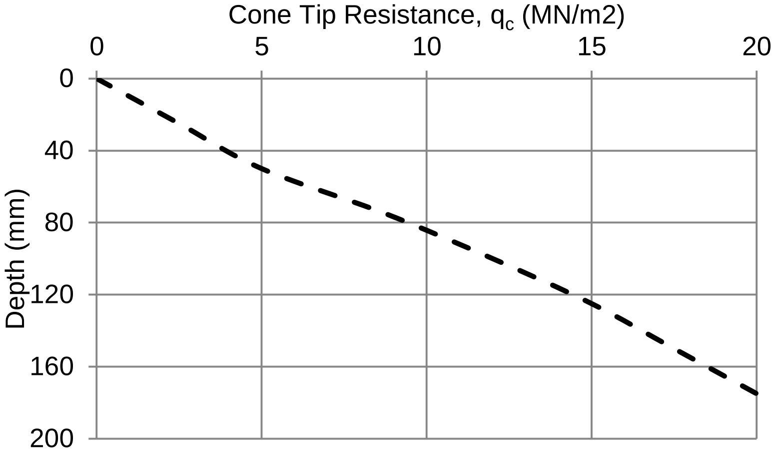

Figure 1. In-flight results for CPT (after Horikoshi et al. (2003a).

4 3D Finite Element Model and 3D FEM Calibration

A finite element analysis (FEA) was carried out using the Plaxis 3D v.2011 software package (Plaxis bv. 2011). A quarter of the piled raft was modeled taking advantage of the similarity across the x and y-axes. The boundaries of the model were set at a distance equal to 1.5b~2b measured from the edge of the raft, and the depth of the model was approximately two times the pile length (see Figure 2). The model was built using about 275,000 3D 10-node tetrahedral elements. The average size of the element was approximately 110 mm. The reason for using this large amount of elements with very small size was to assure high accuracy of the results at locations where non-linearity behavior was anticipated, such as at the raft base, pile base and pile circumference. The interface elements in Plaxis 3D, which was used to model the contact between the soil and the structural elements, allows for both slipping and gapping to occur (Plaxis bv. 2011). The gapping will allows the raft to contribute in transferring the load to the soil and slipping will allows the piles to transfer the load to the soil.

The load was applied using uniform prescribed displacement applied at the top of the raft in which the piled raft was subjected to a certain displacement and the solver obtained the corresponding load (i.e. uniformly distributed load). The analysis was performed using 3 phases: the first phase the was initial phase in which the in-situ stress was calculated and the structural components were not activated; the second phase activated the structural components and soil-structure interface without applying the load in order to restore the equilibrium by solving any out-of-balance force (Plaxis bv. 2011); the third phase applied the prescribed displacement.

The Toyoura sand was modeled using a linear elastic perfectly plastic Mohr-Coulomb constitutive model. Matsumoto et al. (2004b) reported that the maximum friction angle,ϕ_{max}, for Toyoura sand is about 45°and the reduction factor, R_{int}, at the interaction surface between piles and Toyoura sand is 0.43 (Horikoshi et al. 2003a). In the FEM, the angle of internal friction, ϕ, was used as 31° and the Dilation angle was used as 14°. The modulus of elasticity was estimated using the correlation that relates the cone tip resistance, q_c, with the modulus of elasticity, according to Tomlinson (1996) (see Eq.2). All the FEM input parameters for both the initial and the final models are listed in Table 2.

[2] $E = 2{\sim}4\ q_c$

In the initial trials, the soil was modeled using an average modulus of elasticity which led to very high error in the load-displacement curve between the FEM and the centrifuge test. However, by using the advanced function in Plaxis 3D that allows to increase the stiffness of the soil with depth (see Eq. 3), the results were improved dramatically. Moreover, after a number of trials and adjusting the stiffness and strength properties of the soil and interface elements, the FEM was capable of simulating the centrifuge test results with minor errors (see Figure 4). Moreover, the FEM successfully simulated the stress distribution across the model; therefore the load carried by each component in the piled raft (from FEM) was similar to the one evaluated in the centrifuge test with minimum errors (see Figure 5).

[3] $E(\acute{z}) = \acute{E}_o + (z_{ref} - z)\acute{E}_{inc} \qquad z < z_{ref}$

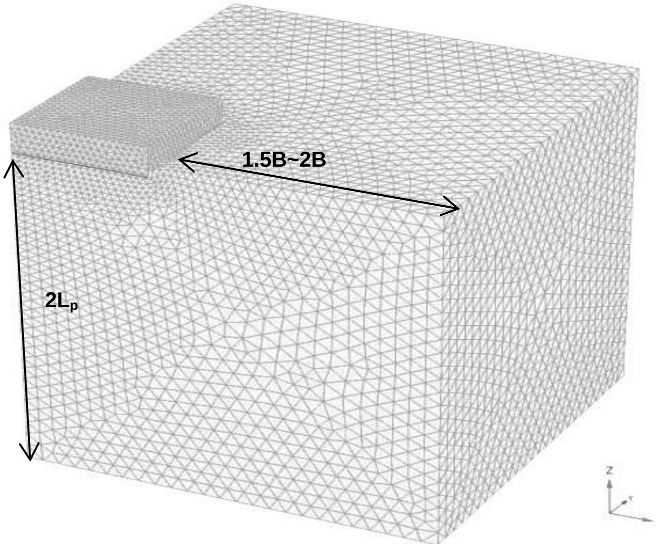

Figure 2. The FEM used in the current study.

Table 2. The parameters used in the FEA.

	Symbols	Soil		Concrete
		Initial FEA	Final FEA	
Constitutive Modeling	-	Mohr-Coulomb	Mohr-Coulomb	Linear Elastic
Unit Weight (kN/m^3)	γ_d	14.6	14.6	23.6
Angle of internal friction	ϕ	36°	31°	-
Dilation angle	ψ	7°	14°	-
Average Modulus of Elasticity		30000 kN/m^2	-	23.6 GN/m^2
Initial Modulus of Elasticity	E_o	-	4500 kN/m^2	-
Reference Depth	z_{ref}	-	1 m	-
Stiffness increases with depth	-	No	Yes	No
Incremental Modulus of Elasticity (kN/m^2/m)	E_{inc}	-	6500	-
Poisson's ratio	ν	0.175	0.175	0.21
Interface reduction factor	R_{intr}	0.43	0.43	-

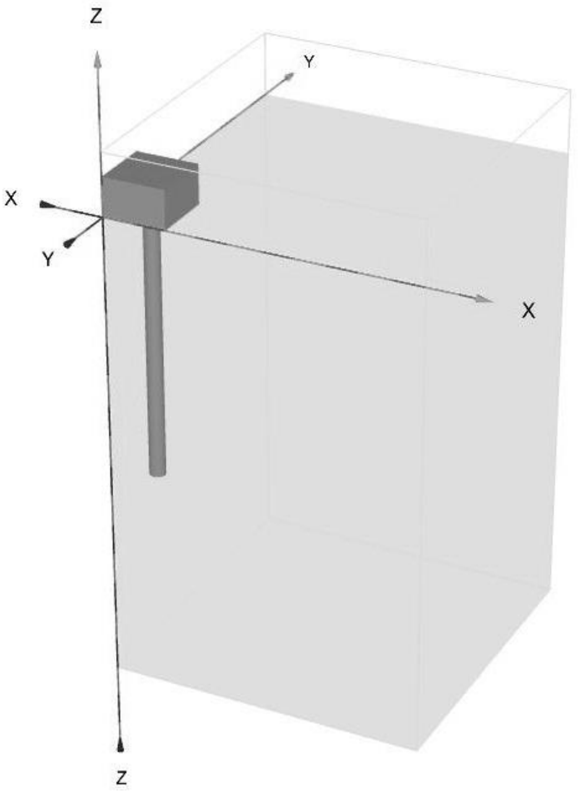

Figure 3. The 3D structural elements of FEM.

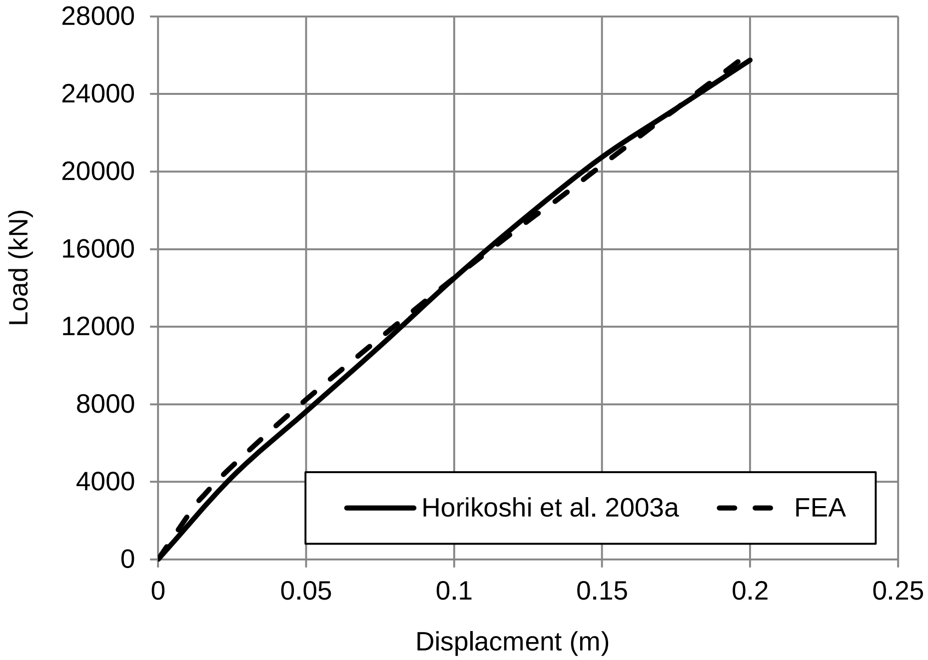

Figure 4. Comparison of the FEA results with the data obtained from the centrifuge test.

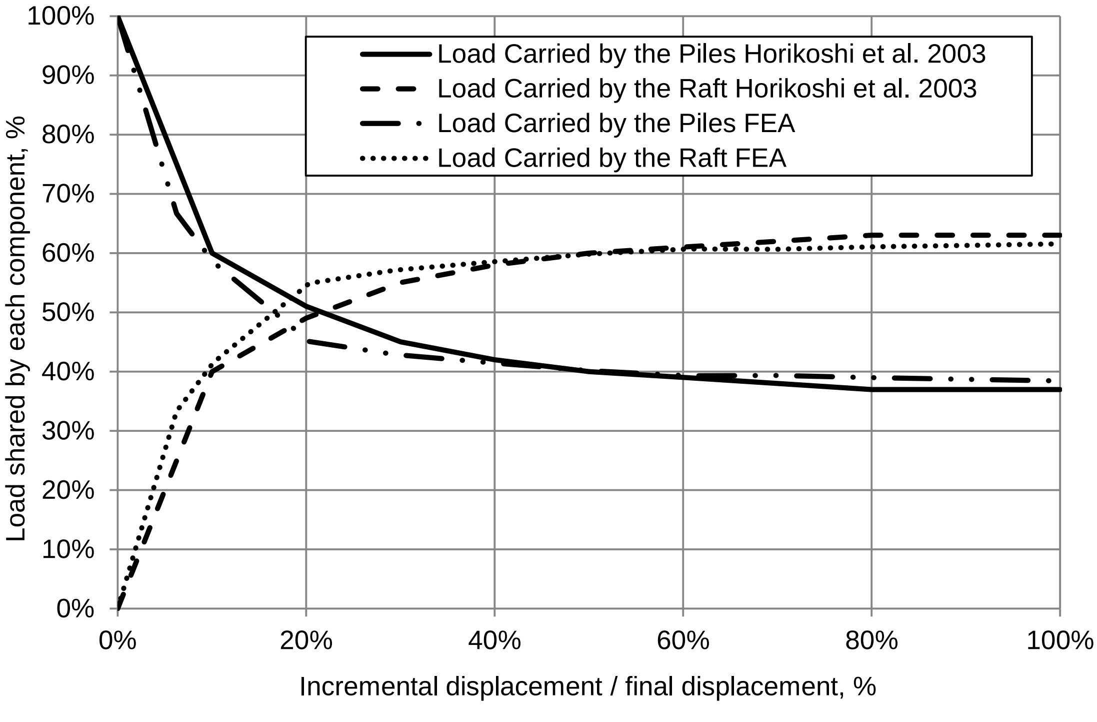

Figure 5. Comparison of the load carried by each component from FEA results with the data obtained from the centrifuge test.

5 Parametric Study

Different factors will affect the load sharing between the raft and piles, and these factors vary between low impact to high impact on the load sharing in a piled raft foundation and the stress distribution in the raft. Many of these factors were investigated. A future comprehensive FEA study will be conducted that will allow a better understanding of the effects of these parameters on the overall performance of a piled raft foundation system. The results of this FEA plan will be presented in future publications; however, some of the results is presented in this paper. Understanding the exact effect of these parameters will help to produce a more suitable design for the piled raft foundation. In this paper, the effect of the flexibility of the raft on load sharing between the raft and the piles, which is normally influenced by the thickness of the raft and spacing between the piles, was studied. All of the load carried by the raft will be presented as a percentage of the total vertical load applied on the piled raft foundation system.

5.1 Effect of raft thickness

There is a direct relationship between the thickness of a raft and its flexibility (see Eq. 4). Thin or flexible rafts tend to deform more than rigid or thick rafts; due to this excessive deformation, the flexible raft establishes much more deformation in the subsoil which leads to more load transferred by the raft and this will induce higher reaction force. Brown (1969) introduced the foundation flexibility based on a finite element analysis. Although Eq. 4 is for a shallow foundation, it was used for the piled raft by using spacing between the piles instead of the raft width, B. This is because the spacing between piles is more accurate in representing the flexibility of the piled raft. Furthermore, the piled raft with small pile spacing will not experience a large deformation at the center of the raft compared to the piled raft with large pile spacing.

$$[4] \quad K_f = \left[{E_f}/{E_s} \right] \left(\frac{2t}{s} \right)^3$$

Where E_f = Young's modulus for the raft; E_s = average soil elastic modulus; t = raft thickness; and s = spacing between piles.

The raft can be characterized according to the following conditions: (i) perfectly rigid if $K_f > 10$; (ii) perfectly flexible when $K_f < 0.01$; and (iii) intermediate flexibility if K_f varies between 0.01 to 10 (Mayne and Poulos 1999). Figures 6 and 7 show the load carried by the raft for two different pile spacing with various raft thicknesses as a function of the piled raft total displacement. At initial displacement, most of the load is carried by the piles; this is believed to be because the piles are in direct contact to the soil due to the confinement pressures and when the piles start to move the pile-soil interface will increase the strains at the pile base, reaching plastic condition. This piles movement resulted in more intimate contact between the raft and soil, which resulted in a portion of the load to be transmitted through the contact at the raft-soil interface; comparable behavior was reported by Horikoshi and Randolph (1996). Subsequently, the proportion of the load carried by the raft was increased significantly at about 7% of the total displacement and the increase was gradual beyond 7% point. At about 80% of displacement the load transmitted by the raft became almost constant. The variation in load carried by the raft was very noticeable at S/D=4 as the load carried by the raft was about 65% and 55% for the t= 0.3 m and t= 2 m respectively. This is due to a high difference in K_f which was about 0.05 and 2.2 for the t= 0.3 m and t= 2 m respectively. On the other hand, K_f was very close in the case of S/D=10 which is about 0.004 and 0.07 for the t= 0.3 m and t= 1.25 m respectively. Therefore, the variation in load carried by the raft was very narrow at about 75%. This is because at large spacing, the thick raft is more flexible, which produces much raft soil interaction, compared to the similar raft with less pile spacing. Poulos (2001) reported a similar percentage of 75% of the load carried by the raft.

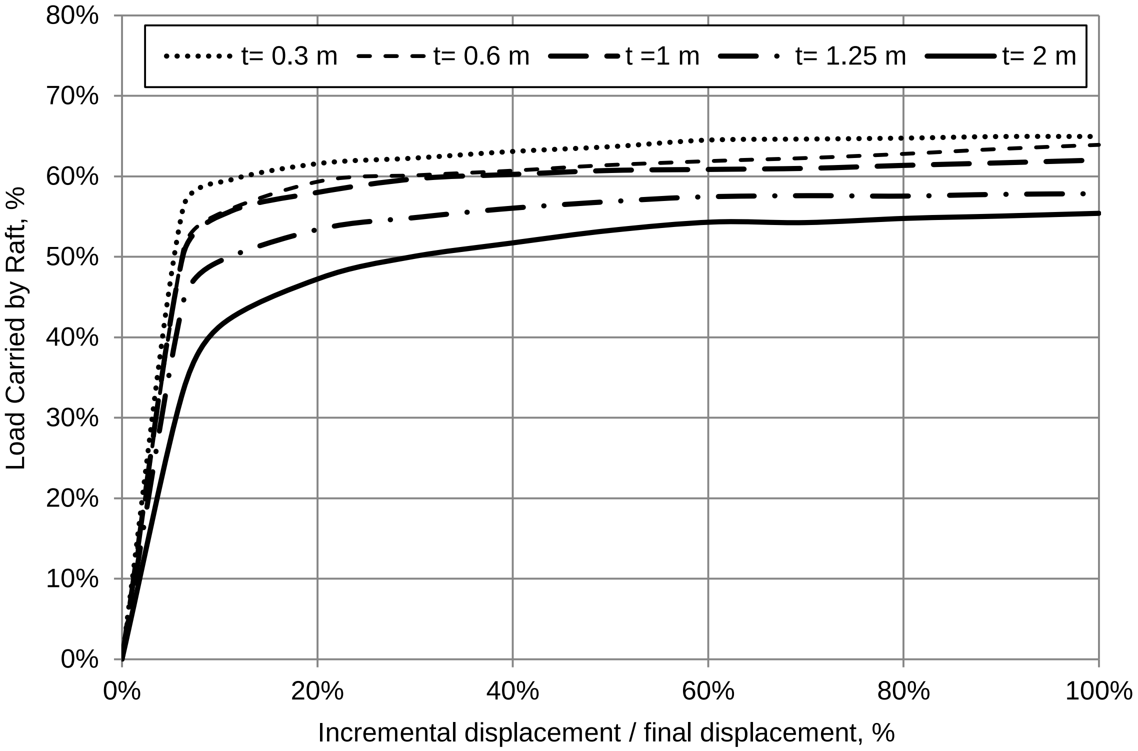

Figure 6. Load carried by raft with different raft thicknesses and S/D=4.

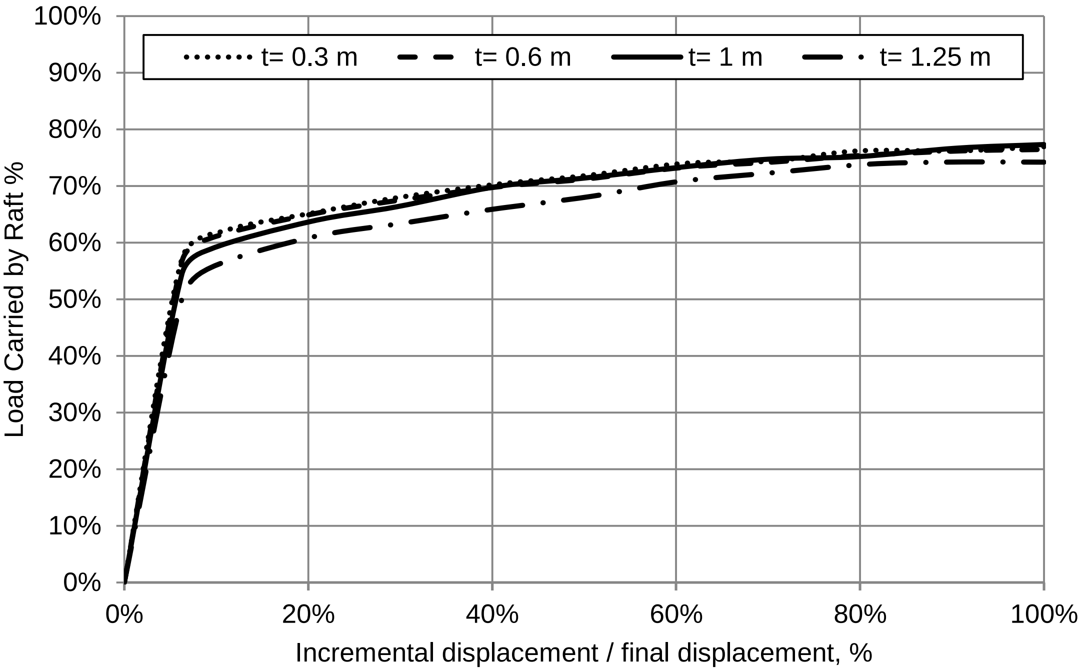

Figure 7. Load carried by raft with different raft thicknesses and S/D=10.

6 Conclusions

The FEM created in this study was able to simulate the results of a centrifuge test for a piled raft foundation under vertical loading; furthermore, the load for each components obtained from the FEM were similar to the loads in the centrifuge model. A number of factors that affect the load carried by the piled raft components will be examined in future studies using this rigorous 3D finite element model that has been calibrated and verified according to geotechnical centrifuge results. Based on the results of the 3D-FEA, the effect of raft thickness on load carried by raft was evaluated and the following conclusions can be drawn: (i) the load carried by the raft is lower for a rigid raft ($K_f > 10$) due to the small interaction between the raft and subsoil compared to the perfectly flexible raft ($K_f < 0.01$); (ii) using the spacing instead of raft width Eq. 4 yields more accuracies in representing the flexibility of the piled raft. More detailed work has to be conducted to evaluate the performance of a flexible piled raft under different circumstances such as the number of piles, pile length, different soil layers and loading scheme.

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