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Parametric Study on Unconnected Piled Raft Foundation Using Numerical Modelling

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ABSTRACT

Piled raft is commonly used as foundation for high rise buildings. The design concept of piled raft foundation is to minimize the number of piles, and to utilize the entire bearing capacity. High axial stresses are therefore, concentrated at the region of connection between the piles and raft. Recently, an alternative technique is proposed to disconnect the piles from the raft in a so called unconnected piled raft (UCPR) foundation, in which a compacted soil layer (cushion) beneath the raft, is usually introduced. The piles of the new system are considered as reinforcement members for the subsoil rather than as structural members. In the current study, the behavior of unconnected piled rafts systems has been studied numerically by means of 3D Finite Element analysis via ABAQUS software. The numerical analysis was carried out to investigate the effect of thickness and stiffness of the cushion, pile length, stiffness of foundation soil, and stiffness of bearing soil on the performance of the unconnected piled raft. The results indicate that when unconnected piles are used, the axial stress along the pile is significantly reduced e.g. the axial stress at head of unconnected pile is decreased by 37.8% compared with that related to connected pile. It is also found that the stiffness and thickness of the cushion, and stiffness of foundation soil have considerable role on reduction the settlement.

Keywords: piled raft, unconnected piled raft, cushion, Finite Element method, ABAQUS.

دراسة تحليلية للاسس الحصيرية المدعمة بالركائز غير المتصلة باستخدام النمذجة الرقمية

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الخلاصة

تستخدم حاليا الاسس الحصيرية المدعمة بالركائز المتصلة بشكل واسع في المباني المرتفعة حيث يتمثل المبدأ الاساسي لهذه الاسس بتقليص عدد الركائز وباستخدام قابلية تحملها القصوى. ولكن بسبب الترابط الانشائي بين الاساس الحصيري والركائز تتركز اجهادات محورية في منطقة الترابط. في الآونة الاخيرة اقترحت تقنية بديلة تقوم على اساس فصل الركائز عن الاساس الحصيري ووضع طبقة مرصوصة من التربة (حشوة) في مايسمى بالاساس الحصيري المدعم بالركائز غير المتصلة. يتم

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التعامل مع الركائز في هذا الاساس البديل على انها تسليح للتربة بدلا عن كونها اجزاء انشائية. في هذه الدراسة, تمت دراسة سلوك الاسس الحصيرية المدعمة بالركائز غير المتصلة باسلوب المحاكاة الرقمي باستخدام طريقة العناصر المحددة باستخدام البرنامج **ABAQUS-3D,** في هذه الدراسة التحليلية تم دراسة تاثير سمك وصلابة طبقة الحشوة, طول الركيزة, صلابة تربة الاساس, وصلابة تربة طبقة التحميل تحت الركيزة على سلوك الاساس الحصيري المدعم بالركائز غير المتصلة. اوضحت الدراسة ان استخدام الاساس المدعم بالركائز غير المتصلة ادى الى تقليل الاجهاد المحوري في اعلى الركيزة غير المتصلة بمقدار 37.8% مقارنة بالركيزة المتصلة. بالاضافة الى ذلك اوضحت الدراسة بان سمك وصلابة طبقة الحشوة وكذلك صلابة طبقة الاساس لها دور واضح في تقليل مقدار هطول منظومة الاساس.

الكلمات الرئيسية: الاساس الحصيري, الاساس الحصيري المدعم بالركائز غير المتصلة, الحشوة, طريقة العناصر المحددة.

1. INTRODUCTION

The piled raft is a composite foundation that comprises three parts; raft, piles and soil. The design philosophy of piled raft differs from that in conventional foundation where it is assumed either a raft or pile group that carry the superstructure loads and insuring a certain value of safety factor. Basically, piled raft herein will be called connected piled raft (CPR) concept is proposed in order to obtain an economic design compared to conventional pile foundation by using the required number of piles that are important to minimize settlement to an acceptable limit and the transmitted loads are shared between the raft and piles (**Al-Mosawe et al., 2011)**, (**Al-mosawe et al., 2013)**. However, relatively large bending moments may be developed when these small number of piles are structurally connected to the raft as well as cracks in the raft and high axial stress concentration at the pile head may be occur. Thus, the probability of structural failure of the foundation is greater than that related to the bearing capacity failure of the supporting soil. To overcome the problem of connection reaction an alternative approach has been proposed where unconnected piles are used and provided an interposed cushion layer between the raft and the piles. The piles in such condition will behave as soil stiffeners instead of as structural members **(Wong et al., 2000)**, **(Burghignoli et al., 2007)**, **(Jamiolkowski et al**., **2009).**

Recently, many numerical studies have been presented to investigate the behavior of unconnected piled raft, UCPR. For instance, **(Wong et al., 2000),** introduced a numerical investigation by means of plane straining FE methods to evaluate the behaviour of unconnected piled raft. The study show that, a much lower factor of safety against structural failure of the piles can be used by disconnecting the piles from the raft. This may be due to the fact that the piles can be considered as soil reinforcement members strengthen the subsoil rather than as structural members carrying the applied load

(Liang et al., 2003) examined numerically in the elastic regime many parameters such as the thickness and stiffness of the cushion layer, the ratio of length to diameter of the pile, and the elastic modulus of piles. This study proposed the way for optimizing the pile configuration so as to allocate the loads evenly and alleviate the pressure concentrating upon the lengthier piles. An elastoplastic numerical analysis was performed by **(Eslami et al.**, **2012)**, showed that the thickness and the stiffness of cushion affects the location of the maximum axial stress along piles. **(Sharma et al., 2011)**, showed that using the cushion will adjust the load-sharing ratio evenly among the piles. **(Hor et al., 2015)** employed a three dimensional finite element method via Plaxis to model the complex interactions of the disconnected piled raft taken into account the load transfer in the interposed cushion layer and along the pile. In this study the stiffness of the soil and the piles, thickness as well as the strength parameters of the cushion layer were investigated. The results obtained from this study showed that, the performance of unconnected piled raft for heavy load structures is better compared with connected system. **(Ata et al., 2015)** performed a parametric study on unconnected piled raft, they showed that unconnected piled raft may be considered as an economical alternative to the connected piled raft.

Most of the aforementioned numerical results are proved by experimental findings obtained from small model tests performed by many researchers. Among them, (**Cao et al., 2004)** reported that the settlement and the bending moments at the piles head are considerably reduced by using unconnected piled raft. **(Fioravante and Giretti, 2010)** studied the stiffness of the foundation when the granular cushion layer was interposed between the raft and piles. They found that the relative stiffness of pile and soil underneath raft affect the load distribution mechanism in the foundation. Also, it is found that the initial stiffness of foundation was essentially a function of the piles stiffness. The present parametric study aims at identifying the most important parameters which affect the performance of the unconnected piled raft foundation such as; thickness and stiffness of the cushion, length of the piles, stiffness of bearing soil, and stiffness of foundation soil.

2. MEHDOLOGY AND DEVELOPED MODEL

Simulation of the behaviour of the connected or unconnected piled raft foundation and the supported soil requires careful selection of the modelling parameters to produce accurate results that are as close as possible to the actual behaviour of the analyzed members. In this analysis the numerical investigations were performed by using the developed ABAQUS 3D model. Where, the behaviour of the soil is modeled as nonlinear elastic perfectly plastic, Mohr Coulomb yield criterion. While, the cushion, raft, and piles are modeled as elastic material. The subsoil used in this study is dry sand soil, and the piles are simulated as bored piles. The properties of the subsoil, cushion, raft, and piles are shown in **Table. 1**.

The finite element discretization of each part was conducted by using eight-node continuum three-dimensional brick element (C3D8R) with reduced integration available in ABAQUS (6.14.1) library. The layout and meshing of the reference model that chosen for this parametric study is shown in **Fig. 1**, it is consist of a (6 x 6) piles group of o.6 m in diameter and 12 m in length, spaced at 2 m (3.33d). A compacted granular cushion layer 1m in thickness with an elastic modulus 60 MPa is placed under a concrete raft of 0.5 m thickness and side dimensions of $(12m \times 12m)$ supporting a distributed load of 300 kPa. ABAQUS presents an advantage of analyzing quarter of the symmetrical model. This advantage was taken into account and only one-fourth of the geometry is considered to simulate the piled raft foundation under consideration as shown in **Fig. 1.C.** The domain of the soil continuum taken in this analysis is extended to a large distance to reduce the effect of the boundaries on the displacement of the foundation. The soil mass is 60 m long (in the *x*-direction), 60 m wide (in the *y*-direction), and 30 m high (in the *z*-direction).

The parametric study was concerned on the most important parameters that are effect on the load-settlement behaviour, axial stress along the piles, and pile load sharing ratio. The parameters considered in this study can be summarized as shown in **Table 2.**

Table. 1 Properties of material of the UCPR for the reference case.

Properties	Foundation soil	Cushion layer	Pile	Raft
$\gamma\ kN/m^3$	18	20	25	25
E (kPa)	4E4	6E4	3E7	3E7
v	0.3	0.3	0.2	0.2
c' *(kPa*	0.1	-	-	-
$\emptyset°$	32	-	-	-
$\psi°$	3	-	-	-
Material model	MC*	Elastic	Elastic	Elastic

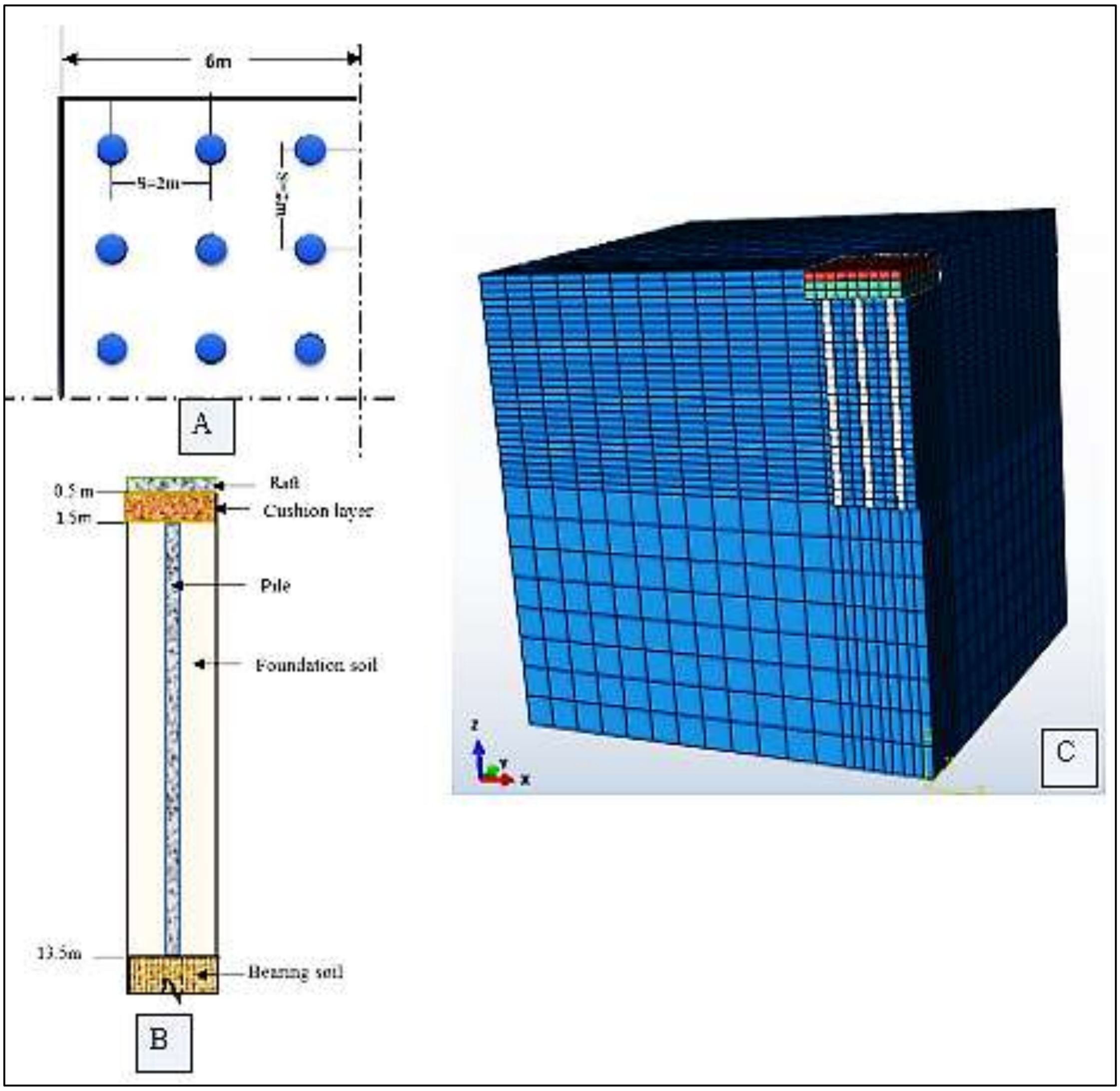

Figure 1.
A. One fourth of the reference piled raft system;
B. Section show soil profile and parts of piled raft;
C. Meshing of ABAQUS 3D model.

Study Parameters	E_{soil} MPa	Raft dimensions		Cushion parameter		Pile group geometry			
		L x B	t	Hc, m	$E_{cushion}$ (MPa)	S	n	D	L
Connected	40	12x12	0.5	-	-	2	6x6	0.6	12
Cushion thickness	40	12x12	0.5	0.25	60	2	6x6	0.6	12
				0.5					
				0.75					
				1					
				1.25					
				1.5					
				2					
Cushion stiffness	40	12x12	0.5	1	20	2	6x6	0.6	12
					40	2	6x6	0.6	12
					60	2	6x6	0.6	12
					100	2	6x6	0.6	12
					150	2	6x6	0.6	12
					200	2	6x6	0.6	12
					30E3	2	6x6	0.6	12
Pile length	40	12x12	0.5	1	60	2	6x6	0.6	6
									12
									18
Bearing soil	40*+40**	12x12	0.5	1	60	2	6x6	0.6	12
	40*+90**	12x12	0.5	1	60	2	6x6	0.6	12
	40*+1.2E3**	12x12	0.5	1	60	2	6x6	0.6	12
Stiffness of foundation soil of Connected piled raft model	10	12x12	0.5	-	-	2	6x6	0.6	12
	15	12x12	0.5	-	-	2	6x6	0.6	12
	20	12x12	0.5	-	-	2	6x6	0.6	12
	30	12x12	0.5	-	-	2	6x6	0.6	12
	40	12x12	0.5	-	-	2	6x6	0.6	12
	60	12x12	0.5	-	-	2	6x6	0.6	12
Stiffness of foundation soil of Unconnected piled raft model	10	12x12	0.5	1	60	2	6x6	0.6	12
	15	12x12	0.5	1	60	2	6x6	0.6	12
	20	12x12	0.5	1	60	2	6x6	0.6	12
	30	12x12	0.5	1	60	2	6x6	0.6	12
	40	12x12	0.5	1	60	2	6x6	0.6	12
	60	12x12	0.5	1	60	2	6x6	0.6	12

**** E of the subsoil of depth from 0 to the bottom of piles;*** ***** E of the end bearing soil layer***

3. MODEL VALIDATION

To confirm the finite element numerical model, it should be compared with an accepted data. For this purpose, the developed ABAQUS 3D model has validated by utilizing the example introduced by Poulos in "*American Society of Civil Engineers (ASCE) Technical Committee – 18 (TC -18) report in 2001*" **(Poulos, 2001),** the details of the example is showed in the appendix A. The Piled raft example presented by Poulos consist of a rectangular raft of plane $(10m \times 6m)$ and 0.5 m in thickness. The raft is supported by 9 piles of 0.5 m in diameter and 10 m in length. For this piled-raft model, (**Poulos, 2001)** reported the load-settlement relationship using different approaches such as, the simple method, PDR-Method and by using software numerical models; GARP5, GASP, FLAC 2D, and FLAC 3D. The results obtained from the developed ABAQUS 3D model compared with other methods are illustrated in **Table. 3** and **Fig. 2**.

Table 3. Summary of computed piled raft behaviour for total load 12 MN

Method	Central settlement, mm	Settlement of corner pile, mm	% of Load taken by Piles
Poulos-Davis-Randolph	36.8		77.0
GARP5	34.2	26.0	65.1
GASP	33.8	22.0	65.5
Burland	33.8	29.7	65.5
FLAC 2-D	65.9	60.5	79.5
FLAC 3-D	39.9	35.8	58.2
Performed ABAQUS model	**36.7**	**25.7**	**53.85**

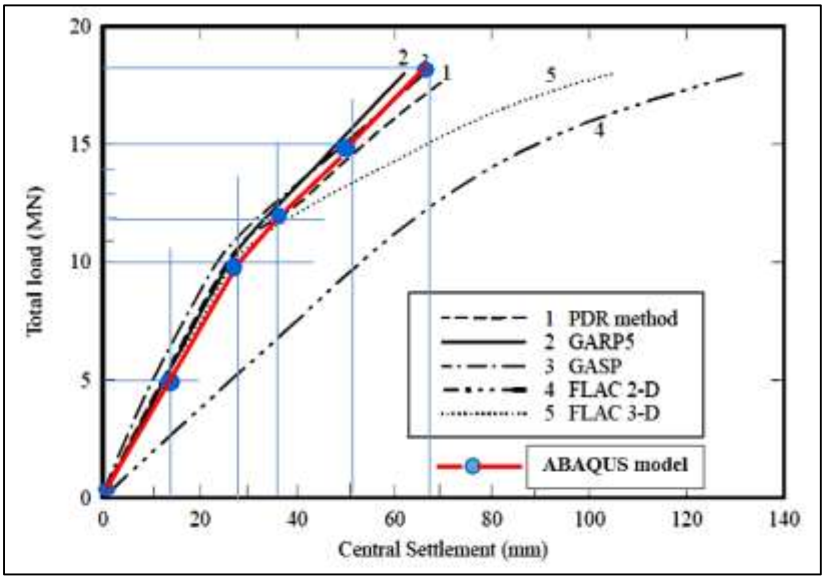

Figure 2. Load-settlement relationship for different approaches for example reported by **Poulos (2001).**

4. RESULTS AND DISCUSSIONS

4.1 Importance of the Interposed Cushion Layer

The cushion layer has main role in performance of unconnected piled raft, which it is utilized to redistribute and transfer the axial stress between the piles and surrounding soil. The effect of the cushion is studied for the following three cases;

4.1.1 General Effect of the Cushion

A comparison between the connected and reference case of unconnected piled raft systems relative to unpiled raft is shown in **Fig. 3**. In general, it can be concluded from this figure, that the settlement of the connected piled raft is decreased by 48.3% compared with the unpiled raft while unconnected piled raft is decreased by 46.4%. **Fig. 4** show the axial stress along the pile length for connected and unconnected piled raft. From the figure it can be seen, that the axial stress along the pile of unconnected piled raft is smaller than that of the connected piled raft, and the maximum axial stress is occurs at the head of connected pile, while it is shifted downward in unconnected pile. This is because the interposed cushion layer between the raft and piles causes a downward soil-pile relative displacement. This displacement is maximum at the pile heads and extends to a specific depth beneath the upper pile heads. This relative displacement becomes zero at a certain depth which is known as the depth of neutral plane at which the axial stress in its maximum value. Initially, the surrounding soil and the raft settle greater than the piles, cause the negative skin friction along the upper portion of the piles (above the neutral plane). Thus, the loading of piles come from their upper head as well as because of the negative skin frictions. Because of these loads, the piles will settled and a mobilized positives skin frictions occurring at the lower portion of the pile shaft.

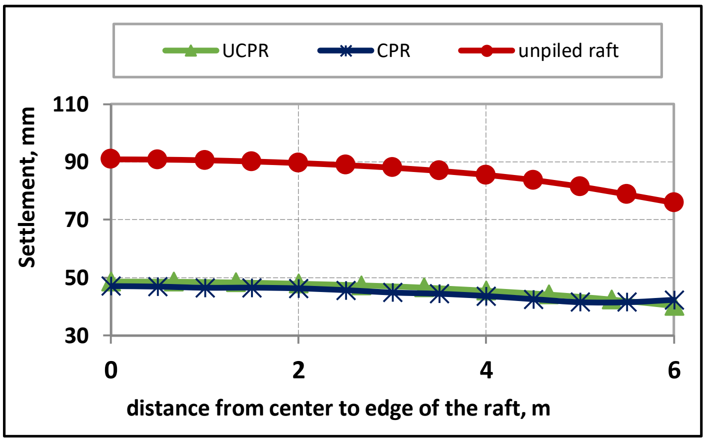

Figure 3. Settlement along centerline of unpiled raft, CPR, UCPR.

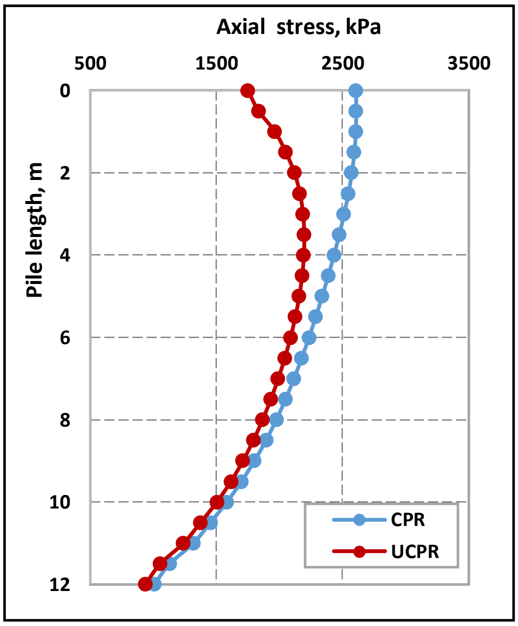

Figure 4. Variation of axial stress along the connected and unconnected center piles.

4.1.2. Effect of the Cushion Thickness

The effect of the cushion thickness is examined by using different values for the cushion thickness, 0.25, 0.5, 0.75, 1, 1.5, and 2 m. **Fig. 5** shows the variation of settlement of the raft with the cushion thickness. This figure indicates that the settlement decreases significantly as the cushion thickness varies from 0.25 m up to 1.25 m. After that no change in settlement values is recognized.

Fig. 6 show the variation of axial stress along the center pile for different values of the cushion thickness. It can be seen that the axial stress along the pile is slightly effected by increasing the cushion thickness. As the pile load sharing ratio is related to the axial stress at the pile, the effect of the cushion thickness on this ratio is similar to that on the pile axial stress. This finding is clearly illustrated in **Fig. 7.**

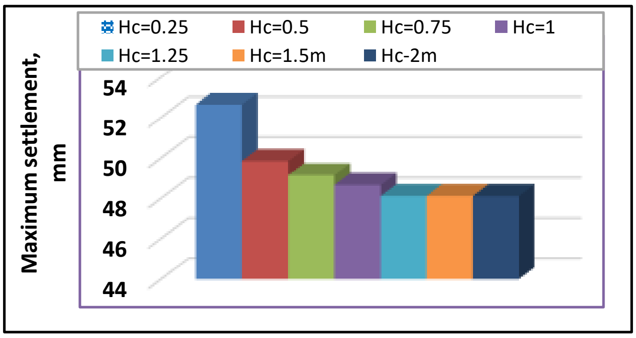

Figure 5. Variation of settlement of the raft with the cushion thickness

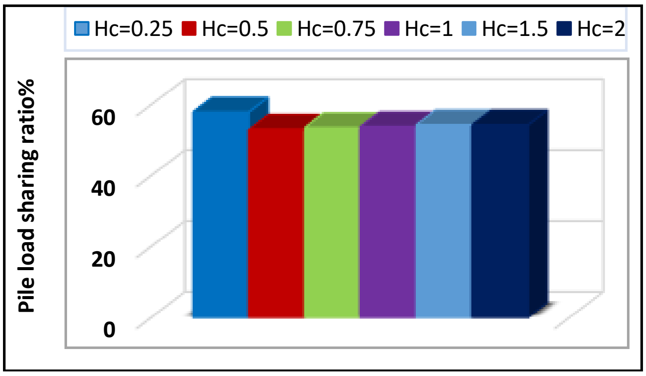

Figure 7. Pile load sharing ratio for different values of the cushion thickness

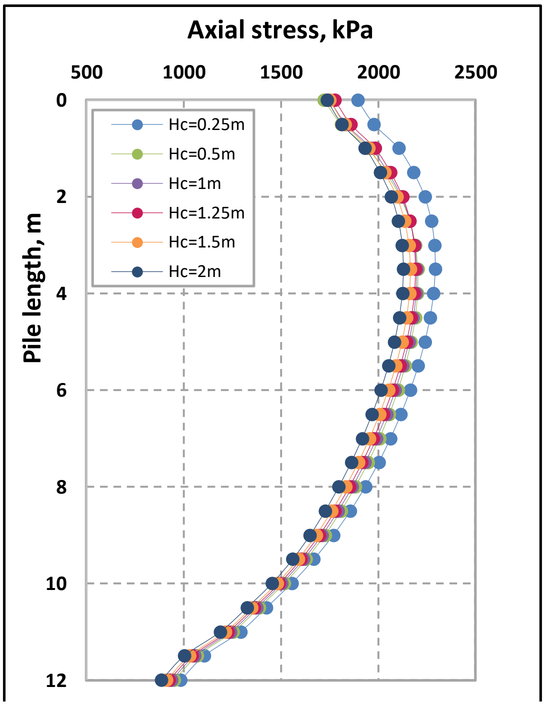

Figure 6. Variation of axial stress along the center pile for different values of the cushion thickness

4.1.3. Effect of the Modulus of Elasticity of the Cushion

To investigate the effect of the elastic modulus of the cushion on the performance of the unconnected piled raft system a wide range of values of elastic modulus was used. It is started from 20 MPa (represent loose soil material) to 30,000 MPa (represent concrete material). The influence of the elastic modulus on the settlement is shown in **Fig. 8**. It can be seen that the elastic modulus of the cushion have a considerable effect on the total and differential settlement. The effect of elastic modulus of the cushion on the axial stress along the pile is shown in **Fig. 9**. From this figure, it can be clearly seen that of the axial stress increases as the elastic modulus is increased. In the case of elastic modulus of 30,000 MPa, the maximum axial stress occur at pile head (similar to connected piled raft). Also, it is clear that the location of the neutral plane (location of maximum axial stress) shifted downward as the elastic modulus decreases. **Fig. 10** shows the pile load sharing ratio for different values of elastic modulus. It is clear the pile sharing ratio increases as the cushion stiffness is increased.

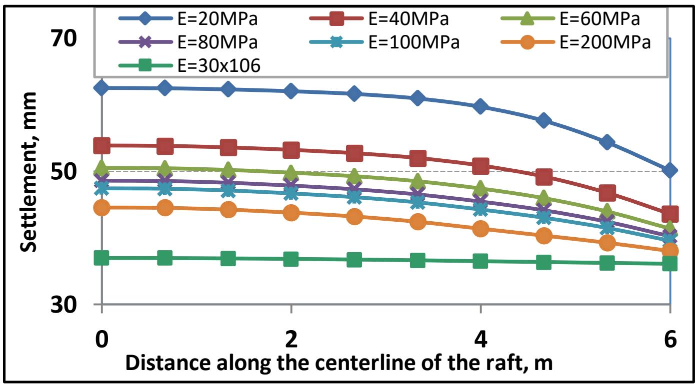

Figure 8. Influence of the elastic modulus on the settlement

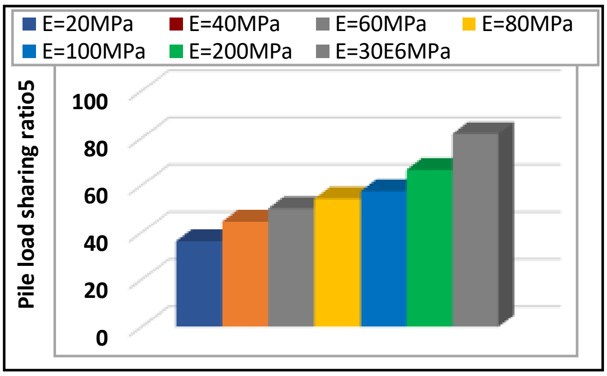

Figure 10. Pile load sharing ratio for different values of elastic modulus

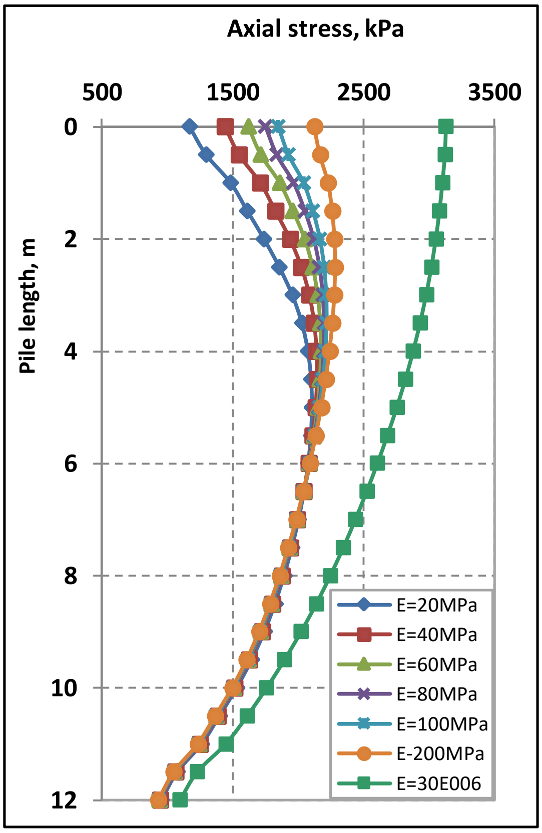

Figure 9. Effect of elastic modulus of the cushion on the axial stress along the pile

4.2 Effect of the Pile Length

In order to examine the effect of the pile length on the performance of the unconnected piled raft, three different pile lengths of 6, 12, and 18 m were utilized. According to the limit stated by **(Fliming, 2009)**, shown in Eq. 1, the piles of 12 m and 18 m are considered as flexible and the pile of long 6 m is considered as rigid;

$$If \quad 0.25\sqrt{\frac{E_p}{G_l}} < \frac{L}{D} < \; 1.5\sqrt{\frac{E_p}{G_l}} \;, \quad \text{then pile is flexible} \qquad (1.a)$$

$$If \quad \frac{L}{D} < 0.25\sqrt{\frac{E_p}{G_l}} \;, \qquad \text{then pile is rigid} \qquad (1.b)$$

Where: L, D, the length and diameter of the pile respectively

E_p, G_l, Modulus of elasticity of pile, shear modulus of bearing soil, respectively.

Fig. 11 show the settlement along the centerline of the raft. It can be noticed that the influence of pile length on the settlement results of unconnected piled raft are similar to these related to the connected piled raft. As the pile length is increased the settlement decreases. The variation of the distribution of the axial stress along the piles are shown in **Fig. 12**. It can be seen that the axial stress along the pile increases noticeably with increasing the pile length, and as the pile shaft be longer the axial stress at the lower pile tip gets smaller. Also, it can be seen that the location of neutral plane gets relatively deeper as the pile gets shorter. For example, for piles of length 6, 12, and 18 m the neutral plane is located at $0.33L_{pile}$, $0.29L_{pile}$, and $0.25L_{pile}$, respectively.

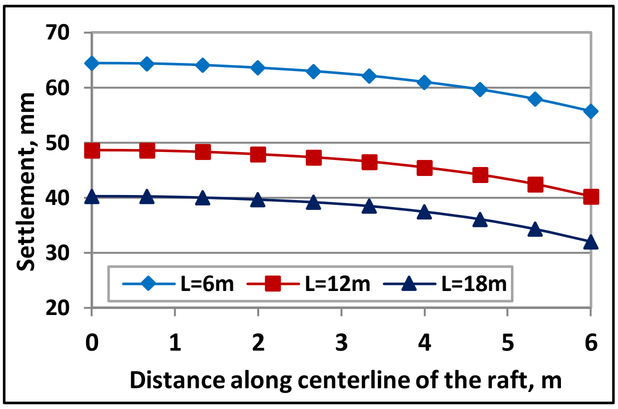

Figure 11. Settlement along the centerline of the raft for piled raft supporting by unconnected piles of different length

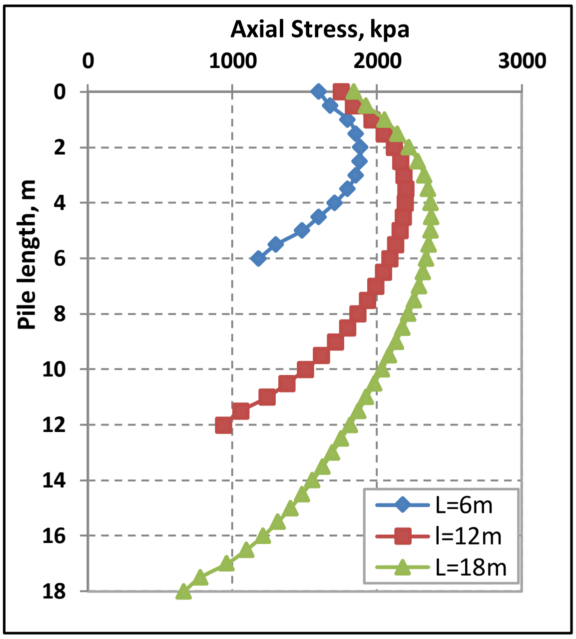

Figure 12. Distribution of the axial stress along the piles of different length

4.3 Effect of the Stiffness of the Bearing Soil

The influence of bearing soil has been studied by chosen three different soil types, fine sand (same as foundation soil), weak rock, and rock. The mechanical properties of this layer are shown in **Table 4**. From **Fig. 13** it can be observed that by increasing the stiffness of the bearing soil will result in considerable reduction in the overall and differential settlement.

The influence of the bearing soil layer on distribution of axial stress along the pile is shown in **Fig.14**. It is obvious that as the stiffness of the bearing soil increases the axial stress also increase. For piles resting on rock bearing soil, the axial stress along the pile exhibits a different variation of axial stress where the load transferred to the pile tip becomes greater than that at the pile head. This is may be attributed to the high stiffness of the bearing layer that prevent the relative displacement in the lower part of the pile where positive skin friction is generated. As mentioned earlier this part of the pile located below the neutral plane. In addition, the depth of maximum axial stress be greater for stiffer bearing layer. For instances, the neutral plane for fine sand, weak rock, and rock are located at $0.29L_{pile}$, $0.41L_{pile}$, and $0.58L_{pile}$, respectively.

Table 4. Mechanical properties of the different bearing soils investigated in this study

Type of soil	Elastic modulus, E, kPa	Cohesion, c', kPa	Friction angle, ∅ , degree
Fine sand	4E4	0	32
Weak rock	9E4	30	33
Rock	1.2E6	200	34

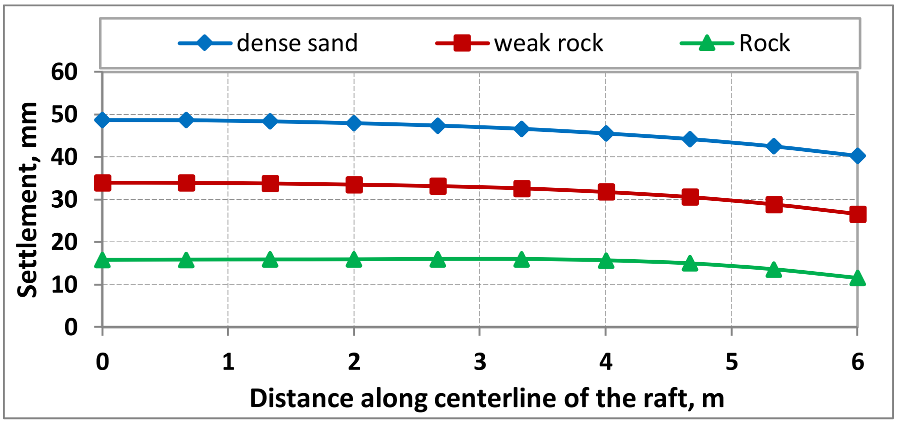

Figure 13. Influence of stiffness of bearing soil on the settlement of the raft.

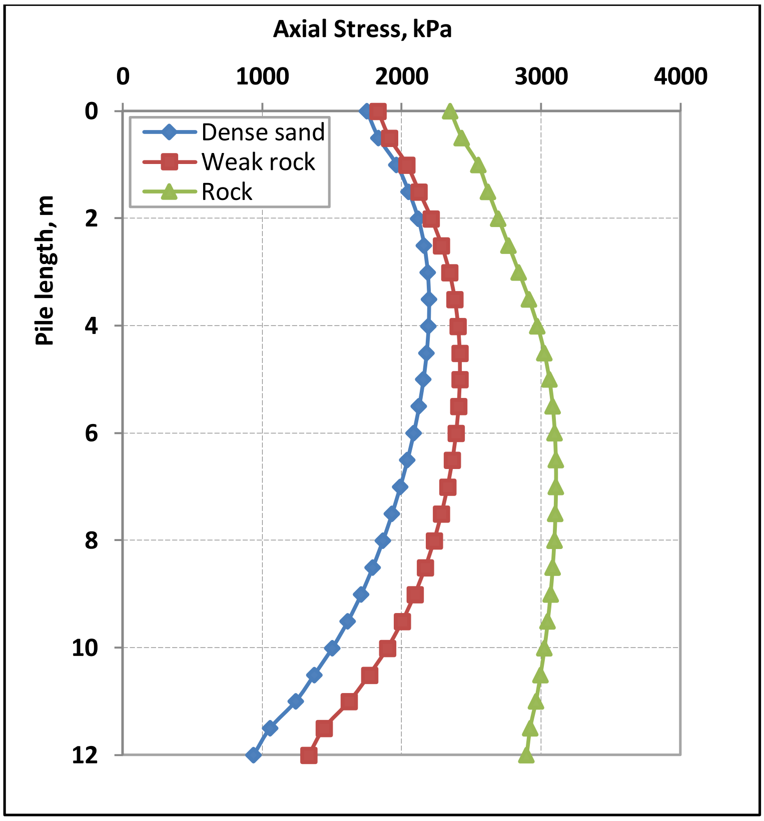

Figure 14. Influence of the bearing soil layer on distribution of axial stress along the pile.

4.4 Effect of Stiffness of Foundation Soil

It is well known that the foundation soil has the essential influence on the bearing capacity of the foundation system. Thus, in this parametric study the effect of the stiffness of foundation soil is taken into account. For this purpose, many numerical jobs for reference connected and unconnected foundation models were performed with variation the elastic modulus of the foundation soil to examine the effect of foundation soil stiffness on the load-settlement behavior and the axial stress along the piles. **Fig. 15** shows the load-settlement relationships for connected and unconnected piled raft foundations. As it is shown in the figure, the settlement of the raft decreases significantly as the elastic modulus of the foundation soil increases for both connected and unconnected piled raft.

The distribution of the axil stress along the pile is shown in **Fig. 16**, it is clear that increasing the modulus of elasticity of foundation soil will decrease the axial stress at pile head and increase the depth of neutral plane.

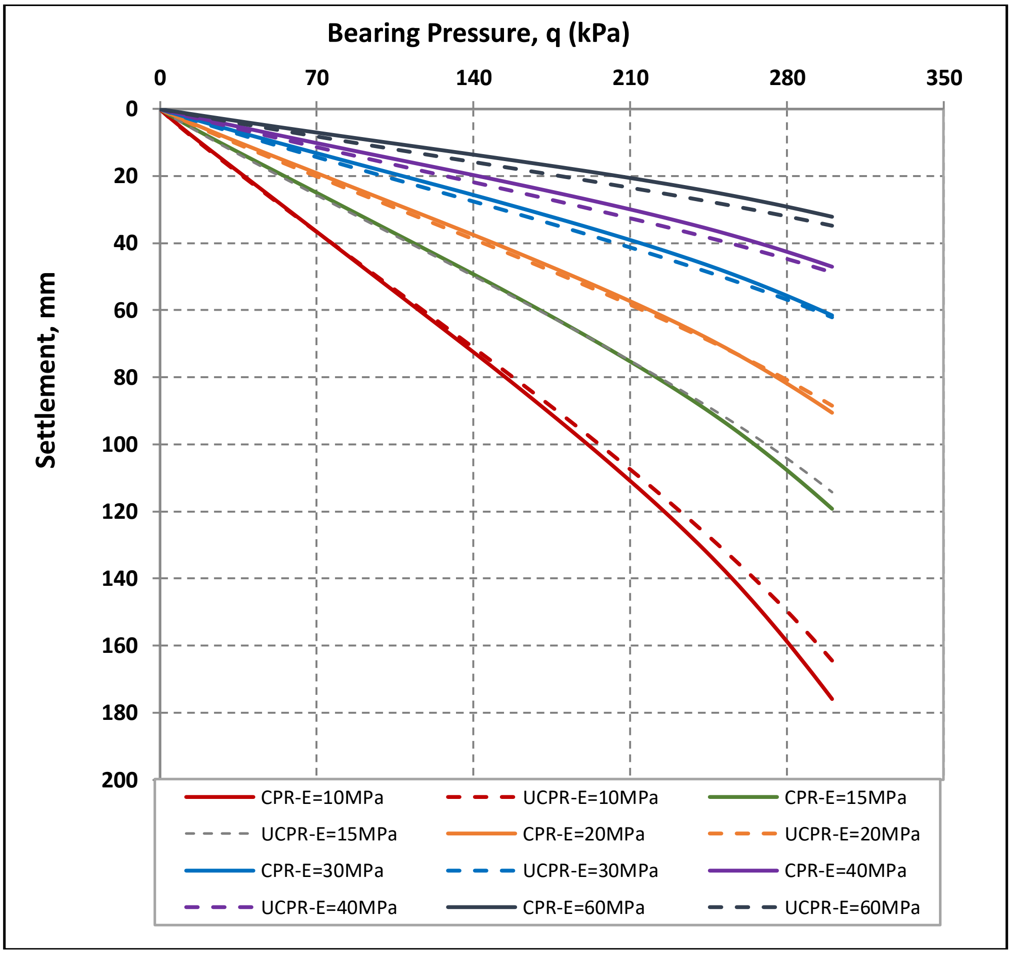

Figure 15. Load-settlement relationship for connected and unconnected piled raft.

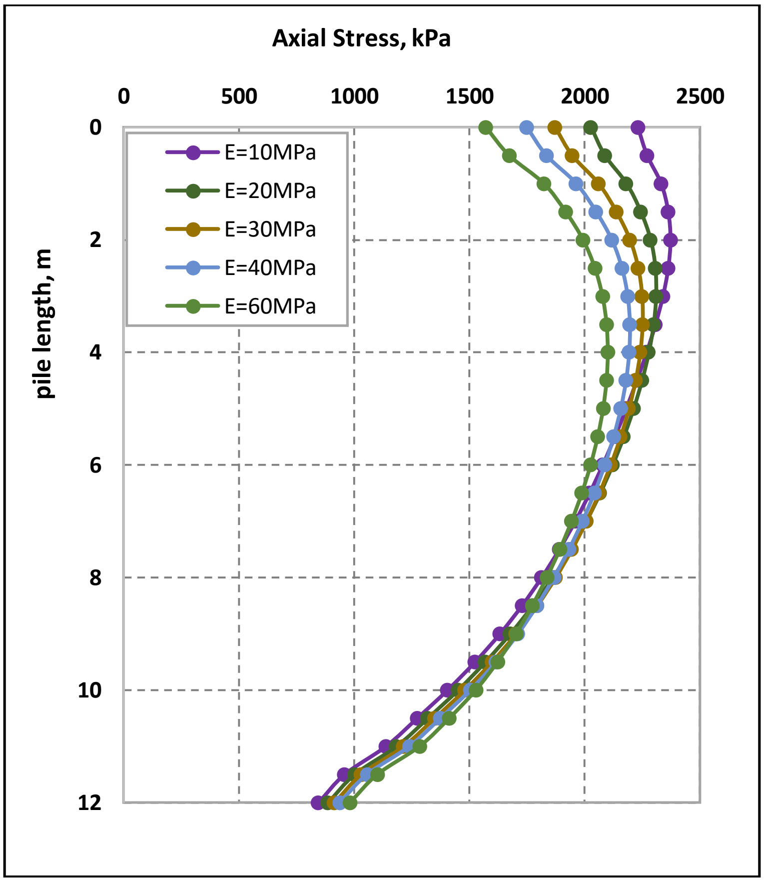

Figure 16. Effect of the foundation soil stiffness on the distribution of the axil stress along the pile.

5. CONCLUSIONS

1. The unconnected piled raft, UCPR is efficient in reducing the axial stress along the pile compared with that related to the connected piled raft, CPR. The maximum axial stress of 2607 kPa is occurs at the head of connected piles. While the axial stress at the head of unconnected piles is equal 1750 kPa and the maximum stress shifted downward.

2. The settlement of the unconnected piled raft foundation system decreases as the thickness of the cushion layer increased up to certain value after that no effect is recorded. For example, for cushion thickness of 0.25, 0.5, 0.75, and 1m; the corresponding settlements are 52.64, 49.85, 49.15, 48.66 mm.

3. The finding shows that the axial stress along the pile and pile load sharing ratio is slightly effected by increasing the cushion thickness.

4. The elastic modulus of the cushion layer has a considerable effect on the settlement of the unconnected piled raft system. For cushion elastic modulus of 20, 40, 60, 100, and 30,000 MPa the maximum settlements are 62.5, 53.8, 48.6, 47.4, and 37.9 mm, respectively.

5. As the stiffness of cushion increases the axial stress will be increases significantly, e.g. for cushion stiffness of 20, 40, 60, 100, and 30,000 MPa the axial stresses at piles head are 1441, 1621, 1750, 1848, and 3180 kPa.

6. The study showed that, as the pile length is increased the settlement of the UCPR decreases, e.g. UCPR with piles of length 6, 12, 18 m showed settlements of 64.4, 48.6, and 40.3 mm, respectively. Meanwhile, the axial stress along the pile increases noticeably.

7. Increasing the stiffness of the bearing soil will result in considerable reduction in the overall and differential settlement, but when the stiffness of the bearing soil increases the axial stress along the pile also increase. For bearing soil of stiffness of 40, 90, and $1.2x10^3$ MPa, the settlement of the UCPR system will be 48.6, 34.0, and 15.7, respectively, while the stress at the pile head will be 1750, 1830, 2351 kPa, respectively.

8. The settlement of the raft decreases significantly as the elastic modulus of the foundation soil increases for both connected and unconnected piled raft.

9. It is concluded that increasing the modulus of elasticity of foundation soil will decrease the axial stress at pile head such as increasing the modulus of elasticity from 10 MPa to 60 MPa the axial stress at piles head decreasing from 2232 kPa to 1573 kPa.

6. RFERENCES

- ABAQUS (6.14), (2014). *Analysis User's Manual*, Dassault Systèmes Simulia Corp., Providence, RI, USA.

- Al-mosawe, M. J., Al-Saidi, A. A. Jawad, F. W., (2013), "Experimental and Numerical Analysis of Piled Raft Foundation with Different Length of Piles under Static Loads", Journal of Engineering, College of Engineering, University of Baghdad, Vol. 19, No. 5, May, pp. 543-549.

- Al-Mosawe, M. J., Fattah, M. Y., Al-Zayadi, A. A. O., (2011). “Experimental Observations on the Behavior of a Piled Raft Foundation”, Journal of Engineering, College of Engineering, University of Baghdad, Vol. 17, No. 4, August, pp. 807 – 828.

- Burghignoli, A., Jamiolkowski, M. B., and Viggiani, C., 2007. Geotechnics for the Preservation of Historic Cities and Monuments: Components of a Multidisciplinary Approach, *In Proceedings of the 14th European Conference on Soil Mechanics and Geotechnical Engineering*, Madrid, Spain. pp. 3-38.

- Cao, X., Wong, I., Chang, M., 2004. Behavior of model rafts resting on pile-reinforced sand, *Journal of Geotechnical and Geoenvironmental Engineering*, 2004, No. 2, Vol. 130, pp. 129-138.

- Eslami, A., Veiskarami, M., Eslami, M., 2012. Study on optimized piled-raft foundations (PRF) performance with connected and non-connected piles-three case histories, *International Journal of Civil Engineering*, (online) No. 2, Vol. 10, pp. 100-111. http://ijce.iust.ac.ir.

- Fioravante, V., Giretti, D., 2010. Contact versus noncontact piled raft foundations, Canadian Geotechnical Journal, No. 11, Vol. 47, pp. 1271-1287. https://www.nrcresearchpress.com/loi/cgj.

- Fleming K., Weltman A., Randolph M., and Elson K. 2009. *Piling Engineering*. 3ed edition, Taylor and Francis, London & New York.

- Hor, B., Song, M., J., Jung, M., H., Song, Y., H., Park, Y., H., 2015, A 3D FEM analysis on the performance of disconnected piled raft foundation, *The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering*, Japanese Geotechnical Society Special Publication

- .

- Jamiolkowski, M., B., Ricceri, G., Simonini, P., 2009. Safeguarding Venice from high tides: site characterization & geotechnical problems. *In Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, Alexandria, Vol. 4, pp. 3209-3230.

- Liang, F., Y., Chen, L., Z., Shi, X., G., 2003. Numerical analysis of composite piled raft with cushion subjected to vertical load, *Computers and Geotechnics*, No. 6, Vol. 30, pp. 443-453. https://www.journals.elsevier.com/computers-and-geotechnics.
- Poulos, H., G., 2001. Piled raft foundations: design and applications. Ge´otechnique, 51(2): 95–113. doi:10.1680/geot.2001.51.2.95.

- Sharma, V., Vasanvala, S., Solanki, C., 2011. Effect of cushion on composite piled–raft foundation, *Journal of Engineering Research and Studies*, Vol. 2.

- Wong, I. H., Chang, M. F., and Cao, X. D. 2000. Raft foundations with disconnected settlement reducing piles. *Design application of raft foundations and ground slabs*, Chap. 17, Thomas Telford, and London, 469–486.

Appendex A

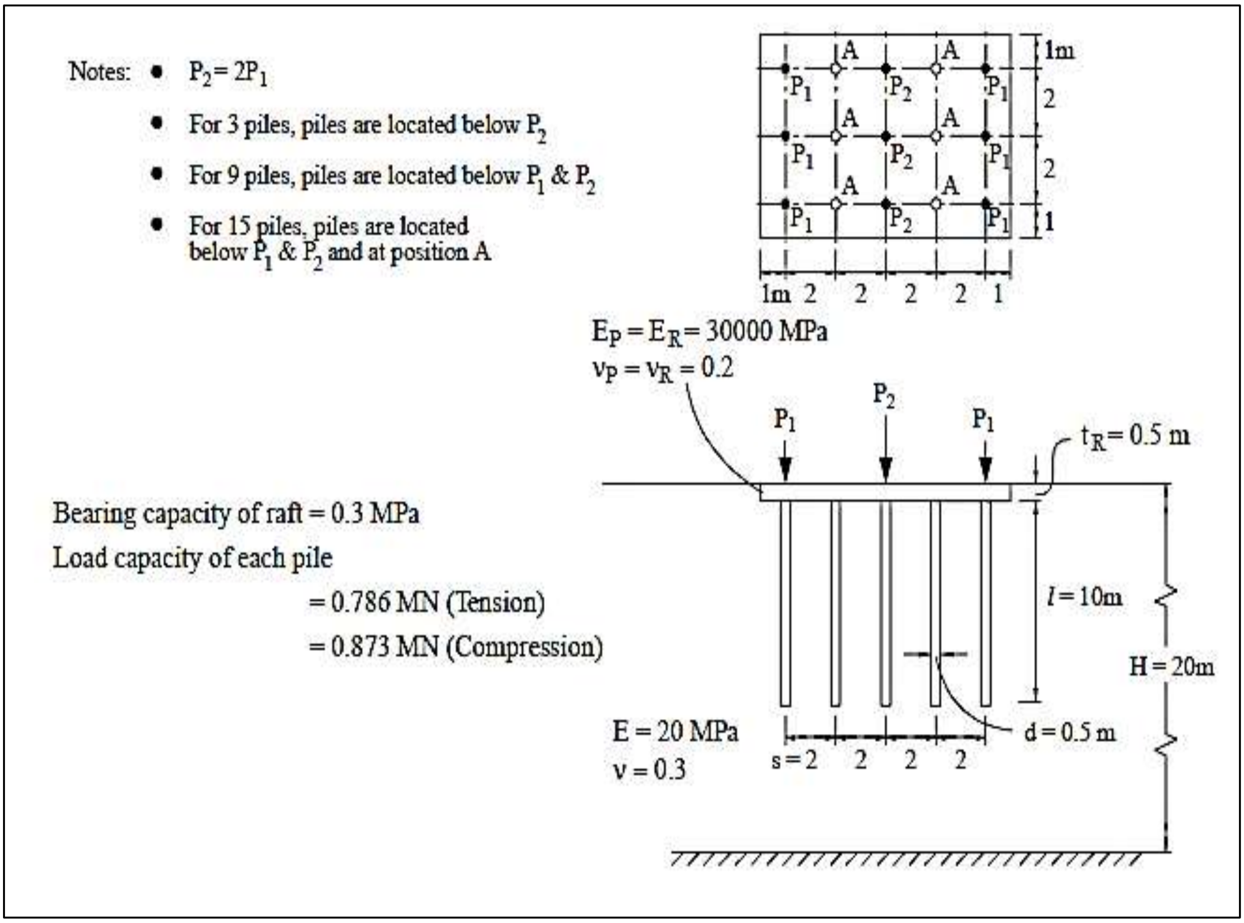

Figure A.1 Layout and material properties of piled raft example stated by Poulos (**Poulos, 2001**).