Numerical Analysis of Piled Raft Foundation on Clayey Soil

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ABSTRACT

The piled raft foundations allow an increase in the load capacity and reduction of settlements in a very economic way as compared with the traditional foundation concepts. Due to the development of structures that use piled rafts as a foundation system, an extensive numerical modeling study was performed considering different factors and conditions. This study highlights the percentage ratio of bearing loads between the pile and the pile cap (raft). Present modeling results obtained by computer program (Plaxis 3D Foundation V 1.1) have been verified with an experimental work of the same problem using the same configuration but extended to include 8 and 16 piles with raft for different soil layers. In addition, a comparison of the present results is achieved with another a theoretical study using the program (Ansys). The finite element method through Plaxis program evaluates the effect of parameter on the load-settlement behavior of the piled raft foundation. The effect of spacing between piles on the load-settlement behavior of the piled raft foundation was also studied. The percentage of the load carried by piles to the total applied load of the numerical model for case sixteen piles with raft is around 42%. The contribution to carry the load of piles relative to the total load is decrease with the increase of the spacing to diameter ratio. The percentage of the load carrying for piled raft for the case of two piles with raft only decreases about 23% when the spacing between piles increases from 3 to 10 times pile diameters.

keywords: Numerical Modeling; Piled Raft Foundations; Load-Settlement Behavior; Load Carrying Capacity; Settlement; Clayey Soils

التحليل العددي للأساس الحصيري المدعم بالركائز في التربة الطينية

الخلاصة

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ان الأسس الحصيرية المدعمة بالركائز تسمح بزيادة التحمل و تقليل الهطول وبشكل اقتصادي بالمقارنة مع مجاميع الأسس التقليدية. ونتيجة التطور الحاصل في التراكيب المستخدمة للأسس الحصيرية المدعمة بالركائز, أجريت هذه الدراسة النمذجية أخذين بنظر الاعتبار عوامل وظروف مختلفة. تسلط الدراسة الحالية الضوء على النسبة المئوية للتحمل ما بين الركيزة والأساس. تم التحقق من نتائج النمذجة الحالية المستحصل عليها باستخدام برنامج (PLAXIS 3D Foundation V 1.1) من خلال مقارنتها مع عمل مختبري يعالج نفس المشكلة وبنفس الترتيب وتم حل النموذج مع اضافة حالتين هما ٨ و ١٦ ركيزة مع الأساس و لطبقات تربة مختلفة. وبالإضافة إلى ذلك، تم إجراء مقارنة اخرى بين النتائج الحالية مع دراسة نظرية باستخدام برنامج (ANSYS). تهدف البرامج التي تعتمد طريقة العناصر المحددة من خلال برنامج (PLAXIS) الى تقييم تأثيرسلوك علاقة الحمل- الهطول للأسس الحصيرية المدعمة بالركائز. كما درس تأثير المسافة بين الركائز على هذه العلاقة. وجدت النسبة المؤية لقابلية تحمل الركائز الى الحمل الكلي في النموذج النظري لحالة ستة عشر ركيزة مع الاساس هي بحدود 42 %. وتبين من الدراسة أن مقدار مساهمة الركائز في قابلية التحمل الكلية تقل بزيادة المسافة بين الركائز. وقد وجد في حالة ركيزيتين مع الأساس الحصيري تقل قابلية التحمل بمقدار ٢٣ % مع زيادة المسافة بين الركائز من ثلاثة أضعاف الى عشرة أضعاف قطر الركيزة.

INTRODUCTION

A piled raft foundation is a new concept in which the total load coming from the superstructure is partly shared by the raft through contact with soil and the remaining load is shared by piles through skin friction. Such piled raft foundations on thick clay deposits have been found successful in places like coastal belt of Frankfurt and London. In conventional piled foundation (Figure 1), it is assumed that the raft does not carry any load even if raft is in contact with ground [1].

Also in conventional piled foundation, as the contribution of raft is ignored, long piles are provided which extends up to the deep strata. On the other hand, if only raft has to carry the total load coming from the superstructure, very thick raft is needed which increase the cost of the foundation [2]. Such raft foundation undergoes excessive settlement. In such a condition piled raft foundation can be considered a best solution in which shorter piles and raft of lesser thickness can be provided [3]. Piled raft foundations are classified on the basis of the design requirements to be satisfied into two main types. Russo and Viggiani (1998) [4] grouped piled rafts into two broad categories: small piled rafts and large piled rafts.

The present article highlights the percentage ratio of the bearing loads between the piles and the pile cap (raft). The finite element method through a PLAXIS 3D-Foundation (V 1.1) program is used to evaluate the effect of some parameters, such as the spacing between piles and the pile number, on the load-settlement behavior of the piled raft foundation.

PREVIOUS STUDIES

Poulos (1994) [5] employed a finite difference method via program GARP (Geotechnical Analysis of Raft with Piles) for the plate and has allowed for the various interactions via approximate elastic solutions.

Maharaj (1996) [6] reported the linear and nonlinear three dimensional finite element analysis of piled raft foundation using ANSYS software. Three models of piled raft foundation are analyzed. The raft, pile and soil have been discretized as eight nodded brick finite elements.

Prakoso and Kulhawy (2001) [7] analysed piled raft foundations using linear elastic and non-linear plane strain finite element models. The analysis was performed by PLAXIS and six noded triangular elements were used to model the piled raft and the soil.

Seo and Cho (2003) [8] considered the behavior of piled raft foundation and soil system using PLAXIS software. For the element type, six node triangular elements were used. The contact between the raft and the soil is assumed to be frictionless.

Chow (2007) [9] developed a numerical method for the analysis of piled rafts with piles of different lengths and diameters using the finite layer method for the analysis of the layered soil and the finite element method for the analysis of the piles and the raft.

Engin (2008) [10] studied embedded pile model using PLAXIS 3D Foundation Program. In the numerical analyses, the pile group behavior is considered by applying embedded piles onto idealized problems.

Al-Zayadi (2010) [11] used the numerical modeling of the piled raft problem by the finite element method through the program ABAQUS. It is found that: in comparison to shallow (raft) foundations, piled rafts reduce effectively the settlements; and the average load carried by piles depends on the number of piles in the group.

El Sawwaf (2010) [12] studied the effectiveness of using short piles either connected or unconnected to the raft (instead of long piles) on the behavior of an eccentrically loaded raft. The load configuration was designed to simulate rafts under vertical loads and over turning moment.

Al-Tameemi (2011) [13] investigated the behavior of piled raft system in different types of sandy soil. It is found that when the number of piles within the group is four or less, there is no evident of raft contribution to the load carrying capacity. The failure load for a piled raft is greater than free standing pile group containing the same number of piles.

FINITE ELEMENT ANALYSIS

The finite element method is one of the most popular numerical methods used for obtaining an approximate solution for complex problems in various fields of engineering. At the beginning, the method is developed as an extension of a matrix method for the analysis of structural engineering problems. However, later it has also been recognized as the most powerful method for analyzing problems in other fields of engineering, such as fluid mechanics, soil mechanics, rock mechanics, heat flow, etc. The generation of its application coupled with the availability of high-speed electronic digital computer has put the finite element method in a wide range of use.

In the finite element method, a continuum is divided into a number of elements. Each element consists of a number of nodes, and each node has a number of degrees of freedom that correspond to discrete values of the unknowns in the boundary value problem to be solved. In the present case, the degrees of freedom correspond to the displacement components. The basic of the finite element equation for elastic analyses can be written as (Zienkiewicz and Taylor, 2005) [14]:

$$[K]\,\{\delta\}=\{F\} \qquad \dots (1)$$

where:

[K] = stiffness matrix,

{δ} = vector of unknown nodal displacements, and

{F} = nodal forces due to external applied traction.

$$\{u\} = \{N\}\{\delta\} \qquad \ldots \quad (2)$$

Where:

{u} = the displacement vector,

{N}= the shape function vector of the element

$$\{\varepsilon\} = [B]\ \{\delta\} \qquad \ldots \quad (3)$$

where:

{ε} = the strain vector,

[B] = the strain – displacement matrix.

$$\{\sigma\} = [D]\ \{\varepsilon\} \qquad \ldots \quad (4)$$

Where:

{σ} = the stress vector

[D] = the stress – strain matrix

PLAXIS 3D Foundation Program

The computer oriented finite element method has become one of the most powerful tools in the analyses of engineering problems. In the present work, the PLAXIS Structural Static Analysis has been adopted for numerical modeling of the structural response.

PLAXIS 3D Foundation is a high-performance software package developed by Vermeer and Brinkgreve (1995) [15] is used. It enables nonlinear, static and many types of analysis for a large spectrum of engineering problems. The PLAXIS program provides embedded pile model in which the pile is assumed to be a slender beam element, which virtually connected to the soil by means of skin and foot interfaces. Since these elements may have arbitrary inclination and cross the soil elements at any arbitrary position. The interaction between the pile and soil at the skin interface is modeled by means of line-to-volume interface elements and the interaction at the base by means of point-to-volume interface elements in addition to the embedded beam approach which developed by Adek and Shahrour (2004) (In Vermeer and Brinkgreve, 2004 [16]). The basic soil elements of a three-dimensional finite element mesh is shown in figure 2.

PLAXIS 3D Foundation is finite element analysis software. The flexibility, capabilities, and options have been developed over many years, at the request of a worldwide user community, such that the PLAXIS program can be applied to a wide variety of engineering applications. PLAXIS 3D Foundation enables to perform the following tasks:

a. Build computer models or transfer CAD models of structures, products, components or systems.

b. Apply operating loads or other design performance conditions.
c. Study physical responses, such as stress levels, distributions, or the impact of electromagnetic fields.
d. Optimize a design early in the development process to reduce production costs.

There are two types of structural analyses in the PLAXIS family of products, which are explained below (Vermeer and Brinkgreve, 2004) [16]:

1. Static Analysis: It is used to determine displacements, stresses effect under static loading conditions. Linear and non–linear static analyses. Nonlinearities can include plasticity, stress stiffening, large deflection, large strain, hyper elasticity, contact surface and creep.
2. Modal Analysis: It is used to calculate the natural frequencies and mode shapes of structure. Different mode extraction methods are available.

Finite Element Mesh

When the full geometry model has been defined and all geometry components have their initial properties, the finite element mesh can be generated. From the geometry model, a 2D mesh is generated first. The basic soil elements used for 2D and 3D finite element mesh are the 15-node wedge elements. These elements are generated from the 6-node triangular elements. The accuracy of the 15-node wedge element and the compatible structural elements are comparable with the 6-node triangular element and compatibles in a 2D PLAXIS analysis. Higher order element types, for example comparable with the 15-node triangle in a 2D analysis, are not considered for a 3D foundation analysis because this will lead to large memory consumption and unacceptable calculation times (Vermeer and Brinkgreve, 2004) [16].

CASE STUDY

As the computer oriented finite element method has become one of the most powerful tools in the analyses of engineering problems for numerical modeling of the structural response, it is necessary in such studies to make verification before any analysis. Thus, in order to give support to the results obtained by the computer program, PLAXIS 3D Foundation, two cases are taken for verification between Plaxis results with that of an experimental work and ANSYS software.

The first case study chosen for this comparison is performed on the results of the experimental work for the analysis of single pile achieved by Hameedi (2011) [17] (Figures 3 and 4). The experimental model is with raft size (15 x 15) cm and pile dimensions are: embedment length, L= 40 cm and pile diameter, D_p= 2.5 cm with the ratio, L/D_p=16. The soil at the site consists of clay with cohesion 25 kPa, Poisson's ratio 0.3 and the modulus of elasticity 15000 kPa. The properties values of the pile and raft (Table 1), given by Hameedi (2011) [17] and Bowles (1997) [18], are used.

The second case study of comparison is performed on the results of Ansys program for raft analysis carried out by Khdear (2007) [19] who implemented Drucker–Prager model (Figures 5 and 6). The raft (concrete) diameter is 10 m and thickness of 1 m.

The soil at the site consists of clay with cohesion 55 kPa, Poisson's ratio of 0.45 and modulus of elasticity 22000 kPa.

After reviewing the results of the analysis (Figures 4 and 6), it can be concluded that the results obtained from the experimental study and theoretical study are close indicating that PLAXIS results are accurate and can be adopted practically. Besides, the program is specified for geotechnical Engineering.

The models which are performed by the finite element program with different configuration of piles are shown in figure 7. Nine models are analyzed by the finite element program, these are:

a. Raft only.
b. Single pile only.
c. Raft with single pile.
d. Raft with two piles (2×1).
e. Raft with three piles (triangular shape).
f. Raft with four piles (2×2).
g. Raft with eight piles.
h. Raft with sixteen piles.
i. As above cases but pile group only

The soil is modeled as elastic-perfectly plastic solid. One layer of soft clay is used. The material properties and pile model for the numerical model are shown in table (2).

Material Model

The solution theory is based on the material. Material model is described by a set of mathematical equations that give a relationship between stress and strain. Material models are often expressed in a form in which infinitesimal increments of stress (or 'stress rates') are related to infinitesimal increments of strain (or 'strain rates'). All material models implemented in PLAXIS are based on a relationship between the effective stress rates σ', and the strain rates ε.

The program can account for three types of material model (Vermeer and Brinkgreve, 2004) [16]:

1. The Mohr-Coulomb model (Elastic-perfectly plastic).
2. The hardening-soil model (Isotropic hardening).
3. Linear and non-linear behavior models for structural elements.

The Mohr-Coulomb Model

Plasticity is associated with the development of irreversible strains. In order to evaluate whether or not plasticity occurs in a calculation, a yield function, f, is introduced as a function of stress and strain. A yield function can often be presented as a surface in principal stress space. A perfectly plastic model is a constitutive model with a fixed yield surface, i.e. a yield surface that is fully defined by model parameters and not affected by (plastic) straining. For stress states represented by points within the yield surface, the behavior is purely elastic and all strains are reversible (Vermeer and Brinkgreve, 2004) [16]. The basic principle of elasto-plasticity is that strains and strain rates are decomposed into an elastic (ε^e) part and a plastic (ε^p) part:

$$\varepsilon = \varepsilon^e + \varepsilon^p \quad \dots (5)$$

According to the classical theory of plasticity (Hill, 1950) [20], plastic strain rates are proportional to the derivative of the yield function with respect to the stresses. This means that the plastic strain rates can be represented as vectors perpendicular to the yield surface. This classical form of the theory is referred to as associated plasticity. For Mohr-Coulomb yield functions, the theory of the associated plasticity overestimates dilatancy.

The Mohr-Coulomb model requires a total of five parameters, which are generally familiar to most geotechnical engineers and which can be obtained from basic tests on soil samples. These parameters are: Young's modulus, E (15000 kN/m^2); Poisson's ratio, ν (0.45); friction angle, Ø (0°); cohesion, C (25 kN/m^2); and dilatancy angle, ψ (0°).

RESULTS AND DISCUSSION

One of the most challenging problems in soil-structure interaction is the piled raft. Piled-raft foundations have proved to be a viable alternative to conventional pile foundations or mat foundations. The load carrying capacity for the numerical model of one layer of soft clay, the settlement is plotted with the vertical applied load. Figures 8 to 15 show the load-settlement behavior of piled rafts, single pile and rafts of the same size of (10×10 m) and thickness 25 cm as well as the load carried on single pile, unpiled raft, piled raft with 1, 2, 3, 4, 8 and 16 piles. Figure 16 shows the same previous groups of piles only.

The aforementioned figures (Figures 8 to 16) show that the shape of load settlement indicates the local shear failures which are controlled. In addition, it is found that the tangent proposal can be adopted in specifying the ultimate piled raft capacity. Considering the settlement, it is clearly shown from the above figures that the settlement decreases with increasing number of piles in the group.

The carrying capacity of the pile groups with different numbers of piles are shown in Table (3). From this table, it can be seen that the percent of load carried by piles relative to the total applied load [(piles capacity/ piled raft capacity) x100] also increases with the increasing the number of piles in the group. It is found that the maximum value of carrying capacity reaching about 42 % of the total applied load for 16 piles group. Besides, the results show that the pile raft capacity increases with the increasing number of piles.

The effect of spacing between piles on carrying capacity load is also studied through a certain piled raft configuration of two piles group with constant pile diameters and lengths as shown in figure (17). The pile diameters of 0.6 m and length 24 m with ratio L/D = 40 were considered and spacing 3*D-10*D are considered. The results show a decrease in carrying capacity around 23% when the spacing between piles increases from 3 to 10 times the pile diameter which is due to the pile group action.

CONCLUSIONS

The numerical modeling of the piled raft problem considering the load effect using the finite element method through the program PLAXIS reveals the following conclusions:

1. The average load carried by piles depends on the number of piles in the group. The percentage of the load carried by piles to the total applied load from the numerical model for the case of sixteen piles with raft is around 42%.
2. Spacing between the piles affects directly the interaction between piles. The percentage of the load carrying for piled raft for the case of two piles group with constant pile diameters and lengths is decreasing by about 23% when the spacing between piles increases from 3 to 10 times the pile diameter.
3. In comparison to shallow (raft) foundations, piled rafts reduce effectively the settlements.

REFERENCES

[1]. Maharaj, D.K. "Load-Settlement Behavior of Piled Raft Foundation by Three-Dimensional Nonlinear Finite Element Analysis", Electronic Journal of Geotechnical Engineering, Vol. 8, Bundle (C), pp.1-14, 2003.

[2]. Franke, E., "Measurements Beneath Piled Rafts", Keynote lecture, 1991.

[3]. Yamashita, K., Kakurai, M. and Yamada, T., " Investigation of a Piled Raft Foundation on Stiff Clay", XIII International Conference on Soil Mechanics and Foundation Engineering, New Delhi, India, pp. 543-546,1994.

[4]. Russo, G. and Viggiani, C., "Factors Controlling Soil-Structure Interaction for Piled Rafts", Darmstadt Geotechnics, Darmstadt University of Technology, No. 4, pp. 297-322,1998.

[5]. Poulos, H. G., "An Approximate Numerical Analysis of Pile-Raft Interaction. Int. J. of Numerical and Analytical Methods in Geomechanics", Vol. 18, pp. 73-92, 1994.

[6]. Maharaj, D. K., "Application of Elastic and Elasto-Plastic Analysis for Piled Raft Foundation", Ph.D. Thesis, Madras, India,1996.

[7]. Prakoso, W.A. and Kulhawy, F.H. " Contribution to Piled Raft Foundation Design", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.127, No.1, pp.17-24,2001.

[8]. Seo,Y.K., and Choi, K.S., "Design Charts of Piled Raft Foundations on Soft Clay", International Offshore and Polar Engineering Conference Honolulu, Hawaii, USA, May 25–30, 2003297-322, 2003.

[9]. Chow H., "Analysis of Piled-Raft Foundation with Piles of Different Lengths and Diameters", Ph.D. Thesis, School of Civil Engineering, The University of Sydney, 2007.

[10]. Engin, H.K, "Estimation of Pile Group Behavior Using Embedded Piles", The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG) 1-6 October, Goa, India, 2008.

[11]. Al Zayadi, T. M., " Three Dimensional Analysis of Pile Raft Foundation", Ph.D. Thesis, University of Technology, Iraq, 2010.

[12]. El Sawwaf, M.,"Experimental Study of Eccentrically Loaded Raft with Connected and Unconnected Short Piles", J. Geotech. Geoenviron. Eng., Vol. 136 Issue 10, 1394–1402, 2010.

[13]. Al-Tameemi, S.M., "Experimental Study for the Behavior of Piled Raft Foundation on Sandy Soil", M.Sc. Thesis, Al-Mustansiriya University, Iraq, 2011.
[14]. Zienkiewicz, O.C., and Taylor, R.L., "The Finite Element Method for Solid and Structural Mechanics" 6th edition, Butterworth-Heinemann, Amsterdam, Boston, London, 2005.
[15]. Vermeer, P. A., and Brinkgreve, R. B. J., "PLAXIS User's Manual,Version 6.1", Balkema, Rotterdam, The Netherlands, 1995.
[16]. Vermeer, P. A., and Brinkgreve, R. B. J., "PLAXIS 3D User's Manual, Version 1.1", Balkema, Rotterdam, The Netherlands, 2004.
[17].Hameedi, M. K., "Experimental and Theoretical Study for Piled Raft Foundation in Soft Clay", Unpublished M.Sc. Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq, 2011.
[18]. Bowles, J. E., " Foundation Analysis and Design", Fifth edition, McGraw-Hill, 1144P, 1997.
[19]. Khdear M. T., "Effect of Pile Length and Raft Size on the Load –Settlement Behavior of Pile Caps", M.Sc. Thesis, University of Technology, Iraq, 2007.
[20]. Hill, R., "The Mathematical Theory of Plasticity", Clarendon Press, Oxford, 1950.

Table (1) Properties of the pile and raft.

Raft (Steel Plate) • Modulus of Elasticity, E ***** • Poisson's Ratio, υ *****	 2×10^8 kPa 0.33
Pile(Concrete Pile) • Modulus of Elasticity, E ****** • Poisson's Ratio, υ *	 2.9×10^5 kPa 0.15

* Bowles(1997) [18]; ** Hameedi (2011) [17].

Table (2) Material properties and pile model used for the numerical model.

Material Properties	Type of Layer	Cu kN/m^2	υ	E kN/m^2	Ø (°)
	Soft Clay	25.0	0.45	15000	0.0
Pile Model	**Pile Diameter (D_p) (m)**	**Pile Length (L) (m)**	**Raft Width (B_r) (m)**	**L/D_p**	**L/B_r**
	0.6	24	10	40	2.4

Table (3) Piled raft and pile group capacity for one-layer numerical model.

Case	Piled Raft Capacity (kN)	Piles Capacity (kN)	Raft Capacity (kN)	% of Load Carried by Piles[= (Piles Capacity /Piled Raft Capacity) × 100]
Single pile		1750		100
Raft (10 m×10 m)			20000	0
Raft with single pile	21000	1750	20000	8
Raft with 2 piles	21600	2100	20000	9
Raft with 3 piles	22500	3000	20000	13
Raft with 4 piles	25000	5000	20000	20
Raft with 8 piles	26000	7650	20000	29
Raft with 16 piles	30000	12500	20000	42

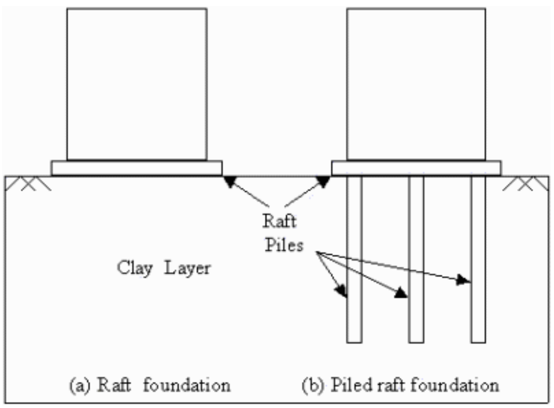


Figure (1) Piled raft foundation [1].

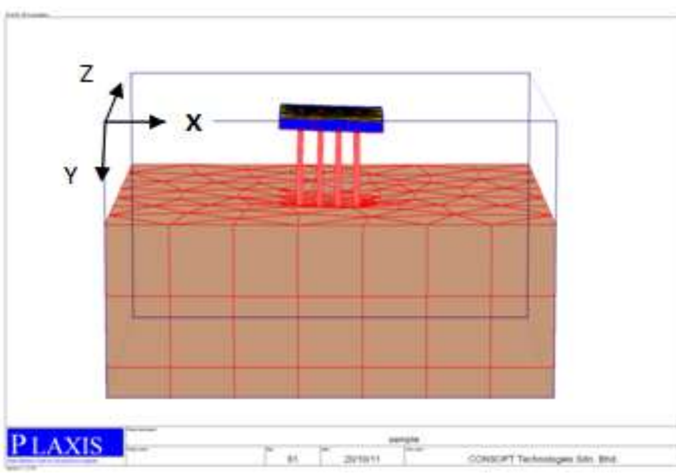


Figure (2) Sample of finite element models.

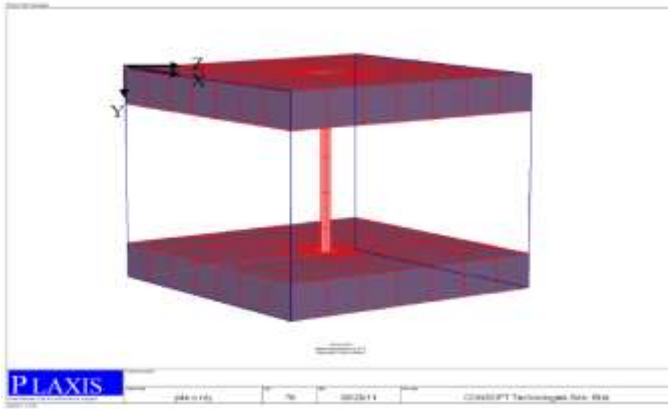


Figure (3) The finite elements mesh for the first case study of verification.

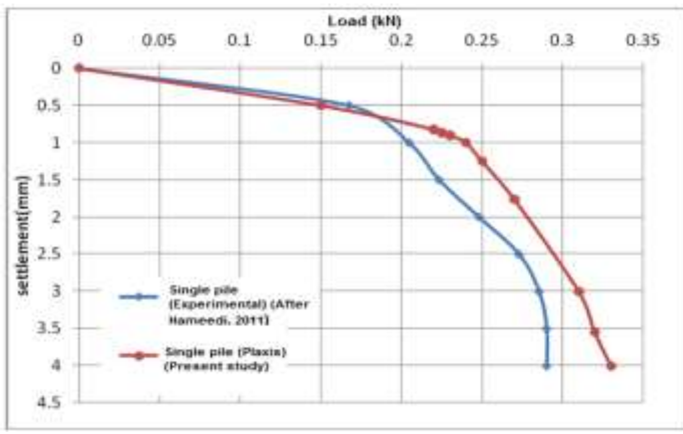


Figure (4) Comparison of load–settlement curves for singe pile.

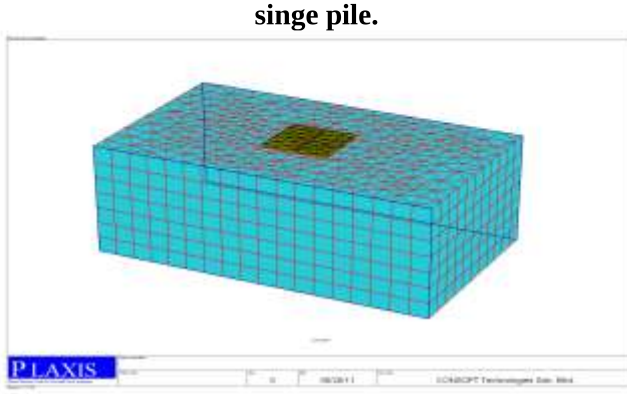


Figure (5) The finite elements mesh for the second case study of verification.

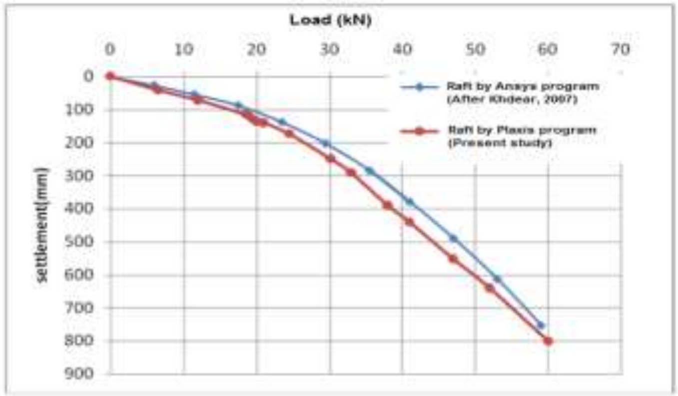
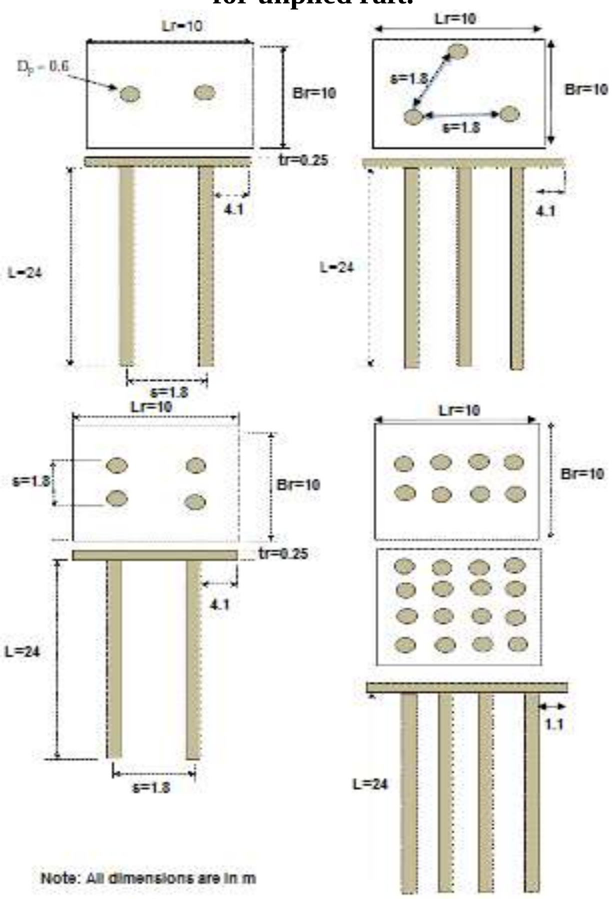


Figure (6) Comparison of load–settlement curves for unpiled raft.



L_r = length of raft; B_r = width of raft; t_r = thicknesses of raft; L= length of pile; D_p = diameter of pile; s = spacing between piles.

Figure (7) Piled raft Models for finite element program.

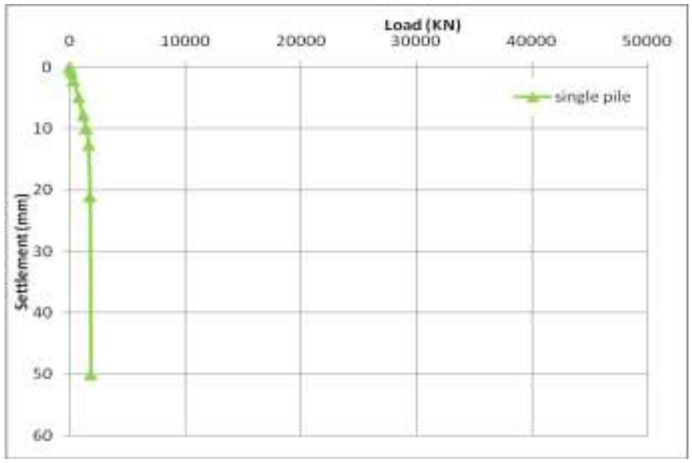


Figure (8) Load–settlement curve of single pile (L=24m and D=0.6m).

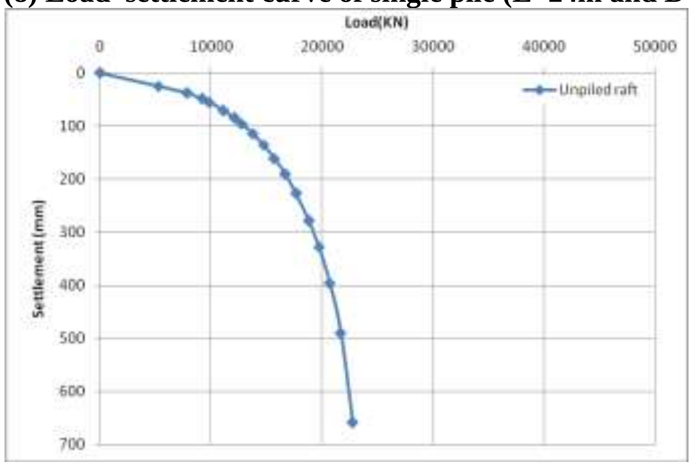


Figure (9) Load–settlement curve of unpiled raft with size (10×10 m).

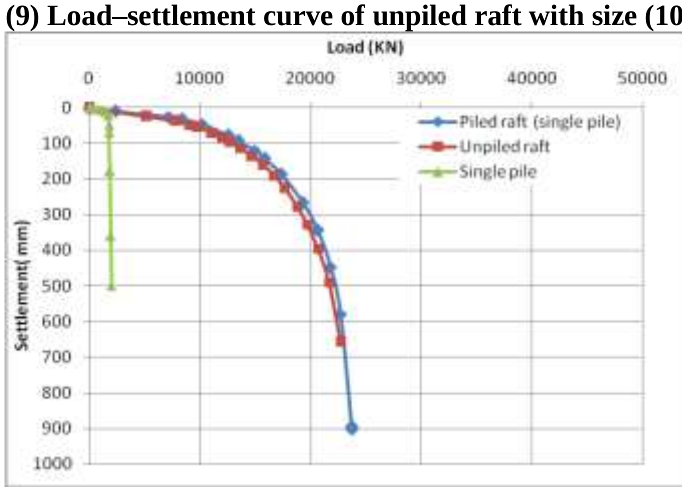


Figure (10) Load–settlement curve of piled raft (single pile).

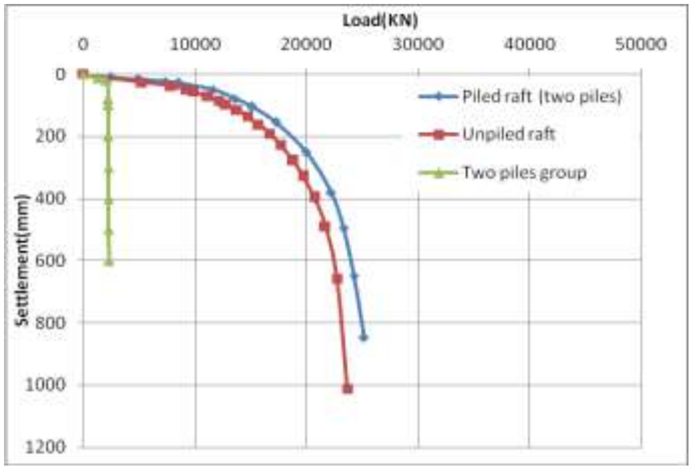


Figure (11) Load–settlement curve of piled raft (two piles).

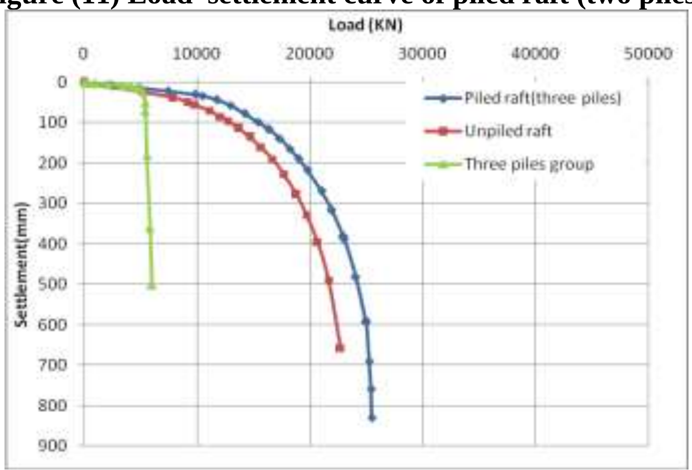


Figure (12) Load–settlement curve of of piled raft (three piles).

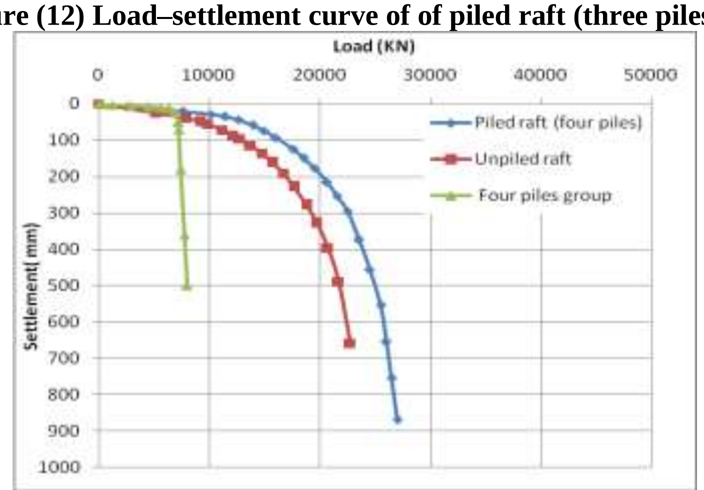


Figure (13) Load–settlement curve of piled raft (four piles).

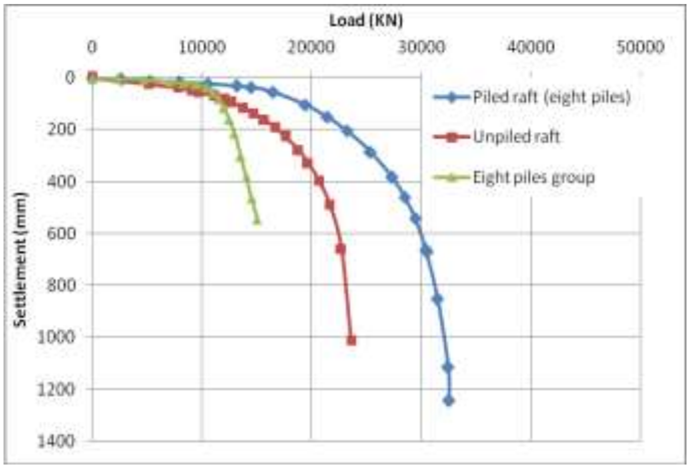


Figure (14) Load–settlement curve of piled raft (eight piles).

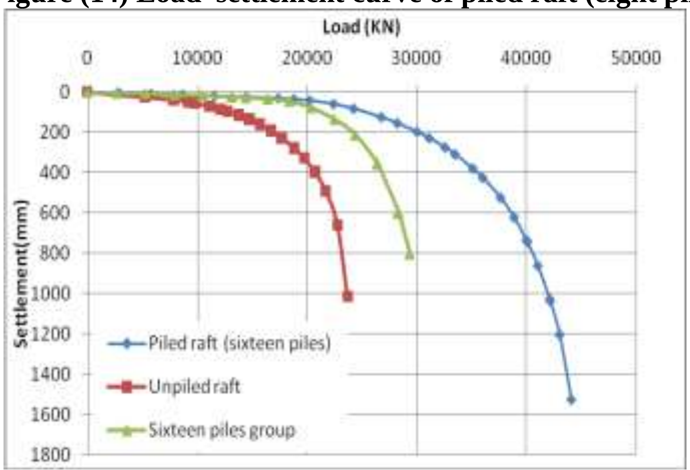


Figure (15) Load–settlement curve of piled raft (sixteen piles).

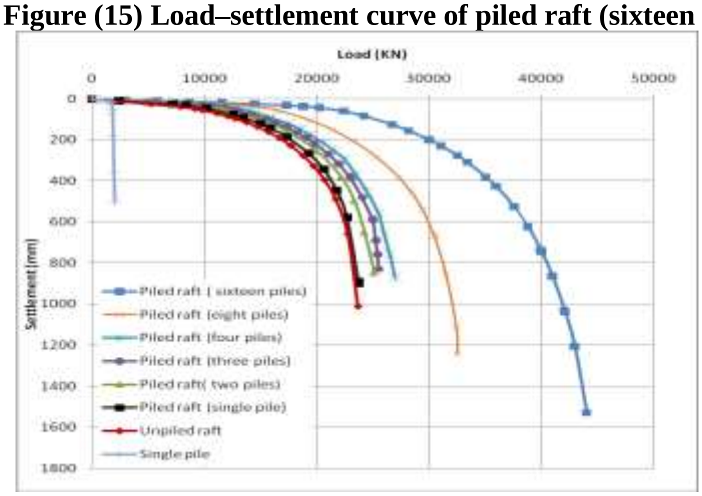


Figure (16) Load–settlement curve for all cases.

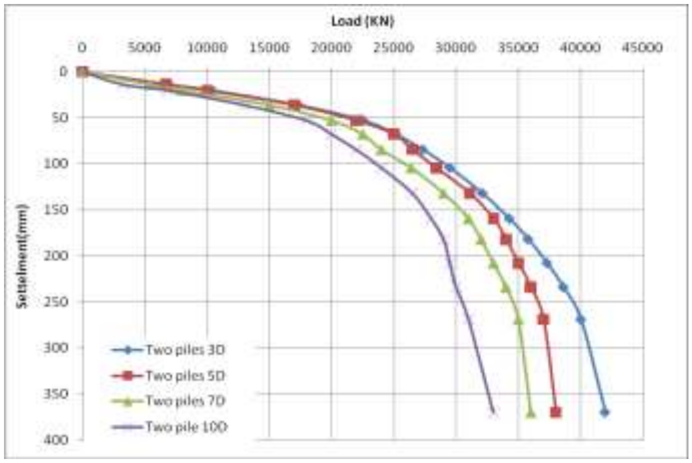


Figure (17) Effect of spacing between piles.