

## Finite element simulation of piled raft capacity under different loading conditions

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### ABSTRACT:

In the general design of piled raft foundations, total loads are assumed to be taken by the pile. The contact pressure between raft and the soil is neglected. This may lead to loading piles with larger loads than they should be which could be reduced by sharing it with soil on which the raft is based. In this study, a trial was made to separate the amount of load carried by piles and that carried by soil. This was achieved by elevating raft one meter above ground surface. 3D finite element program PLAXIS 3D was used to simulate this case. In this paper, the effect of different parameters on carrying capacity of the piled raft were taken into consideration, such as pile spacing, pile diameter and raft thickness. Finally, to introduce an economical design for piled raft foundation, the settlement reduction ratio (SRR) and load sharing ratio of piles ( $\alpha_{pr}$ ) were determined. The numerical results showed that the load carry by soil increases with the increases of pile spacing. In case of elevated piled raft, the load carried by piles was constant, although the pile spacing was increased under the raft thickness and pile diameter are constant. The discussion of results shows that the load carried by soil ranges from 7-14% of the total load, and maximum settlement at the elevated piled raft was higher than the maximum settlement at piled raft rested on soil with different pile spacing.

**Keywords:** Piled Raft, Settlement, PLAXIS 3D, Finite element method, load carried by soil

### 1. INTRODUCTION:

The foundation of any structure transmits the total load to the soil. It should be designed to satisfy the strength, usability and constructability requirements. The effective and economical way to

control a total and differential settlement is considered when using the piled raft concept. In conventional piled raft foundation design concept, the piles are designed to carry the total load, but it is necessary to take into account the effect of soil in load sharing between piles and soil. Several researchers investigated the behavior of piled raft

analytically, They indicated that, settlement reduction ratio (SRR), load sharing ratio of piles ( $\alpha_{pr}$ ) and maximum settlement of piled raft was influenced by raft position [1, 2] . According to [3, 4], the SRR and  $\alpha_{pr}$  are effected by pile diameter, while Oh, E., et al [5] concluded that the SRR and  $\alpha_{pr}$  are effected by the raft thickness The load sharing ratio of piles( $\alpha_{pr}$ ) and settlement reduction ratio (SRR) are defined as follows :

$$\alpha_{pr} = \frac{\sum P_{pile}}{P_{total}} \quad (1)$$

$$SRR = \frac{\text{settlement of piled raft foundation}}{\text{settlement of un piled raft foundation}} \quad (2)$$

Where  $\sum P_{pile}$  is the sum of loads at pile head, and  $P_{total}$  is the total applied loads.

In recent years, the concept of the piled raft has been used extensively in the world. An increasing number of structures, especially buildings, have been founded on them [6-9]. Piled rafts are a combined foundation type of raft and piles, usually selected when large settlements are expected, or additional bearing capacity is required. The raft in contact with soil surface directly shares loads from superstructure contact with piles at a certain load-sharing ratio. If the piled raft system did not take the raft part's load carrying capability into account, the design of piled rafts would become conventional and may be uneconomical[10]. In this paper, the three-dimensional finite element method using the PLAXIS 3D program is used to simulate the behavior of piled raft under different loading locations as shown in Fig. (1). In a numerical study, the influence of various diameter, spacing of piles and varying raft thickness were investigated.

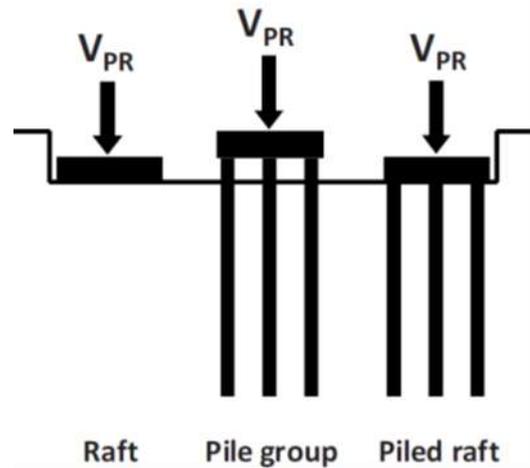


Figure 1. Representation of total vertical load 'VPR' carried by different foundation systems.

## 2. Numerical Model:

In this study, two systems of piled raft were studied. First, piled raft was elevated above soil by 1m. Second, piled raft was rested on cohesionless soil. Numerical analyses performed in this investigation were compared with the numerical results reported by Engine 2009 [11] for the verification of used PLAXIS 3D program , then parametric analyses have been carried out to investigate the effect of different parameters on the carrying capacity of piled raft system.

### 2.1 Model Verification:

Prior to performing any numerical analysis, the described simulation procedure was investigated through a comparison with existing research by Engine (2009) [11]. He studied a 130 m high rise building (Torhaus) located in Frankfurt, which was constructed between 1983 and 1986. Torhaus building consists of two rafts away a part of 10 m from each other. Two rafts were symmetric with the size 17.5 m x 24.5 m x 2.5m. Raft bottom was located at 3m depth from ground level and constructed on 42 bored pile with 0.9 m diameter

and 20 m length for each raft as shown Figure (2). The soil profile consisted of two layers. They were quaternary sand placed at 5.5 m underground surface, and Frankfurt clay under the quaternary sand. The groundwater level was 3m depth from the ground surface, [11]. The building load at each raft was  $2 \times 10^5$  KN, a uniform load on each raft was 466 KPa. Table (1) lists the material used in this verification for modeling the soil using hardening soil model. Embedded pile parameters are given in Table (2). According to Engine (2009) [11] , the unit weight of raft  $\gamma = 25\text{KN/m}^3$  , the

Young's modulus of raft is equal to  $3.7 \times 10^7 \text{KN/m}^3$  , Poisson ratio of raft  $\nu$ . The piles under each raft are arranged as a  $6 \times 7$  rectangular configurations with a center-to-center spacing of 2.9 m and 3.5 m along the shorter and the larger side of the raft, respectively. According to (Katzenbach et al. 2000), the piled raft foundation's design was based on a traditional method where the piles are assumed to be loaded to their ultimate bearing capacities and raft assumed to transmit the remaining part of the load.

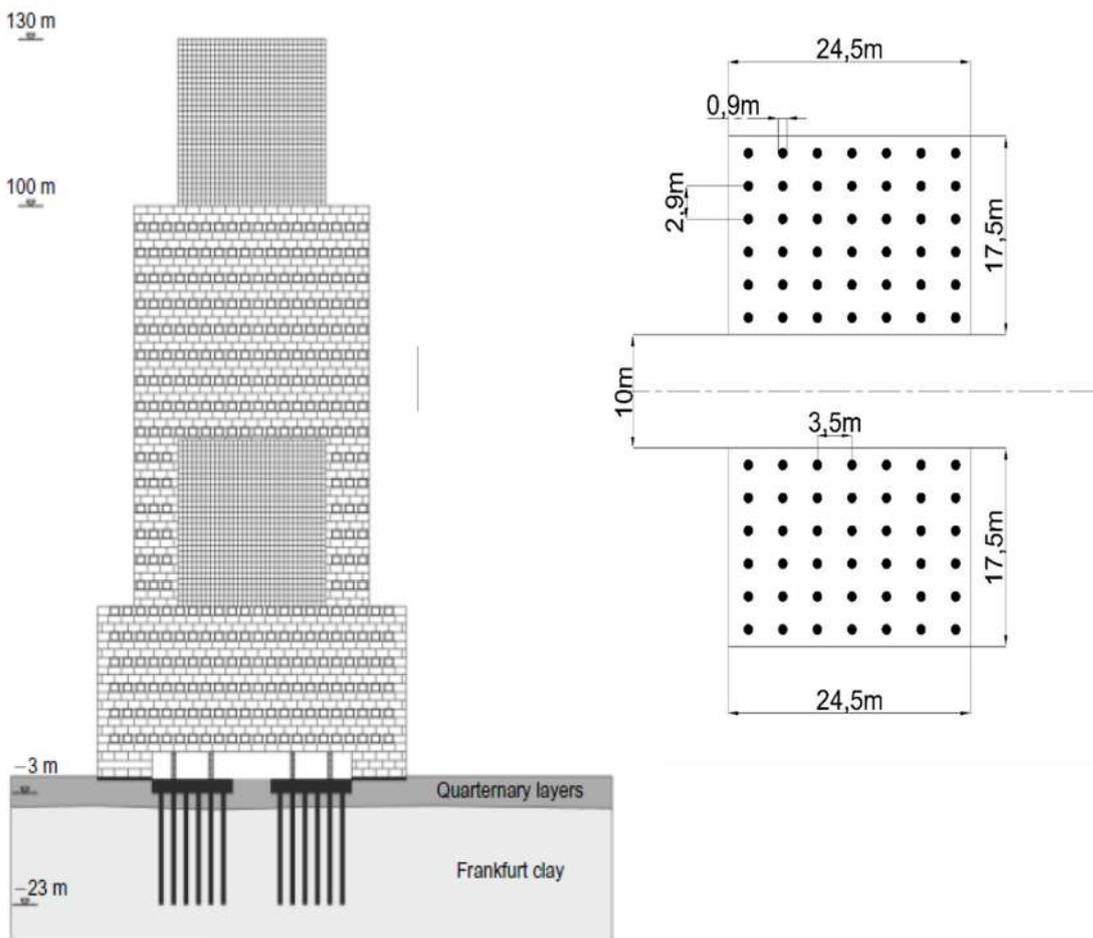


Figure 2. (a) Side view of Torhaus building (b) Top view of the foundation

Table 1. Model parameter used in the analysis  
H.K Engine 2009 [11]

Property	Unit	L1**	L2**
Material model	Material model	H.S.*	H.S.*
Unit weights $\gamma / \gamma_{dry}$	KN/m <sup>3</sup>	11/19	10/20
Reference Secant stiffness, $E_{50}^{ref}$	KN/m <sup>2</sup>	$3 \times 10^4$	$3.5 \times 10^4$
Ref. oedometer stiffness, $E_{oed}^{ref}$	KN/m <sup>2</sup>	$3 \times 10^4$	$4.28 \times 10^4$
Ref. unloading-reload. stiffness, $E_{ur}^{ref}$	KN/m <sup>2</sup>	$75 \times 10^4$	$1.05 \times 10^5$
Stress dependency power, m	-	0.5	1
Poisson's ratio, $\nu_{ur}$	-	0.2	0.2
Cohesion, c'	KN/m <sup>2</sup>	0.0001	20
Internal friction, $\phi$	°	35	20
Dilatancy angle, $\Psi$	°	0	0
At rest lat. Press. coeff. for NC, $K_o^{NC}$	-	0.426	0.8
Over consolidation ratio, OCR	-	1	1
Past overburden press., POP	KN/m <sup>2</sup>	0	0
Interface stiffness ratio, $R_{int}$	-	1	1
* HS: Hardening Soil Model, ** L1: Quaternary sand and gravel, L2: Frankfurt Clay			

Table 2. Embedded pile properties

Property	Unit	Value
Pile diameter, D	m	0.9
Pile length, L	m	20
unit weight, $\gamma$	KN/m <sup>3</sup>	15
Moment of inertia, $I_2=I_3$	m <sup>4</sup>	.032
Poisson's ratio, $\nu_{ur}$	-	0.2
Young's modulus, E	KN/m <sup>2</sup>	$2.35 \times 10^7$
Max. skin friction:		
$T_{top}^{max}$	KN/m	453
$T_{bottom}^{max}$	KN/m	453
Max. tip resistance	KN	1200
Material type	Concrete circular pile	

Figure (2) shows the results of the FEM and conducted by Engine (2009) and the load-settlement behavior results obtained by present work analyses is in reasonable agreement with the measured behavior by Engine (2009). The results show agreement between Present and Engine (2009) study with a maximum difference as indicated in Table (3)

The finite element PLAXIS 3D results showed that the piles carry 94% of total load, whereas the piles carry 92% of the total load as given by Engine (2009), and this is an agreement to some extent as shown in Table (3).

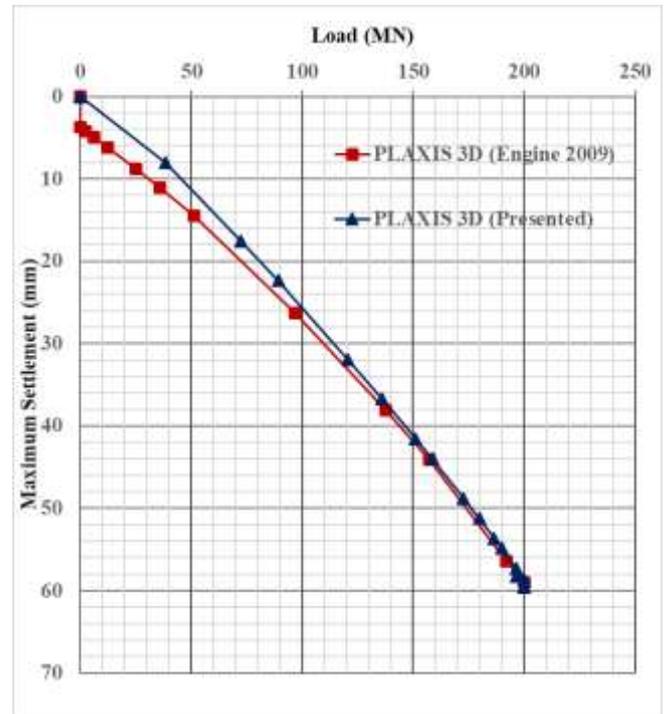


Figure 2. Load settlement of northern piled raft of Messe Torhaus Building

Table 3. Summary of results

Name of Study	Maximum settlement (mm)	$\alpha$	Difference (mm)	%Diff
Engine 2009	60	92%	1mm	1.6%
PLAXIS 3D Presented	59	94%		

## 2.2. Finite element simulation:

As mentioned before, 3-D numerical analysis was performed using 3D Finite element program PLAXIS 3D to simulate the settlement of piled raft under different load conditions. The parametric study's main purpose is to evaluate the load transmission between piles and raft. Also, to investigate the piled raft performance under a variable parameter such as pile spacing, pile diameter, the thickness of raft, and raft location. The following physical properties were adopted in the PLAXIS 3D program.

### 2.2.1. Material model parameter:

#### 1. Soil properties:

The soil in all cases was assumed as medium sand according to Egyptian Code of Practice for Soil mechanics and Foundations Design (2001) [12]. The soil properties used in the model are listed in table (4).

#### 2. Raft properties:

In this study, three different positions of raft were chosen as shown in Fig (4.a). To simulate the raft in PLAXIS 3D, "plate" is used. All properties of raft used in this study is listed in Table (5).

#### 3. Pile Properties:

Modeling a pile in PLAXIS 3D was selected as "Embedded Pile". Resistance of pile in soil depended on the friction resistance only so the value of the tip resistance force equal zero. Table (6) illustrates the pile properties used in the numerical model.

### 2.2.2. Modeling Mesh and boundary condition:

The FE mesh comprised 15-noded wedge is a parametric element and the necessary detailed mesh sensitivity. The lateral boundary of the computational domain allows vertical movement but the boundary sensitivity studied indicated that these should be positioned at a distance of 5B according to (Mali 2019) [13].

The model dimension is (150×150×75m) carrying a piled raft with dimension (30×30m), and the pile length is 20m as shown in Fig. (4.b) and Fig. (5). When the geometry model is completed, the finite element mesh can be generated as shown as in Fig (6).

### 2.2.3. STUDY RESULTS :

Thirteen different series of numerical analysis contained thirty one cases were carried out as input parameter such as ( $D_{pile}$ ), ( $T_{raft}$ ) and ( $S_{pile}$ ) were varied to assess their effects on Raft position, and ( $\alpha_{pr}$ ) which are summarized in Table (7). Series 1 and 2 were conducted to investigate the effect piles spacing on raft position to determine load sharing ratio of piles ( $\alpha_{pr}$ ) while ( $T_{raft}$ ) and ( $D_{pile}$ ) were kept constant. Secondly, series 3 of unpiled raft was performed to determine the settlement reduction ratio (SRR) while ( $T_{raft}$ ) was also kept constant. In series 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13, the effects of ( $D_{pile}$ ), ( $T_{raft}$ ), ( $S_{pile}$ ), Pile position on (SRR) and ( $\alpha_{pr}$ ) were investigated numerically while some parameters were kept constant such as raft dimension and pile length. Table (7) summarized these series.

Table 4. Soil properties used in the numerical model

Parameters of Medium Sand			
parameter	Symbol	Medium sand	unit
model	Hardening model		
Drained Behaviour	Drained		
Unsaturated unit weight	$\gamma_{unsat}$	17.00	KN/m <sup>2</sup>
Saturated unit weight	$\gamma_{sat}$	19.00	KN/m <sup>2</sup>
Young's modulus	E'	$4 \times 10^4$	KN/m <sup>3</sup>
Secant stiffness in standard drained triaxial test	$E_{50}^{ref}$	$4 \times 10^4$	KN/m <sup>3</sup>
tangent stiffness for primary oedometer loading	$E_{oed}^{ref}$	$4 \times 10^4$	KN/m <sup>3</sup>
Unloading / reloading stiffness	$E_{ur}^{ref}$	$12 \times 10^4$	KN/m <sup>3</sup>
Cohesion	$S_{u,ref}$	0.0001	KN/m <sup>2</sup>
angle of internal friction	$\phi'$	35.00	°
Angle of dilatancy	$\Psi$	5.00	°
power of stress-level dependency of stiffness	M	0.500	
Poisson's of ratio	$\nu'_{ur}$	0.300	
value of normal consolidation	$K_o^{nc}$	0.426	
Reference stress for stiffness	$P_{ref}$	100	KN/m <sup>2</sup>
Failure ratio	$R_f$	0.900	
initial void ratio	$e_{init}$	0.500	

Table 5. Raft properties used in the numerical model

parameter	Symbol	Values	unit
Unit weight	$\gamma$	15.5	KN/m <sup>2</sup>
Width	B	30	m
Length	L	30	m
Thickness	T	2	m
Young's Modulus	E	$25 \times 10^6$	KPa
Poisson ratio		0.20	

parameter	Symbol	Values	unit
Unit weight	$\gamma$	6	KN/m <sup>2</sup>
Poisson's ratio	$\nu_{ur}$	0.2	
Young's Modulus	E	$25 \times 10^6$	Kpa
Lenght	L	20	m
Diameter	D	1	m
Skin friction per unit length	$T_{top,max}$ $T_{bot,max}$	Calculated for each case	KN/m
Tip resistance force	$F_{max}$	Calculated for each case	KN
Material type	Concrete Pile		
Pile type	Massive circular pile		

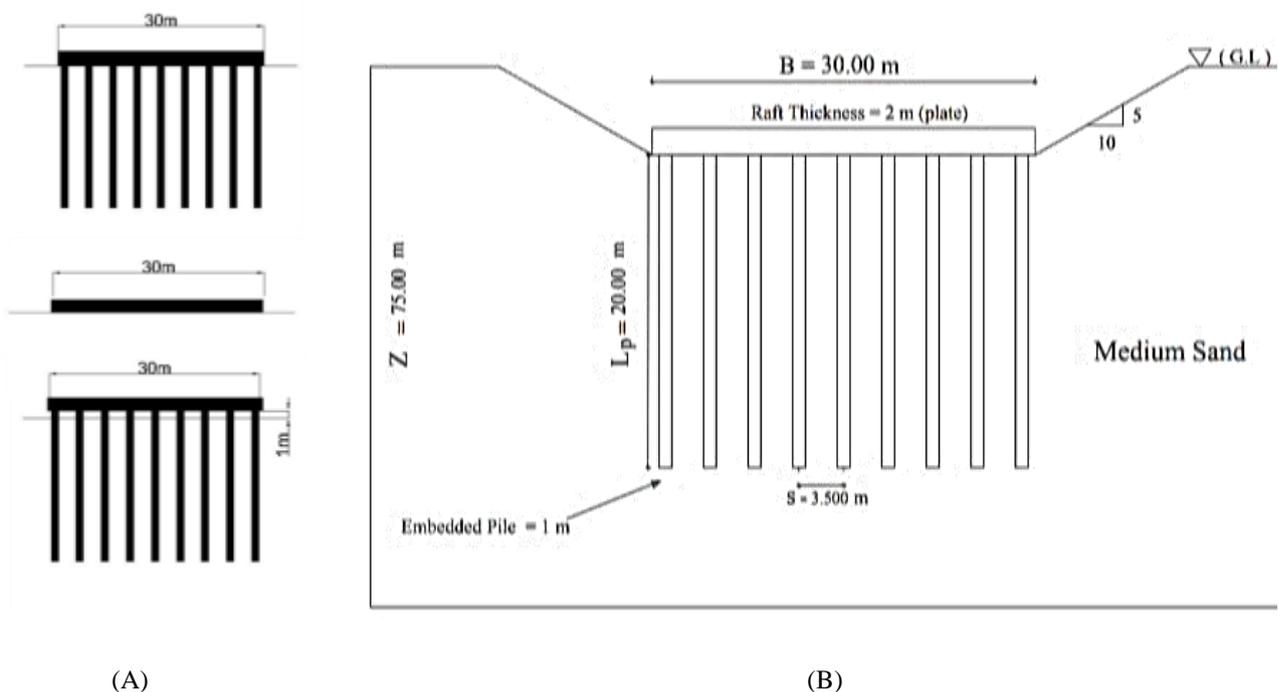


Figure 4. (A) Position of raft (B) Geotechnical model

Piled raft modeled in PLAXIS 3D were composed of square raft dimensions, pile diameter and raft thickness were equal to 30×30m, 1m and 2m, respectively. Number of piles were changed due to change pile spacing while keeping 1m distance from center of edge and corner pile to raft edge constant. Four spacing between piles were considered 2.0, 2.8, 3.5 and 4.0m. The bottom of

the raft is located at 5 meters below the ground, the site must be excavated for 5 meters from top to bottom However, 5-meter-deep excavation may be impossible because of stability problems. Therefore, the "Soil body collapses" error may occur during the excavation phase. To overcome this stability problem, the 1V:2H approach is applied by excavating the ground angularly.

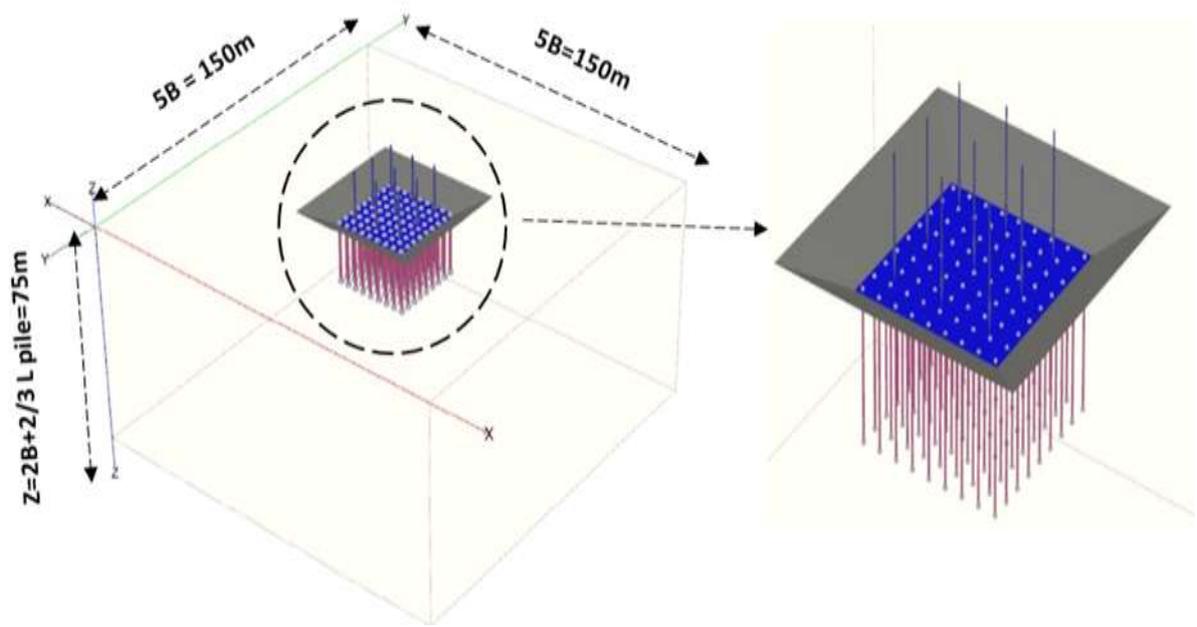


Figure 5. Piled raft model at PLAXIS 3D

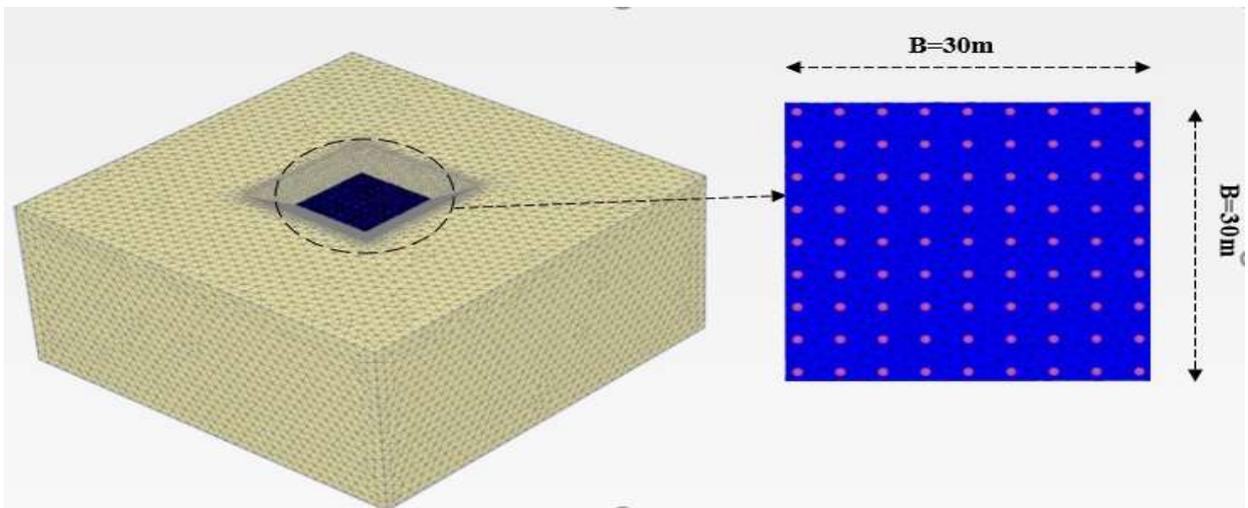


Figure 6. Finite element model for a piled raft

Table 7. of Numerical analysis program conducted in this study on medium sand

Series	Raft location	Pile diameter	Raft thickness	Pile spacing
1	Raft rested on soil	1m	2m	2,2.8,3.5and4m
2	Raft elevated by 1m above soil	1m	2m	2,2.8,3.5and4m
3	Unpiled raft	-	2m	-
4	Raft rested on soil	1.25m	2m	2,2.8,3.5and4m
5	Raft elevated by 1m above soil	1.25m	2m	3.5m
6	Raft rested on soil	1.5m	2m	2,2.8,3.5and4m
7	Raft elevated by 1m above soil	1.5m	2m	3.5m
8	Raft rested on soil	1m	1.5m	2,2.8,3.5and4m
9	Raft elevated by 1m above soil	1m	1.5m	3.5m
10	Unpiled raft	-	1.5m	-
11	Raft rested on soil	1m	2.5m	2,2.8,3.5and4m
12	Raft elevated by 1m above soil	1m	2.5m	3.5m
13	Unpiled raft	-	2.5m	-

### 3. Results and Discussion

The aim of study is to evaluate maximum settlement accompanied with unpiled raft, piled raft rested on soil and piled raft elevated by 1m above soil. In addition to calculate load sharing ratio of piles ( $\alpha_{pr}$ ), settlement reduction ratio (SRR) and load carried by piles and soil under the effect of various parameters.

#### 3.1. Effect of raft location

Piled raft rested on soil and piled raft elevating by 1.0m above soil was analyzed considering the pile spacing 2.00m, 2.8m, 3.5m, and 4.00m. The pile length is kept constant at 20m. The diameter of the pile was set to 1m and raft thickness equal 2m. The uniform load is equal to 300 KPa.

A relationship between load and settlement for different pile spacing as shown in Figure (7). It can be seen that maximum settlement of 77mm, 81.77mm, 87.2mm and 93.6mm was obtained with pile spacing of 2.0, 2.8m, 3.5m and 4m, respectively. When piled raft elevated by 1m above soil, the total load transmitted to piles was found to be equal to 315000KN.

Figure (8) shows that maximum settlement of 70.1mm, 72.9 mm, 76.8 mm and 80.3 mm, respectively was obtained with pile spacing of 2.0m, 2.8m, 3.5m and 4m, respectively. when piled raft rested on soil, for case of unpiled raft, the maximum settlement was 150.3 mm. Figure (9) shows a relationship between load carried by piles

against pile spacing. It was noticed that the total load transmitted to piles was ( $2.88 \times 10^5 \text{KN}$ ,  $2.85 \times 10^5 \text{KN}$ ,  $2.79 \times 10^5 \text{KN}$ , and  $2.75 \times 10^5 \text{KN}$ ), respectively with pile spacing of 2.0m, 2.8,3.5m and 4m, respectively, in case of piled raft rested on a soil. Figure (10) shows that SRR values ranged from 0.47 to 0.54 for all used pile spacing.

Figure (11) indicates that pile spacing increased with the loading carried by soil in the.

piled raft system increased for medium sand soil

Figure (12) explains that load carried by piles in piled raft increased while load carried by the soil in the piled raft system decreased. when pile spacing decreased. The effect of pile spacing on the load-sharing coefficient ( $\alpha_{pr}$ ) as shown in Figure (13). It can be noticed that its value decreases with the increase of pile spacing.

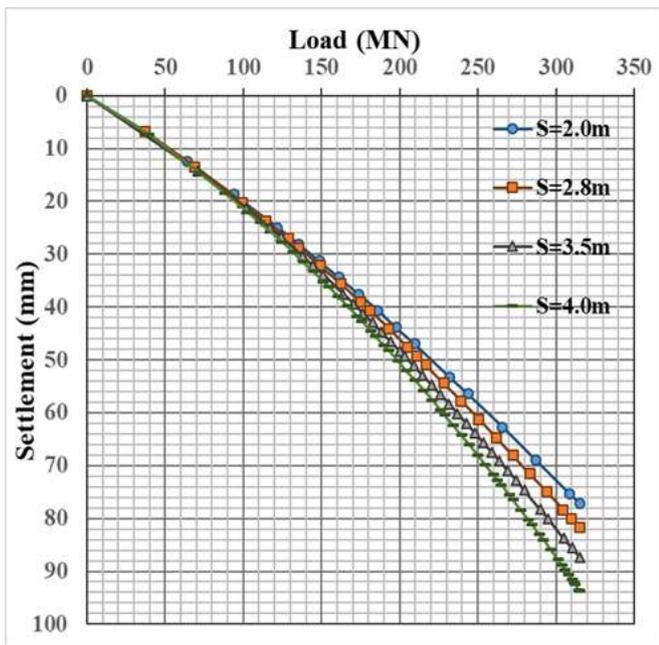


Figure 7. load-settlement curve for piled raft (Raft above soil 1m)

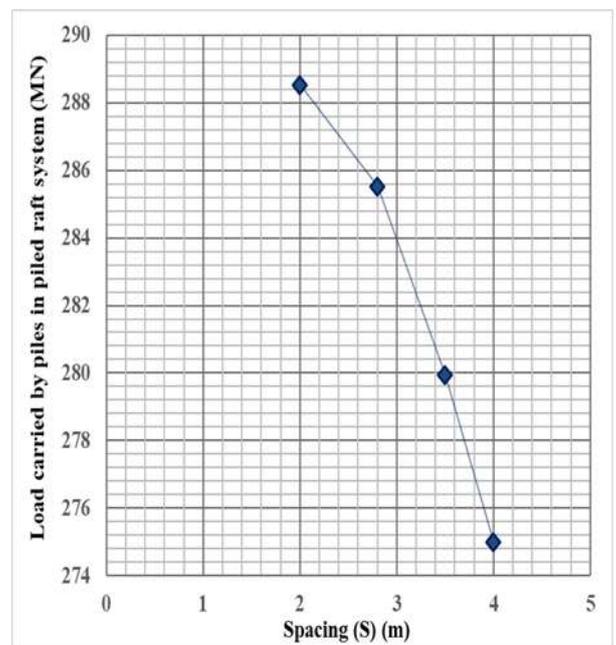


Figure 9. Relation between load carried by piles and the piles spacing (Raft rested on soil )

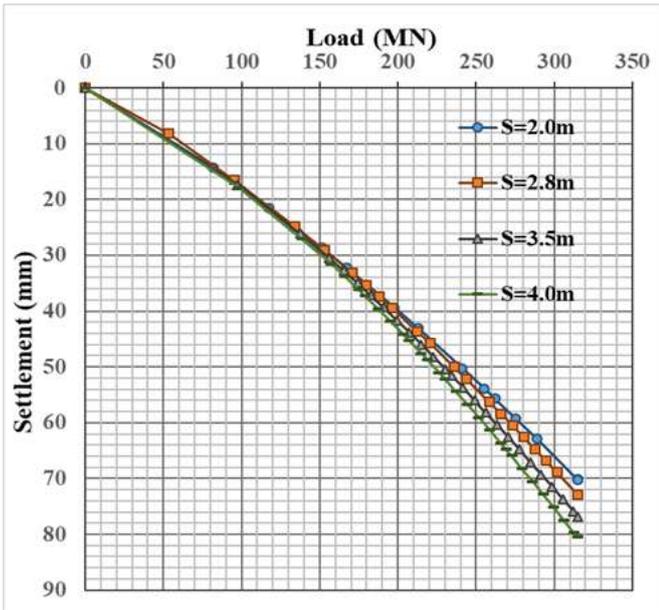


Figure 8. load -settlement curve for piled raft (Raft rested on soil)

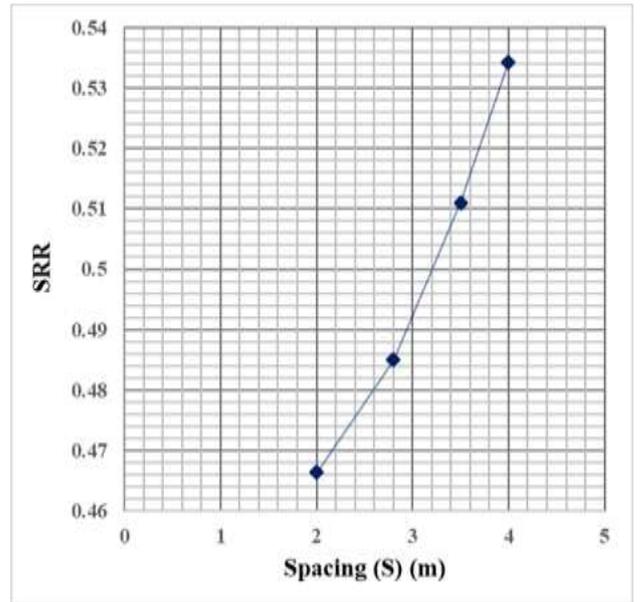


Figure 10. Figure 9. SRR VS Spacing between piles (Raft rested on soil)

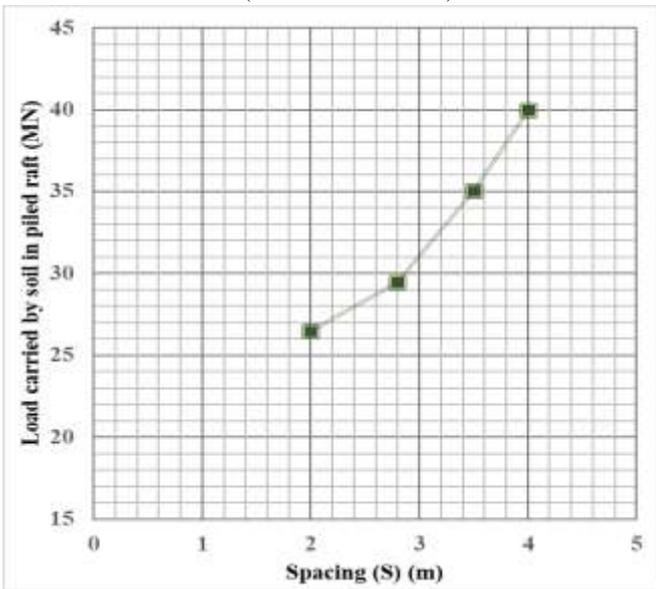


Figure 11. Load carried with soil in a piled raft system VS. spacing between piles (S)

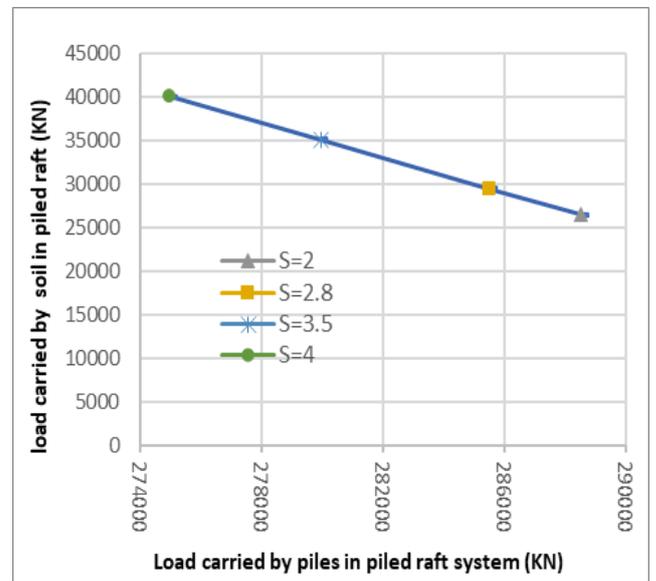


Figure 12. loading carried with soil in the piled raft Vs. Loading carried with piles in the piled raft system

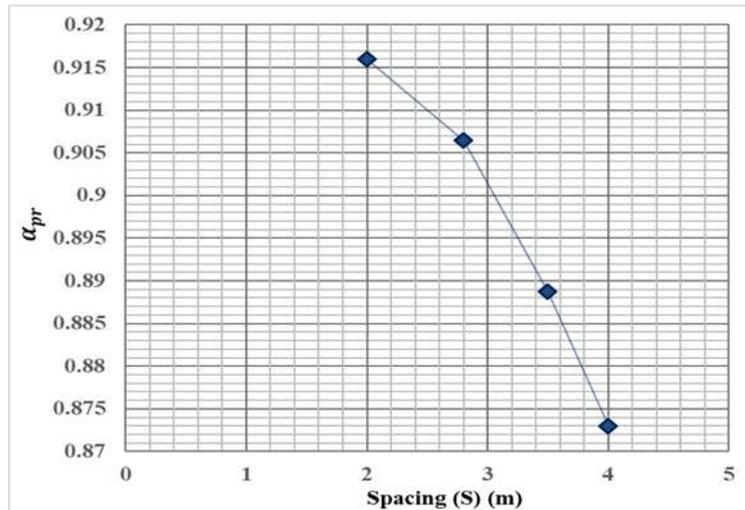


Figure 13. Load sharing coefficient ( $\alpha_{pr}$ ) VS spacing(S)

### 3.2.Effect of raft thickness

For piled raft rested on the soil with pile spacing of 2.00m, 2.80m, 3.50m and 4.00m. Various raft thickness equal to 1.5m, 2m, and 2.5m were studied to determine the effect of raft thickness on the settlement of piled raft. Assume the pile length 20m and the pile diameter 1m.

According to Figure (14), it can be noticed that load carried by piles decreases with increasing the pile spacing for different raft thickness rested on soil in all cases. As the thickness of raft increased piles load in a piled raft system increased

due to the increasing in the raft self-weight. Figures (14) and (15) show that the total load carried by soil decreases with increasing of the load carried by piles. Moreover, as pile spacing increased, load carried by soil increased in all

cases of raft thickness. On the contrary, as the pile spacing increased, piles load decreased.

The pile load increased in case of elevated piled raft as raft thickness due to the increase in the raft's weight. The piles load for ( $T_{raft}$ ) is 1.5m, 2.00m and 2.50m are  $303 \times 10^5$  KN,  $3.15 \times 10^5$  KN, and  $326 \times 10^5$  KN. For example, at 3.5 m spacing, the maximum settlement of piled raft rested on soil (PR) at any raft thickness was less than maximum settlement of elevated pile raft (EPR). The change of maximum settlement is slight for PR at difference raft thickness, as shown at Figure (16). Figure (17) shows that, the value of Settlement reduction ratio is constant for raft thickness 2.0m and 2.5m with change pile spacing while the value of SRR decreased as pile spacing decreased for raft thickness 1.0m

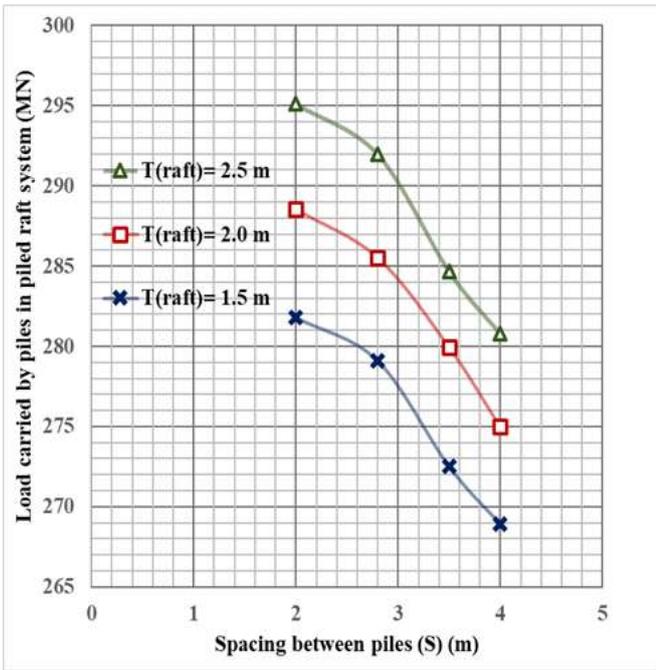


Figure 14. spacing between piles VS. Load carried by piles in a piled raft system

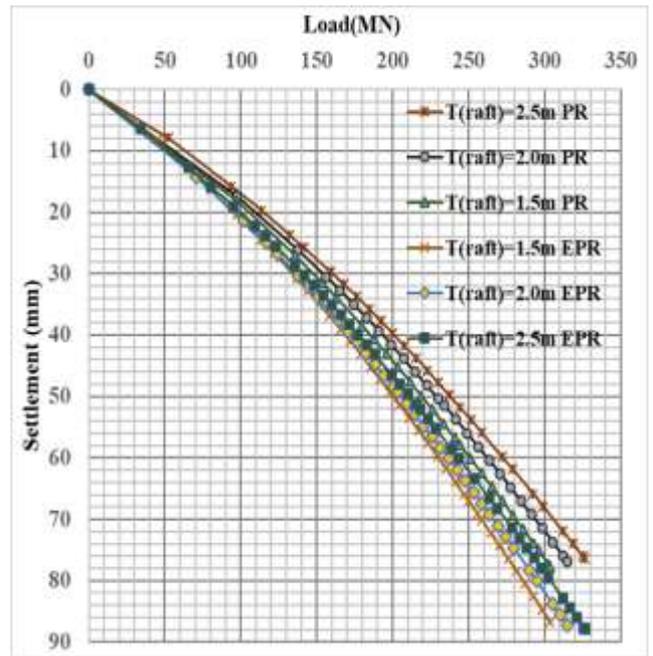


Figure 16. Load -settlement for elevated piled raft at S=3.5m with difference raft thickness

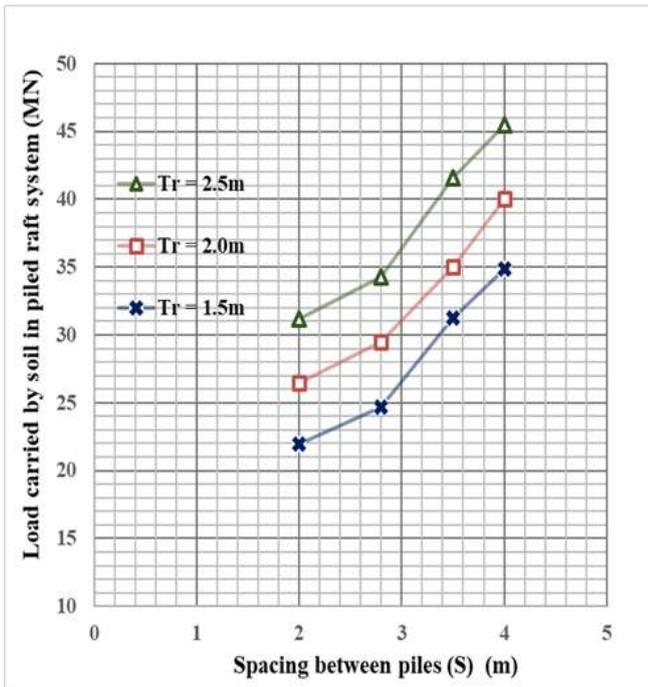


Figure 15: Spacing between piles VS. Load carried by the soil in the piled raft

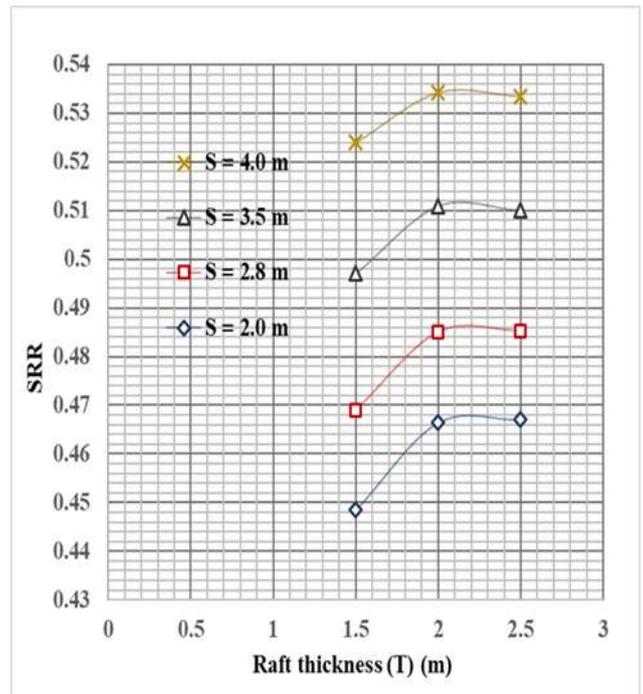


Figure 17. SRR VS. raft thickness

**3.3. Effect of pile diameter:**

The effect of pile diameter on the settlement of the piled raft rested on soil was studied using pile spacing of 2.00m, 2.8m, 3.5m and 4.00m. Also, the pile diameter was taken from 1.00m, 1.25m, and 1.5m for the raft thickness equal 2m and pile length equal 20m.

For example, at spacing 4.0m, settlement reduction ratio decreased as pile diameter increased. At diameter 1.0m, SRR decreased as pile spacing decreased, as shown at Figure (18). According to Figure (19), as pile diameter decreases, the soil load in a piled raft system

increases with different pile spacing. As pile spacing increases, the load carried by soil increases. According to Figure (20), as pile diameter increases, pile load increases with the different pile spacing. Also, as pile spacing between piles increases, the soil's load in the piled raft system increases for raft thickness.

In Fig (21), it could be observed that, for spacing 3.5m, the maximum settlement of piled raft rested on soil (PR) is less than a maximum settlement of elevated piled raft (EPR). On the other hand, as the pile diameter increases, the maximum settlement decreases whether in PR or EPR.

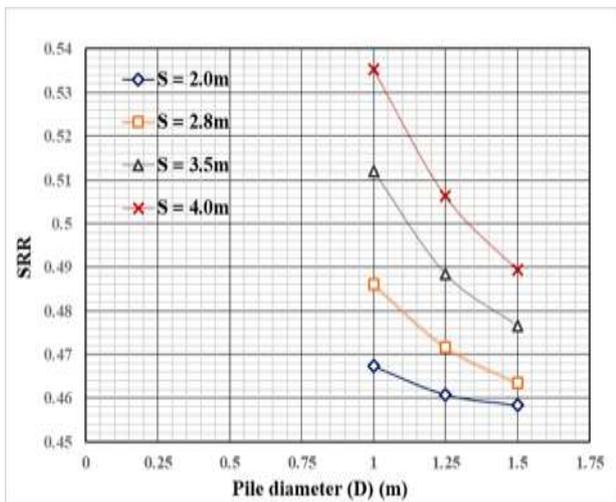


Figure 18. SRR VS. pile diameter

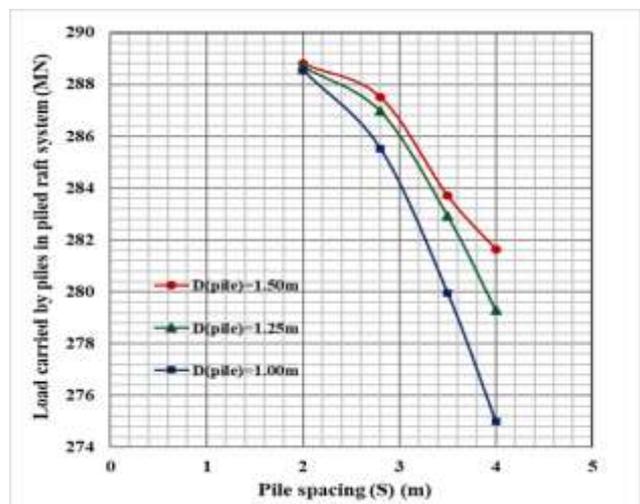


Figure 20: Spacing between piles VS. load carried by the piles in the piled raft

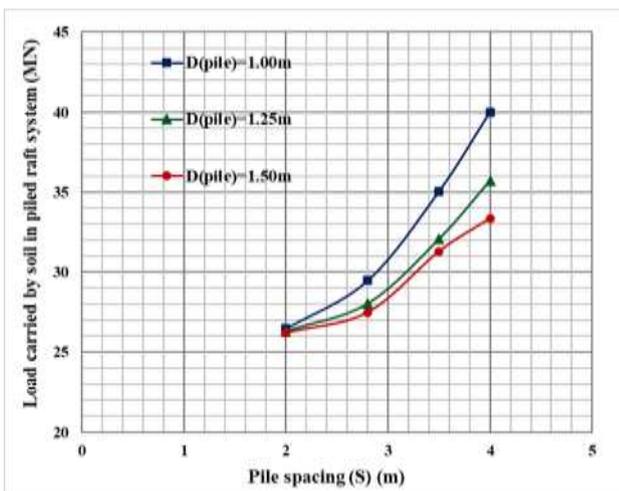


Figure 19. loading carried by the soil in a piled raft system VS. spacing between piles (S)

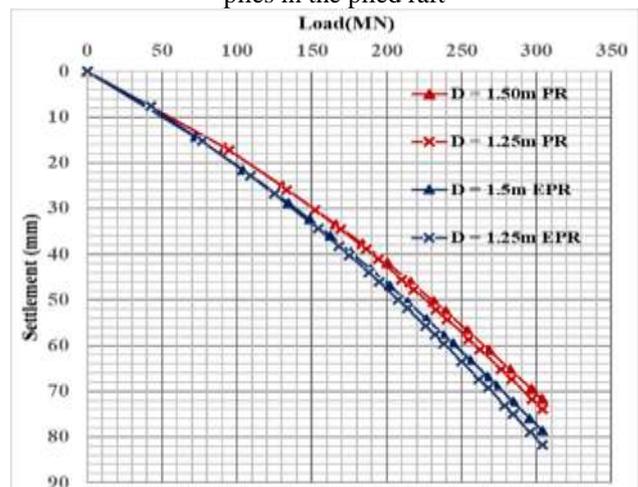


Figure 21. Load -settlement for elevated piled raft and piled raft at S=3.5m with a difference pile diameter

#### 4. Conclusion:

Based on the current study, it could be concluded that:

1. The results obtained from finite element analyses using PLAXIS 3D with Hardening Soil Model (HSM) have a good agreement with load-settlement behavior of piled raft system results presented by Engine (2009).
2. The maximum settlement at elevated piled raft 1m above soil was higher as compared to piled raft settlement rested on soil in all analyzed pile spacing.
3. In case of elevated piled raft, the load carried by piles was constant although the pile spacing was increased due to the absence of contact between soil and raft. However, the load of single pile load, within grouped piles, increased, as the pile spacing increased.
4. Load carried by soil at piled raft system increased as the spacing between piles increased and load carried by piles decreased.
5. The load carried ratio by soil ranged from 7 - 14%. Whereas the greater the distance between piles, the greater is this ratio. According to the previous domain, load carried by soil increased with the increase of raft thickness and decrease of pile diameter.
6. The settlement reduction ratio ranges between 0.45 - 0.54, which increases with the increase in pile spacing, and therefore, the settlement reduction ratio decreased as piles diameter increased and pile spacing decreased.
7. Both piles load and load sharing ratio of piles increased as pile spacing decreased and pile diameter increased. Also, both piles load and load sharing ratio of piles increase with increasing of raft thickness.

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**NOTATION:**

**$\alpha_{pr}$**  Load sharing ratio  
of piles

**SRR** Settlement  
reduction ratio

**PR** Piled raft rested  
on soil

**EPR** Elevated piled raft

**$T_{raft}$**  Raft thickness

**$D_{pile}$**  Pile diameter

**$S_{pile}$**  Pile Spacing