Geomechanics and Engineering, *Vol. 14, No. 1 (2018) 43-50*
DOI: https://doi.org/10.12989/gae.2018.14.1.043

Evaluation of performance of piled-raft foundations on soft clay: A case study

Mohammadreza Khanmohammadi* and Kazem Fakharian[a]

Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran 15875-4413, Iran

(Received December 1, 2016, Revised March 18, 2017, Accepted June 22, 2017)

Abstract. Applicability of constructing piled raft foundations on soft clay has been given attention in recent years. Lack of sufficient stiffness for soil and thus excessive settlements to allow higher contribution of piles is the major concern in this regard. This paper presents a numerical investigation of performance of piled-raft foundations on soft clay with focusing on a case study. A 3D FEM numerical model is developed using ABAQUS. The model was calibrated by comparing physical and numerical modeling results of other researchers. Then the possibility of using piled-raft system in construction of foundation for a water storage tank in Sarbandar, Iran is assessed. Soil strength parameters in the numerical model were calibrated using the instrumentation data of a heavily instrumented preloading project at the construction site. The results indicate that choosing the proper combination of length and spacing for piles can lead to acceptable differential and total settlements while a high percentage of total bearing capacity of piles can be mobilized, which is an efficient solution for the project. Overall, the construction of piled-rafts on soft clays is promising as long as the total settlement of the structure is not imposing restrictions such as the common 25 mm allowable settlement. But instead, if higher allowable settlements are adopted, for example in the case of rigid steel tanks, the method shall be applicable with considerable cost savings.

Keywords: piled-raft; soft clay; numerical modeling; case study

1. Introduction

Combined piled-raft foundation (CPRF) is an innovative idea proposed since 1970s (e.g., Davis and Poulos 1972, Hooper 1973, Hight and Green 1976). Adding piles to raft foundations contributes to reduction of settlement and increase in the bearing capacity of the raft. Generally speaking, using CPRF systems will result in a considerable reduction of number and lengths of piles, improving serviceability in both total and differential settlements and minimizing tilt and instability probabilities. On the other hand, reducing number and length of piles contributes to significant savings in construction costs (Randolph 1992, Horikoshi and Randolph 1998).

It has been proven that if soil layers retain a relatively high bearing capacity, using a piled-raft system will be considerably cost effective compared to a conventional (rigid) pile group system, but designers are reluctant to use the piled-raft system in soft soils due to excessive settlements (Randolph 1992, Poulos 2001). However, there are successful cases that piled-raft systems were used on soft clays. Piles with different lengths in the piled-raft system (long piles on central region and short piles on the sides) can be used as a method to control the differential settlements. (Poulos 2005, Tan *et al.* 2005, Cho *et al.* 2012).

In order to evaluate the behavior of piled-raft systems, some researchers carried out laboratory tests (e.g., Horikoshi and Randolph 1996, Lee *et al.* 2014, Fattah *et al.* 2015). Some used computational methods to evaluate and predict the performance of piled-raft foundations. For example, Nakanishi and Takewaki (2013) presented an optimal design method for determining pile lengths of piled-raft foundations using a simplified settlement analysis procedure or Leung *et al.* (2009) presented the optimization analyses of piled rafts and pile groups, where pile lengths are varied across the group to improve the overall foundation performance. Numerical simulations can also be employed to predict piled-raft behavior with acceptable precision in computations (Cho *et al.* 2012, Lee *et al.* 2010, Poulos 1994, Katzenbach *et al.* 1998, Kim *et al.* 2001, Fakharian and Javanbakht 2012, Fakharian and Khanmohammadi 2012). Some researches have presented the data obtained from instrumentation and monitoring of the field projects (e.g., Tan *et al.* 2005, Yamashita *et al.* 2016). Finite Element Method (FEM) as a practical numerical solution to complicated problems is used by some researchers for investigation of piled-raft foundations and their behavior (e.g., Ata *et al.* 2015, Fattah *et al.* 2013, Sawant *et al.* 2012, Chore and Siddiqui 2016, Al-Omari *et al.* 2016). Three-dimensional simulation using FEM and also using field data monitoring have been employed in this study to predict the settlements of piled-raft foundations.

This paper evaluates the performance of piled-raft foundation systems in soft clayey layers of Sarbandar water storage tanks located near Mahshahr Petrochemical Zone (PETZONE). Mahshahr, located in southwest of Iran, is a center of extensive industrial projects. The existence of soft clay at top layers of stratification of the region and excessive loading due to large storage facilities lead to

*Corresponding author, Ph.D. Candidate
E-mail: m.r.kh@aut.ac.ir or mkhanmohammadi@ymail.com
[a]Associate Professor

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

major settlements in foundation systems. Rigid pile group systems are normally used to reduce the settlements to allowable limits. However, piled-raft foundation systems can lead to significant time and cost saving of the project, if some additional total settlement could be allowed compared to conventional rigid pile group systems.

A 3D finite element model has been utilized in this study to simulate the piled-raft system on the soft soil. The model has been calibrated using the results of a heavily instrumented preloading project at the study site. Using the instrumentation data of the consolidation settlement period, strength and deformation parameters of the soil (especially Young Modulus) are back-calculated so that the predicted settlements of the soil layers and the numerical model match the field measurements both at the ground surface and along the depth of stratification. The model is then used to evaluate the effects of different parameters on total settlements, differential settlements and pile bearing factor for various pile arrangements. In addition, the results are also used to evaluate the stiffness of piles (load to displacement ratio) at different locations in the group.

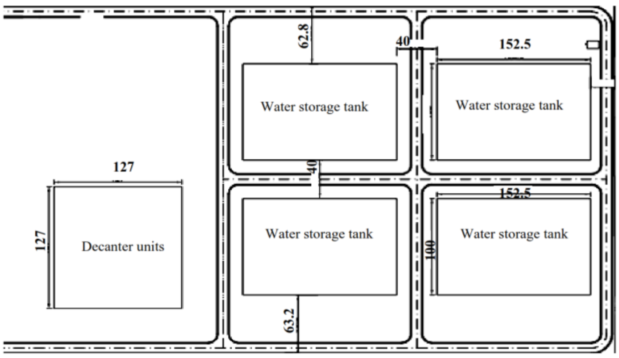

Fig. 1 Water storage tanks and decanter units layout – Sarbandar City, Khuzestan, Iran

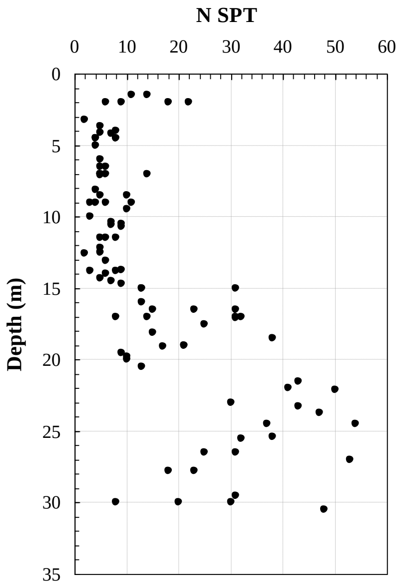

Fig. 2 SPT N-value results with depth across the construction area

2. General specifications of the project

This project is located northwest of Sarbandar city, which is approximately 20 km out of Mahshahr PETZONE in the southern part of Khuzestan province, Iran. Fig. 1 shows the layout of water storage facility including four water storage tanks, each 152 m×100 m, and a 130 m×130 m area for decanter units. The applied pressure from water storage tanks foundation and decanter units to the soil underneath are estimated at 100 kPa and 60 kPa, respectively. Two of the water storage tanks were already executed on micro-piles. The other two water storage tanks and the decanter units were the main scope of study as the expansion units.

Based on feasibility studies of different soil improvement methods, preloading of the construction area using Prefabricated Vertical Drains (PVD) was chosen for the two water storage tanks and the decanter units. In order to evaluate and control the preloading construction stages, a well-planned instrumentation and monitoring program was adapted. The instrumentation program included utilization of 19 surface settlement gauges, 4 magnetic settlement gauges (to measure settlement at the surface as well as in depth), 12 vibrating wire piezometers (to measure pore water pressure at depths of 4 m and 12 m), 4 Casagrande piezometers and 2 inclinometers.

2.1 Site stratification

Geotechnical studies show that the soil in the region can be divided into three major layers. The top 16 m layer is constituted of low plastic soft clay (CL). This is the layer having the maximum consolidation settlement potential. The soft clay layer sits on the top of an 8 m layer of non-cohesive soil constituted of silty-sand and sandy-silt with clusters of clay and silty-clay with a thickness of about 3 m. The bottom layer is dominantly constituted of stiff and hard clay starting at extending down to 30 m which is the maximum depth of borehole drillings.

Standard Penetration Test (SPT) results from different boreholes drilled across the site are shown in Fig. 2. A noticeable increase in SPT N-value can be observed at a depth of about 16 m confirming the existence of the sandy layer starting at that depth.

3. Numerical model

Due to symmetry, only one quarter of the entire geometry of the foundation system was modeled using ABAQUS/Standard (Hibbitt *et al.* 2001). An isotropic elastic model was used to determine the properties of piles and raft materials. Soil material response was defined with a linear elastic-perfectly plastic model using Mohr-Coulomb (MC) failure criterion. The main advantage of this numerical model is its simplicity as well as the convenience of material constants determination. Linear hexahedral volume elements with 8 nodes and 8 integration points (C3D8) are used in the model. The mesh type and geometry for all the models were kept identical to eliminate the meshing size effects on the results. Meshing size was chosen to be adequately fine immediately under the raft and pile tips and started to grow gradually as the distance to the footing increased.

The Coulomb friction model was used to implement the sticking and sliding properties (interface element) between pile surface and surrounding soil. The critical shear stress is hence μ, σ_n, where μ is the coefficient of friction and σ_n is the normal contact stress. In Coulomb friction model, sliding happens when shear stress between the surfaces exceeds critical shear stress. In other words, when shear stress is less than the critical shear stress, no relative displacement (sliding) takes place. When the shear stress reaches the critical shear stress, sliding occurs in the direction of the shear stress. In addition, a critical shear displacement of 5 mm was adopted for full mobilization of skin friction as suggested by Lee *et al.* (2002). Coefficient of friction for clays is suggested to be between 0.2-0.4 (Lee *et al.* 2010). In this study, the value of μ was chosen to be 0.3.

Attention was paid on long-term response of a piled-raft resting on clay, so all the calculations were performed assuming effective stress conditions as the Young modulus and strength parameters defined for soil layers are drained parameters. Thus, consolidation effects were neglected. The structure load was applied as a uniform loading after the initial equilibrium stage was attained.

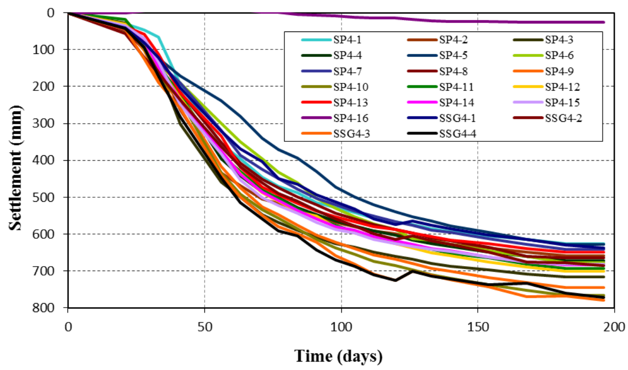

Fig. 3 Ground surface settlement variations at different points during preloading period

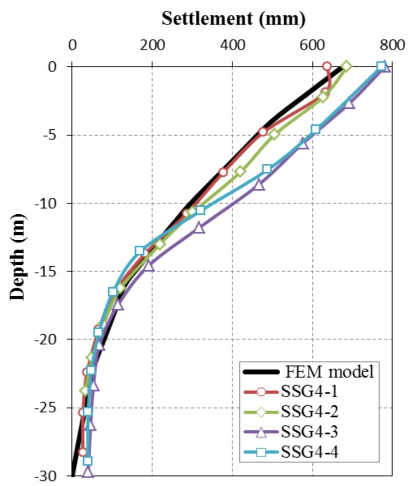

Fig. 4 Settlement profiles (with depth) from 4 extensometers and comparison with numerical model

3.1 Calibration of numerical model using instrumentation data

Using the project instrumentation data for water storage tank number 4, which is 152 m×100 m in plan-view, and considering the soil stratification properties, the numerical model was calibrated to show good correlations between field measurements and model predictions. The ground surface settlement was measured during the 196 days period after starting the backfilling. Fig. 3 shows the surface settlement variations during this period.

A uniform loading of 135 kPa was defined as the preloading stage in the numerical model. The soil block depth is specified 30 m and divided into 6 layers. Based on the soil profile information, the materials for the first four layers which are 16 m deep are defined by the soft clay properties. The fifth layer has sand properties and the final layer is representing stiff clay. Table 1 summarizes the soil parameters used in the numerical model. The soil parameters were selected based on the geotechnical investigation, and subsequently modified using the numerical model. This model was calibrated with the real-case instrumentation data. The average settlement recorded at the end of consolidation by several instruments across the tank was 690 mm, as shown in Fig. 3. Fig. 4 presents the settlements obtained from the calibrated numerical model exhibiting a reasonably close correlation with extensometer settlement instruments. It is observed from the figure that at a depth of 30 m below the ground surface, the soil has a small settlement with a negligible magnitude. Therefore, specifying the bottom boundary of the numerical model at 30 m depth has not been far from reality.

Table 1 Soil parameters used in the calibrated model based on the instrumentation results of preloading

Layer No.	1	2	3	4	5	6
Depth (m)	0-4	4-10	10-13	13-16	16-22	22-30
Density, γ (kN/m^3)	19.5	20	20.2	20.2	20	20
Poisson's ratio, ν	0.3	0.3	0.3	0.3	0.3	0.3
Modulus of Elasticity, E (MPa)	1.5	2	2.3	3.5	35	35
Effective cohesion, c' (kPa)	11	11	12	12	10	18
Effective friction Angle, φ' (degree)	22	20	19	19	28	26

3.2 Validation of numerical model for piled-rafts

Centrifuge modeling of foundation performed by Horikoshi and Randolph (1996) was used for verification of the numerical model for piled-rafts. A 3D simulation of the same foundation was carried out by Lee *et al.* (2010) by ABAQUS which is used here for comparison purposes.

The model contains a circular raft sitting on stiff clay. A total number of 9 piles, 15 m long each and 0.32 m in diameter were placed under a circular raft at 2.5 m center-to-center distances. The raft is 14 m in diameter and 0.05 m in thickness. Soil layer surrounding the footing is 25 m deep. A load equivalent to 12 MN was applied uniformly over the entire raft area. Dimensions, loading condition, material and strength properties of soil and piled-raft materials used in the model are shown in a 2D schematic drawing (ABAQUS model is 3D) in Fig. 5.

Comparisons of the results of the 3D simulations in this research along with centrifuge and 3D models of Lee *et al*. (2010) are summarized in Table 2. Good correlations are observed between predictions and measurements for the average settlement and load carried by piles.

3.3 Configurations of piled-rafts Investigated

The piled-raft is placed on a soil profile as described in Table 1 in all the simulations. Pile diameter is 0.45 m in all cases. The variables among the models are length of the

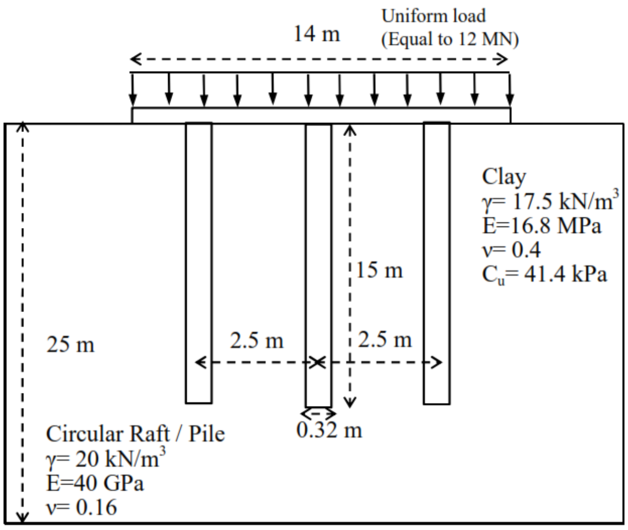

Fig. 5 Geometry and material properties used in the FEM model

Table 2 Comparison of results obtained from 2 numerical models and centrifuge test

Result	Average settlement (mm)	Load carried by piles (%)
Measured (Horikoshi and Randolph 1996)	22	19
FEM (Lee *et al*. 2010)	21	22
FEM model (Present study)	22.3	18

Table 3 Geometry and pile arrangements of the piled-raft models studied

Model No.	Raft dimensions* (m)	Pile arrangement	Pile length (m)	S_1 (m)	S_2 (m)
1	20×20×0.5	0	0	-	-
2	20×20×0.5	8×8	11 14 18	2.5	1.25
3	20×20×0.5	6×6	11 14 18	3.5	1.25
4	20×20×0.5	4×4	11 14 18	2.0	2.5

*Raft dimensions: length×width×thickness

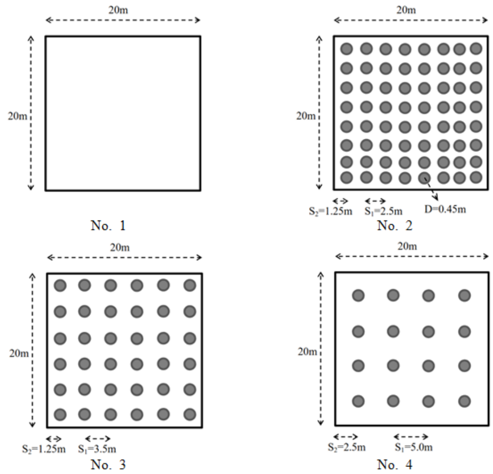

Fig. 6 Pile arrangements used in the numerical analyses

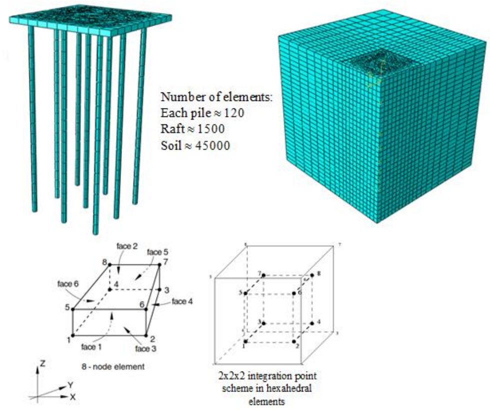

Fig. 7 A C3D8 element and a sample discretized piled-raft model

piles and the distance between them. Geometrical arrangements of piled-raft models are summarized in Table 3 in which S_1 is the center-to-center distance between the piles and S_2 is the distance from the raft's edge to center of outside piles. Furthermore, the pile arrangements are shown in Fig. 6.

Fig. 7 shows the C3D8 solid element used in the numerical model and also a quarter of the discretized model of the piled-raft. The model is comprised of 36 piles, 18 m long each.

4. Analysis and results

4.1 Analysis of single piles

A single pile for each of the proposed lengths (11 m, 14 m and 18 m) embedded in the soil profile was simulated to ascertain that single piles perform properly. A static load test was carried out on an 18 m pile at the nearby sites with similar geological formations and the results show that the a 1000 kN compressive load on the pile head has caused a movement of 10 mm. Mechanical properties of the soil at tip of the pile should be modified to reach a proper load-movement behavior (Feizee and Fakharian 2008); hence a cylindrical block of soil with a diameter of 3 m was defined at the tip of pile with modified parameters as summarized in Table 4.

There is no data available for the static load tests of 11 m and 14 m single piles. The modified strength parameters of soil block at pile tip for shorter piles are estimated based on the 18 m pile test results and judgment from past experiences. Modified strength and deformation parameters for soil block at the tip of 14 m and 11 m piles are presented in Table 4.

Fig. 8 presents load-movement graphs for the above noted piles. The 18 m pile sits on a dense sand layer while 11 m and 14 m piles are floating in the soft clay layer and could be considered as frictional piles.

Assuming the failure criteria of 10% of pile diameter movement (equivalent to 45 mm for the piles of this study), total bearing capacity of piles can be achieved from the graphs. Table 5 presents tip, skin friction and total resistances for all the 3 piles.

Thereafter, single raft and piled-rafts with different pile configurations as described in Table 4 were modeled. The loading condition for all the cases was defined as a uniform loading equivalent to 100 kPa applied onto the raft, induced by the water storage tank. The results are presented in the next section.

Table 4 Modified parameters of cylindrical block of soil under the pile tip

Pile length (m)	Block diameter (m)	Modulus of Elasticity, E (MPa)	Effective cohesion, c′ (kPa)	Effective friction Angle, φ' (degree)
18	3	400	20	45
14	3	70	50	28
11	3	45	40	28

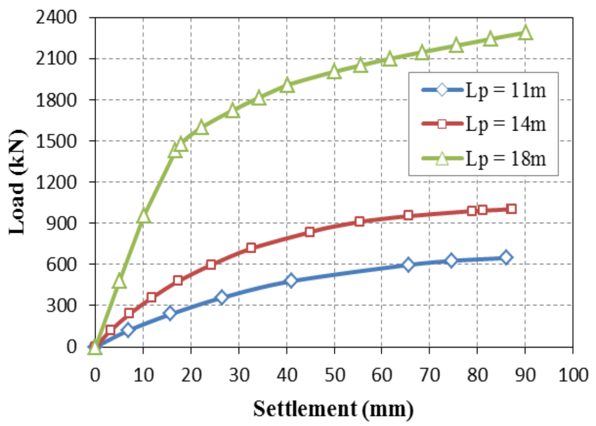

Fig. 8 load-movement graphs for 11 m, 14 m and 18 m single piles

Table 5 Ultimate resistances for 11 m, 14 m and 18 m single piles

Pile length (m)	Shaft resistance, $Q_{SP\text{-}s}$ (kN)	Tip resistance, $Q_{SP\text{-}t}$ (kN)	Ultimate resistance, $Q_{SP\text{-}tot}$ (kN)
11	160	360	520
14	300	540	840
18	700	1180	1880

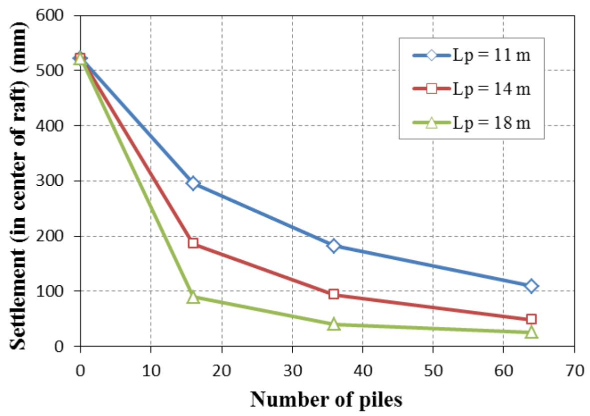

Fig. 9 Settlement of center of the raft for different number of piles and lengths

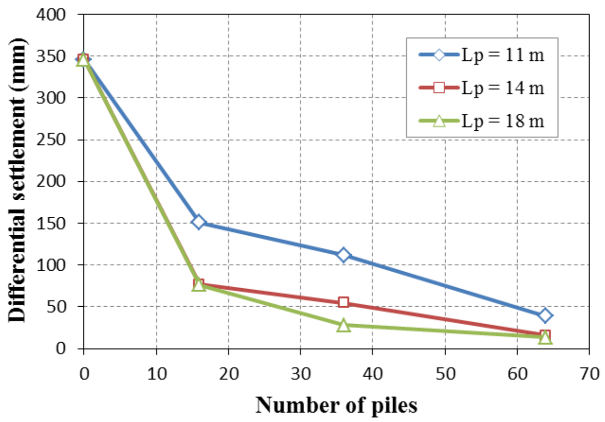

Fig. 10 Differential settlements of the raft for different number of piles and lengths

4.2 Piled-raft settlements

Fig. 9 shows the settlements at the center of the raft for different pile arrangements and lengths. As expected, increasing the length and number of piles shall contribute to reducing the total settlement. However, the rate of reduction drops as the number of piles increases. The settlement of the raft only (no piles) is approximately 520 mm and adding 64 piles with length of 14 m will reduce the settlements to less than 50 mm. It is worth mentioning that 14 m piles are considered as friction piles as pile tip is embedded in soft layer. Having the same number of piles, 18 m long piles which are the piles with the large end bearing capacity contribute to reducing the settlements to less than 25 mm. However, 11 m long piles with the same number and the same arrangement show a considerably higher settlement (110 mm).

The effect of number and length of the piles on maximum differential settlements is depicted in Fig. 10. The raft only has resulted in 350 mm differential settlement. Supporting the raft with 64 piles of both 14 m and 18 m long piles reduced the differential settlements to 15 mm.

4.3 Load carried by piles

Fig. 11 shows the percentage of the total load that is

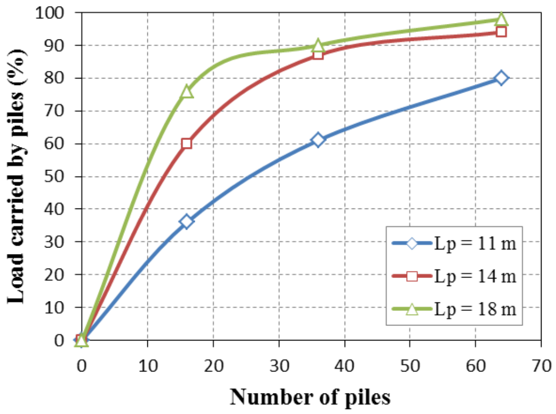

Fig. 11 Load bearing contribution of piles for different pile lengths and numbers in piled-raft system

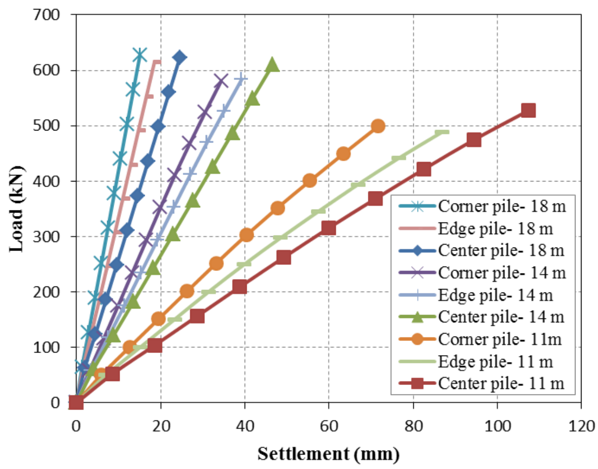

Fig. 12 Load-settlement graphs for three types of piles with different lengths in the 8×8 arrangement

Table 6 Load distribution between the piles in piled-rafts with different arrangements

Model No.	Pile length (m)	$Q_p/Q_{Sp\text{-}tot}$ (%)		
		Center pile	Edge pile	Corner pile
2	11	0.99	0.94	0.96
	14	0.71	0.70	0.69
	18	0.33	0.32	0.33
3	11	1.51	1.14	1.85
	14	1.26	1.09	0.92
	18	0.58	0.52	0.41
4	11	1.92	1.80	1.55
	14	1.93	1.73	1.69
	18	1.06	0.98	1.02

being carried by piles. Since the top 16 m of the soil layering is soft clay with a low bearing capacity, piles have to tolerate the major portion of the applied loads. In case of 64 end-bearing piles (18 m long piles), approximately the entire load is carried by piles, and thus, the raft has almost no interaction with the soil underneath. Fig. 11 shows that supporting the raft by up to 36 piles would immediately reduce the load bearing share of the raft and transfer the applied load to piles. However, expanding the number of piles from 36 to 64 has not significantly affected the load bearing proportions. Load carried by piles for piled-rafts with shorter piles (those with tips floating in the soft clay layer) is noticeably lower than the long piles.

4.4 Load distribution between the piles

Piles supporting the raft can be divided into three major groups:

- Central piles which are located within the central area.
- Corner piles which are located at the corners.
- Edge piles which are located on the edge of the raft.

For each of the geometric alignments presented in Table 3, the load distribution for each pile type is presented in Table 6.

Table 6 shows that for Case 2 that the piles are located at a distance of 2.5 m from each other, the load is distributed approximately uniformly between the piles. Nevertheless, for Cases 3 and 4, the applied load is larger for the central piles compared to the corner and edge ones. As a result, the pile load distribution is affected by the pile configurations and pile positions. In particular, increasing the pile load of center piles compared to corner and edge piles can be observed as a result of increasing of the pile spacing. Similar results were reported by Lee *et al.* (2010).

Table 7 Stiffness of single pile and piles in the piled-raft system (from results of Fig. 12)

Pile length (m)	K_p (kN/mm)			
	Single pile	Center piles	Edge piles	Corner piles
11	13.5	4.9	5.6	7.0
14	24.6	13.3	14.9	16.9
18	93.8	26.6	33.2	41.6

4.5 Pile stiffness and subgrade reaction factor

Fig. 12 shows load-settlement behavior for the three types of piles with 8×8 configuration. Under constant loading conditions, settlement of center pile is the highest and settlement of the corner pile is the lowest among different types of piles for all lengths.

Single pile stiffness and the stiffness of the three types of piles were calculated using Figs. 8 and 12 and the results are presented in Table 7. Reduction of pile stiffness in a piled-raft system in comparison with a single pile is attributed to the pile group interaction effects.

Soil subgrade reaction modulus (K_s) was calculated at the centerline of the raft, for different lengths and configuration of piles, as shown in Figs. 13-15. The graphs show that for the same pile configuration, the pile length does not affect the soil subgrade reaction modulus especially in the case of friction piles.

The effect of pile spacing on the subgrade reaction modulus of the central point of raft was also studied. As shown in Fig. 16, K_s has increased as the spacing between the piles increases, or in other words, the number of piles decreases.

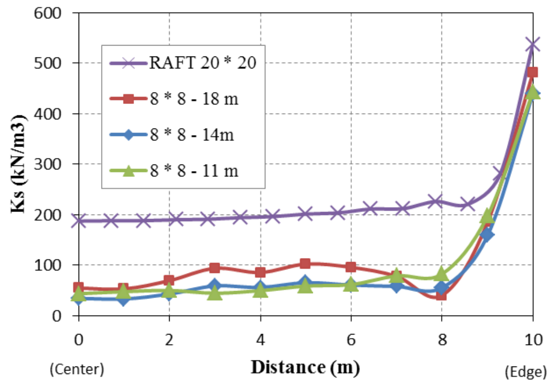

Fig. 13 Soil subgrade reaction modulus under centerline of the raft in 8×8 arrangement

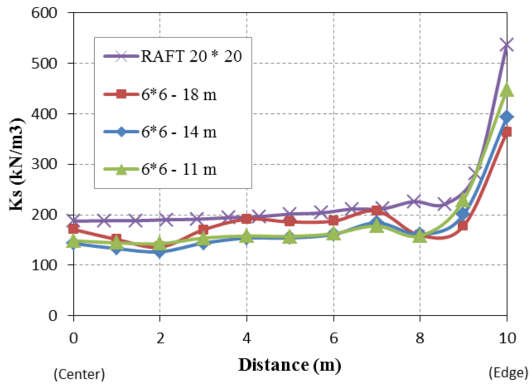

Fig. 14 Soil subgrade reaction modulus under centerline of the raft in 6×6 arrangement

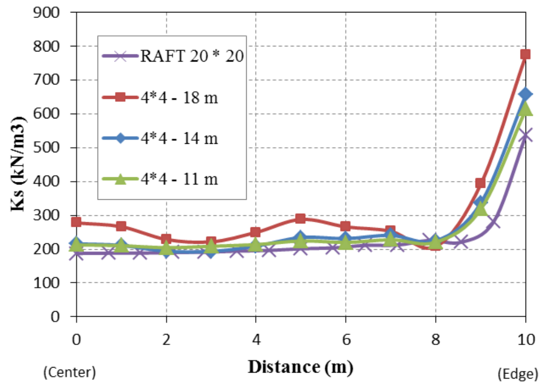

Fig. 15 Soil subgrade reaction modulus under centerline of the raft in 4×4 arrangement

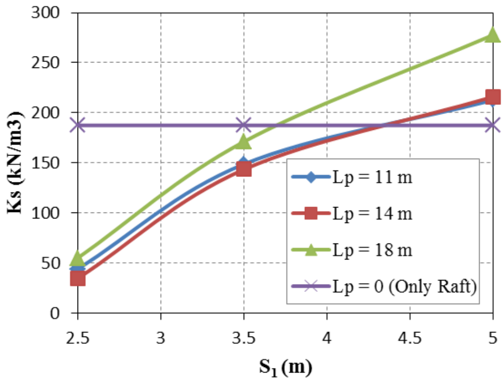

Fig. 16 Variations in soil subgrade reaction modulus under central point of the raft with pile distances

5. Discussion and application

As mentioned earlier, using piled-raft systems on soft soils is not popular among geotechnical engineers. Two major reasons for this lack of tendency are:

• Load bearing capacity and stiffness of soft clay is usually too low that most of the applied load will be transferred to piles.

• If the soft clay is likely to undergo excessive settlements, for example due to backfilling or dewatering, the soil underneath the raft could be detached from base of the raft, further causing the piles to carry the excessive loads (Poulos 2005). In this case, negative skin friction may develop; therefore special measures need to be employed to deal with the negative skin friction consequences.

On the other hand, employing piled-raft foundation system is having a lot of advantages. Moreover, existence of soft clay in significant industrial areas such as Mahshahr where is the home of a lot of major national projects, calls for investigation of this kind of foundation in the area.

At the feasibility study phase, several soil improvement methods such as spun pile, square pile, pre-loading, micro pile, stone column and soil deep mixing have been considered. Looking at the technical implications as well as cost and construction time comparisons, soil improvement by preloading was chosen by the client. Although preloading of the area is cheaper compared to other methods of soil improvement, the construction period is more time consuming compared to other solutions. Therefore, using piled-raft system could be considered as an alternative solution in this project since the required construction time is less than that of the preloading and also fewer piles with shorter length could be used compared to a conventional pile group system. Moreover, installation efforts for piles with shorter lengths are more convenient and cost effective as they would be embedded within the soft clay.

Calculations show that the stiffness of the center piles is the least and increases for edge piles. Corner piles have the highest stiffness among the pile types. Nevertheless, the stiffness of all piles in the raft is lower than that of respective single pile. Furthermore, Subgrade reaction modulus rises as the pile spacing increases.

6. Conclusions

Possibility of using piled-raft system in construction of foundation for water storage tanks in Sarbandar, located in PETZONE of southwest Khuzestan Province, was assessed in this study. Extensive numerical analyses were carried out using ABAQUS/Standard. The most important findings of the study are summarized below:

Strength parameters of soil were modified using instrumentation data to improve the prediction results. Settlement profiles from a heavily instrumented preloading project for different depths can be employed to define the relevant strength and deformation parameters. The parameters for different layers and different depths then should be refined so that the model can have a meaningful prediction to settlement gauge and extensometer records.

A series of 3D numerical analyses on piled-rafts were performed for different pile lengths, spacing between piles and configurations. The results show that an increase in pile length and decrease in pile spacing results in settlement reduction and an increase in the pile contribution ratio, although the pile spacing for piles sitting on the dense soils has less effect than those floating in soft soils. Also increase in pile spacing leads to a non-uniform distribution of loads between piles and an increase in loads transferred to the center piles. Soil subgrade reaction modulus increases with pile spacing.

On basis of the results, pile length and spacing between the piles are significant factors in designing the proper piled-raft system. Interpretations of results also show that choosing the proper combination of length and spacing for piles can lead to acceptable differential and total settlements while a high percentage of total bearing capacity of piles can be mobilized which is an efficient solution for project.

It is evident from this research that application of piled-raft foundation system in soft clay is not an efficient solution to reduce the total settlements. However, the appropriate selection of geometrical aspects of the piled-raft system can considerably control the differential settlements. Construction of piled-raft system in soft clay can be applicable to projects like water storage tanks in which limitation of total settlement in not the major concern and the main purpose is to control differential settlements.

Acknowledgments

The authors would like to thank the technical information provided by Pars GeoEnviro Co. regarding the geotechnical investigation, pile static load test data and instrumentation data of the preloading operations.

References

Al-Omari, R.R., Al-Azzawi, A.A. and AlAbbas, K.A. (2016), "Behavior of piled rafts overlying a tunnel in sandy soil", *Geomech. Eng.*, **10**(5), 599-615.

Ata, A., Badrawi, E. and Nabil, M. (2015), "Numerical analysis of unconnected piled raft with cushion", *Ain Shams Eng. J.*, **6**(2), 421-428.

Cho, J., Lee, J.H., Jeong, S. and Lee, J. (2012), "The settlement behavior of piled raft in clay soils", *Ocean Eng.*, **53**, 153-163.

Chore, H. and Siddiqui, M. (2016), "Soil-structure interaction analysis of a building frame supported on piled raft", *Coupled Syst. Mech.*, **5**(1), 41-58.

Davis, E. and Poulos, H. (1972), "The analysis of piled raft systems", *Austr. Geotech. J.*, **2**(1), 21-27.

Fakharian, K. and Javanbakht, A.S. (2012), "Effect of soil improvement on performance of piled rafts on soft soils", *Proceedings of the 9th International Conference on Testing and Design Methods for Deep Foundations*, Kanazawa, Japan, September.

Fakharian, K. and Khanmohammadi, M. (2012), "Evaluation of the effect of geometric characteristics of a piled-raft on its behavior on soft clay under drained conditions", *Sharif Civil Eng. J.*, **29**(2), 71-76.

Fattah, M.Y., Al-Mosawi, M.J. and Al-Zayadi, A.A. (2013), "Time dependent behavior of piled raft foundation in clayey soil", *Geomech. Eng.*, **5**(1), 17-36.

Fattah, M.Y., Yousif, M.A. and Al-Tameemi, S.M. (2015), "Effect of pile group geometry on bearing capacity of piled raft foundations", *Struct. Eng. Mech.*, **54**(5), 829-853.

Hibbitt, D., Karlsson, B. and Sorensen, P. (2001), *Abaqus/Standard User's Manual*, Hibbitt, Karlsson and Sorensen Inc., Pawtucket, Rhode Island, U.S.A.

Hight, D. and Green, P. (1976), "The performance of a piled raft foundation for a tall building in London", *Proceedings of the 6th European Conference on Soil Mechanics and Foundation Engineering*, Vienna, Austria.

Hooper, J. (1973), "Observations on the behavior of a pile-raft foundation on London clay", *Proc. Inst. Civ. Eng.*, **55**(4), 855-877.

Horikoshi, K. and Randolph, M. (1996), "Centrifuge modelling of piled raft foundations on clay", *Geotechnique*, **46**(4), 741-752.

Horikoshi, K. and Randolph, M. (1998), "A contribution to optimum design of piled rafts", *Geotechnique*, **48**(3), 301-317.

Katzenbach, R., Arslan, U., Moormann, C. and Reul, O. (1998), "Piled raft foundation-interaction between piles and raft", *Darmstadt Geotech.*, **4**(2), 279-296.

Kim, K.N., Lee, S.H., Kim, K.S., Chung, C.K., Kim, M.M. and Lee, H.S. (2001), "Optimal pile arrangement for minimizing differential settlements in piled raft foundations", *Comput. Geotech.*, **28**(4), 235-253.

Lee, C., Bolton, M. and Al-Tabbaa, A. (2002), "Numerical modelling of group effects on the distribution of dragloads in pile foundations", *Geotechnique*, **52**(5), 325-335.

Lee, J., Kim, Y. and Jeong, S. (2010), "Three-dimensional analysis of bearing behavior of piled raft on soft clay", *Comput. Geotech.*, **37**(1), 103-114.

Lee, J., Park, D. and Choi, K. (2014), "Analysis of load sharing behavior for piled rafts using normalized load response model", *Comput. Geotech.*, **57**, 65-74.

Leung, Y., Klar, A. and Soga, K. (2009), "Theoretical study on pile length optimization of pile groups and piled rafts", *J. Geotech. Geoenviron. Eng.*, **136**(2), 319-330.

Masouleh, S.F. and Fakharian, K. (2008), "Application of a continuum numerical model for pile driving analysis and comparison with a real case", *Comput. Geotech.*, **35**(3), 406-418.

Nakanishi, K. and Takewaki, I. (2013), "Optimum pile arrangement in piled raft foundation by using simplified settlement analysis and adaptive step-length algorithm", *Geomech. Eng.*, **5**(6), 519-540.

Poulos, H.G. (2001), "Piled raft foundations: design and applications", *Geotechnique*, **51**(2), 95-113.

Poulos, H.G. (1994), "An approximate numerical analysis of pile-raft interaction", *J. Numer. Anal. Met. Geomech.*, **18**(2), 73-92.

Poulos, H.G. (2005), *Piled Raft and Compensated Piled Raft Foundations for Soft Soil Sites*, Advances in Designing and Testing Deep Foundations, 214-235.

Randolph, M. (1992), "Design methods for pile groups and piled rafts", *Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering*, New Delhi, India, January.

Sawant, V., Pawar, S. and Ladhane, K. (2012), "Parametric study of piled raft for three load-patterns", *Coupled Syst. Mech.*, **1**(2), 115-131.

Tan, Y., Chow, C. and Gue, S. (2005), "Piled raft with different pile length for medium-rise buildings on very soft clay", *Proceeding of the International conference on Soil mechanics and Geotechnical Engineering*, Osaka, Japan, September.

Yamashita, K., Hamada, J. and Tanikawa, T. (2016), "Static and seismic performance of a friction piled raft combined with grid-form deep mixing walls in soft ground", *Soil. Found.*, **56**(3), 559-573.

CC