J. Cent. South Univ. (2013) 20: 1713−1723
DOI: 10.1007/s11771-013-1664-y

Springer

3D finite elements analysis of vertically loaded composite piled raft

Reza Ziaie Moayed[1], Ehsan Izadi[1], Mehrad Mirsepahi[2]

1. Civil Engineering Department, Imam Khomeini International University, Qazvin 3414916818, Iran;
2. Department of Geotechnical Engineering Science and Research Branch, Islamic Azad University, Hamedan 65138734, Iran

Abstract: In recent years, a new type of foundation named composite piled raft foundation (also called long−short composite piled raft) has been developed. Where designing shallow foundations would mean unacceptable settlement, or other environmental risks exist which could impair the structure in the future, composite piled raft foundations could be used. Finite element method was applied to study the behavior of this type of foundation subjected to vertical loading. In order to determine an optimal pile arrangement pattern which yields the minimum settlement, various pile arrangements under different vertical stress levels were investigated. Results show that with increasing the vertical stress on the raft, the effectiveness of the arrangements of short and long piles become more visible. In addition, a new factor named "composite piled raft efficiency" (CPRE) has been defined which determines the efficiency of long−short piles arrangement in a composite piled raft foundation. This factor will increase when short piles take more axial stresses and long piles take less axial stresses. In addition, it is found that the changes in settlements for different long−short piles arrangement are in a well agreement with changes in values of CPRE ratio. Thus, CPRE ratio can be used as a factor to determine the efficiency of piles arrangements in composite piled raft foundation from the view point of reducing raft settlements.

Key words: composite piled raft; settlement; composite piled raft efficiency; long-short pile arrangement; cushion

1 Introduction

In traditional foundation design, it is customary to consider first the use of shallow foundation such as a raft. If it does not satisfy the design criteria, deep foundation such as fully piled foundation is used instead. In the former, it is assumed that load of superstructure is transmitted to the underlying ground directly by the raft and in the latter, the entire design loads are assumed to be carried by the piles [1]. In recent decades, another alternative intermediate between shallow and deep foundation which is called piled raft foundation (settlement reducing piles foundation) has been recognized by civil engineers. The concept of piled raft foundation was firstly proposed by DAVIS and POULOS [2], then it has been described by many researchers [1−10]. In this concept, piles are provided to control settlement rather than carry the entire load. Piled raft foundation has been proved to be economical structures to improve the serviceability of foundation performance by reducing settlement to acceptable levels. The favorable application of piled raft foundation occurs when the raft has adequate loading capacities, but the settlement or differential settlement exceeds allowable values. Conversely, the unfavorable situations for piled raft include soil profiles containing soft clays near the surface and soft compressible layers at relatively shallow depths [1]. Based on the engineering practices, the concept of piled raft foundation to long−short composite piled raft foundation with intermediate cushion has been developed in recent years. The elements of composite piled raft foundation are shown schematically in Fig. 1.

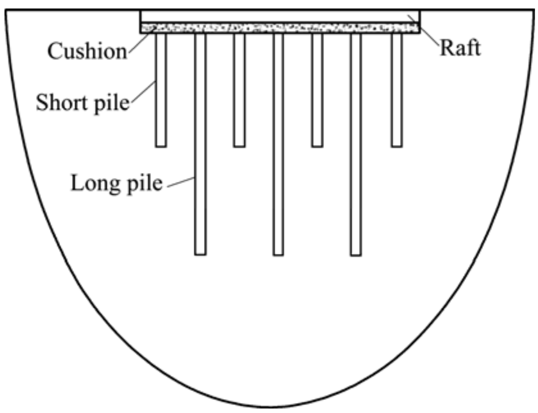

Fig. 1 Sketch of composite piled raft foundation [1]

In this new type of foundation, short piles made of flexible materials were used to strengthen the shallow soft soil, while the long piles made of relatively rigid

Received date: 2012−07−02; **Accepted date:** 2012−09−22
Corresponding author: Reza Ziaie Moayed, Associate Professor; Tel: +98−281−3780038; Fax: +98−281−3780073; E-mail: R_ziaie@ikiu.ac.ir

materials were used to reduce the settlements and the cushion beneath the raft was used to redistribute and adjust the stress ratios of piles to subsoil.

1.1 Working mechanism of composite piled raft

Compared with other piled raft foundations, long−short composite piled raft foundation has its own working mechanism, owing to the different pile lengths. For better understanding the behavior of piled rafts with dissimilar piles under vertical loads, the composite piled raft foundation is divided to three sections, as shown in Fig. 2. The working mechanism for each section is discussed below [4].

Section I, where long piles and short piles are working together, is mainly used to enhance bearing capacity of the foundation.

Section II, where long piles are working solely, is mainly used to reduce settlement.

Section III, where there are soil layers without piles, is mainly used to bear pile body load.

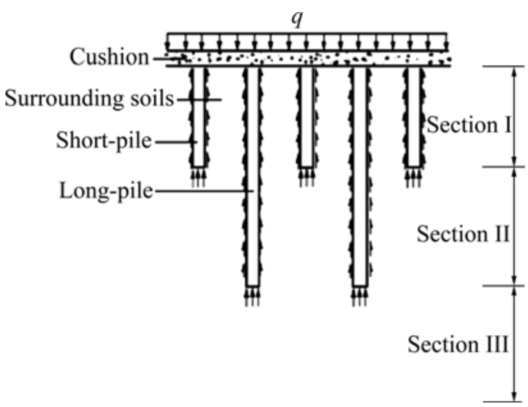

Fig. 2 Working mechanism of long−short pile composite foundation [11]

It should be noted that while these three sections work simultaneously, bearing capacity of the foundation will be enhanced, and displacement will be reduced as well. Moreover, long piles and short piles play different roles in the foundation.

1.1.1 Long piles

In long−short composite piled raft foundations, long piles are mainly used to transfer the load from the piles to the deep ground, reduce the deformation of the compressive soil layers, protect the short-flexible piles, and prevent the soil from protuberating while working together with short piles. In section I, holding effect and shielding effect appear obviously among the piles. In addition, soil and piles deform simultaneously in this section. In section II, different displacements occur in the pile/soil interface near the long pile tip, and in section III, long piles are punched into the subjacent bed.

1.1.2 Short piles

According to the different mechanical properties of soil, short piles have two functions as below.

1) When the soft soil layer under the foundation is thick, short piles are used to enhance the bearing capacity of soft soil layer.

2) If there are two ideal bearing stratums under the basis, long piles and short piles can stand on these two stratums, respectively, so that bearing capacity of the stratums can be brought into full play. Moreover, in the latter case, short piles are mainly used to enhance bearing capacity of the foundation, while long piles are mainly used to reduce settlement.

1.2 Literature review

In recent years, many studies have been performed to investigate the performance of composite piled raft foundations. LIANG et al [12] verified that the increasing in lengths of long piles has an obvious effect on reducing the settlement of foundation rather than improving the elastic modulus of short piles through a numerical investigation. Also the effect of cushion on the performance of composite piled raft was investigated. Cushion can adjust the load-shearing ratios evenly among piles and help to make better use of the bearing capacities of short piles. And the bearing capacities of shallow subsoil can be used better. In Addition, decreasing the modulus of elasticity of cushion causes the stress concentration of long piles to be more uniformly distributed and mobilize the bearing capacity of short piles. The effect of cushion thickness was also investigated in this work. According to Ref. [12], with increasing of cushion thickness, the axial stress of long piles decreases gradually, while the axial stress of short piles on the upper shaft increases first and then decreases along depth.

LIANG et al [13] performed an investigation using integral equation method on composite piled rafts. The plan of piled raft is shown in Fig. 3. Nine piles have the same diameter (d) and are arranged in a 3 × 3 pattern. An optimization study was carried out to find out how different lengths of piles affect the total and differential

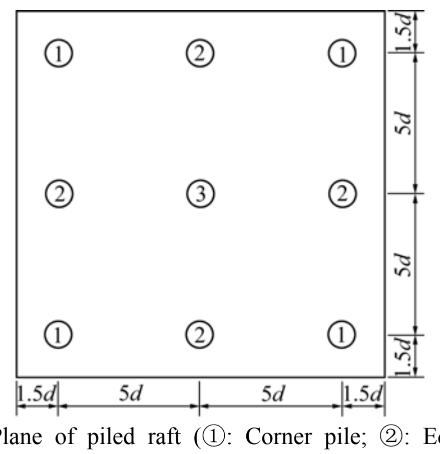

Fig. 3 Plane of piled raft (①: Corner pile; ②: Edge pile; ③: Interior pile) [13]

settlements of the composite piled raft. It is reported that for an optimized design, the length of the inner pile (③) should increase, while the lengths of the corner piles (①) and the edge piles (②) should be reduced. This optimized piles arrangement will increase the load shearing ratio of subsoil slightly. In other words, more bearing capacity of the subsoil was utilized with the use of different pile lengths. It is reported that the optimized design using dissimilar piles would create a more economical design of composite piled rafts. Nevertheless, in this method, the moment in the raft was not considered, thus it is expected that the results differ from reality especially when the moment of the raft has a significant effect on the load shearing ratios of the subsoil and piles.

WANG et al [14] performed physical model tests on a composite piled raft foundation with or without different vertical reinforcing elements. The columns layout and the location of the earth pressure cells are shown in Fig. 4(a). The tests in this work were performed in several cases which are mentioned in the legend in Fig. 4(b). In the case of pure soil ground, no reinforcing vertical element was used; in the sand column case, reinforcing vertical elements consist of sand columns; for all three remained multi- reinforcing elements, column A was made of the first mentioned reinforcing element and column B was made of the second reinforcing elements.

It is found that the bearing capacity of a composite foundation with certain vertical reinforcing elements is obviously higher than that of the soil ground without any reinforcement. Under the lower foundation pressure, the relationship of pressure versus settlement is almost linear for a multi-element composite foundation. But with the increase of the pressure, the relationships show plastic yielding and the foundation soil is in a plastic deformation state. The multi-element composite foundation of a steel pipe pile and sand columns and that of a concrete pile and lime columns have a higher bearing capacity than that of the composite foundation of a sand columns only. But the bearing capacity of the multi-element composite foundation with lime columns and sand columns is not much different from that of the composite foundation with sand columns only for improving the silty fine sand.

ZHENG et al [15] performed a 3D numerical investigation on composite foundations formed by cement-flyash-gravel (CFG) as long piles material, and lime as short piles material. The studied parameters include the length and diameter of piles and thickness of cushion. They concluded that settlement is much more affected by the length and diameter of CFG pile rather than those of lime pile. This means that the CFG pile acts as a settlement-reducing pile, which is in accordance with the working principle of such composite foundations. On the other hand, the load distribution between piles and subsoil is significantly affected by the cushion thickness.

The aim of this work was to investigate the effect of different short and long piles arrangement patterns of composite piled raft in reducing settlements under various vertical stress levels. To this end, several numerical analyses have been performed using ABAQUS finite element software, then the magnitude of settlements in each case can be observed.

2 Modelling and analysis

2.1 Finite element (FE) modelling

The geometry of composite piled raft and the subsoil analyzed in the present work is illustrated in Fig. 5. The concerned geometric domain is determined on the basis of trial calculation method. The criterion for this is set in a way that the calculated results of stresses and displacements distribution do not change apparently with the further expansion of concerned domain. According to the criterion, the trial calculation result shows that the bottom boundary should be set in a depth of $3L_1$ from the head of the piles (L_1 is the length of long pile), while the lateral surrounding boundaries should be located at the place which is $10B$ (B is the width of

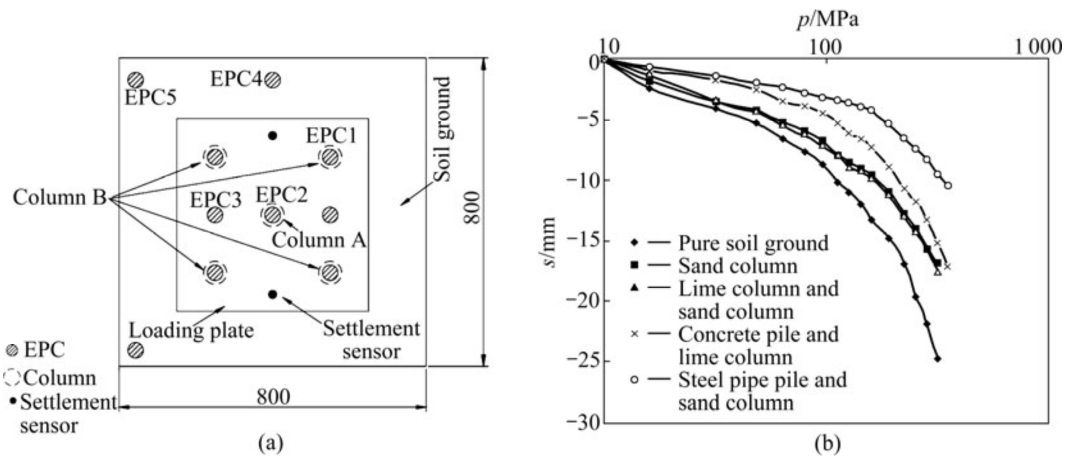

Fig. 4 Layout of columns and earth pressure cells (EPCs) (units: mm) (a) and plots of vertical stress−settlement [13] (b)

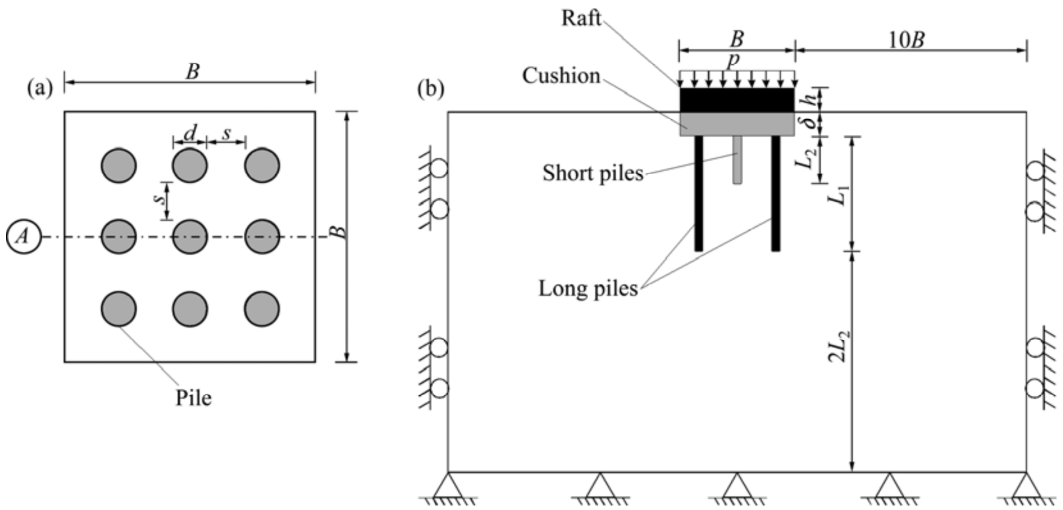

Fig. 5 Schematic diagram (a) and dimensions of occupied model (b)

square raft) to the raft edge. The diameter of piles (d) and the raft and cushion dimensions (width and thickness) have been kept constant with values chosen among those widely used in practice.

The diameter of both short and long piles are taken as d=0.5 m. The raft has the side width of B=9d=4.5 m, and the net spacing between the adjacent piles are taken as s=1 m. The thickness of the raft and cushion is both assumed to be 1 m. The lengths of the short and long piles are assumed to be 5 m and 25 m, respectively. Three stress levels of 100 kPa, 200 kPa and 300 kPa (uniformly acted on the raft) are applied to account the effect of different stress levels on the raft settlement. The details of the arrangements of the short and long piles under the raft will be discussed in Section 2.2.

Pin supports were applied to the base boundary of the subsoil model, so that movements in x, y and z directions for this boundary were restrained. On the front, the rear, the left and the right boundaries, roller supports were applied. This means that the movement in the y-direction was restrained in the front and the rear boundaries while the movement in the x-direction was restrained in the right and the left boundaries. The boundary conditions adopted for the model are shown in Fig. 5.

In the analysis, it is assumed that the long piles and raft are made of concrete; the short piles and cushion are made of sand-gravel. The modulus of elasticity and Poisson ratios of long piles, short piles, subsoil and cushion are listed in Table 1. Since most of the foundations are in elastic state under common working load conditions, and in order to eliminate the existing settlements due to material weight, the raft, cushion and piles all are assumed to be weightless linearly elastic media. The subsoil is considered to behave in elastic state with Mohr−Coulomb plastic failure criterion. Compared with the subsoil, the raft is assumed relatively rigid with elastic modulus E_c=3×10^4 MPa and Poisson ratio μ_c=0.2.

Figure 6 shows the three-dimensional finite element mesh of the model. The eight-nodded brick element (C3D8R) was used for the whole model. The pattern of the occupied mesh is determined in a way that the size of elements in the zones of high stress (or displacement) gradient is as small as possible while the size of elements around the domain boundary is comparatively larger. Note that for the interaction elements no relative displacements are allowed between piles and subsoil surfaces.

Table 1 Material properties

Material	Elastic modulus/ MPa	Poisson ratio	Internal friction angle/(°)	Cohesion/ kPa
Long piles	20×10^3	0.20	—	—
Short piles	1.7×10^3	0.30	—	—
Subsoil	5	0.35	10	25
Cushion	60	0.30	—	—

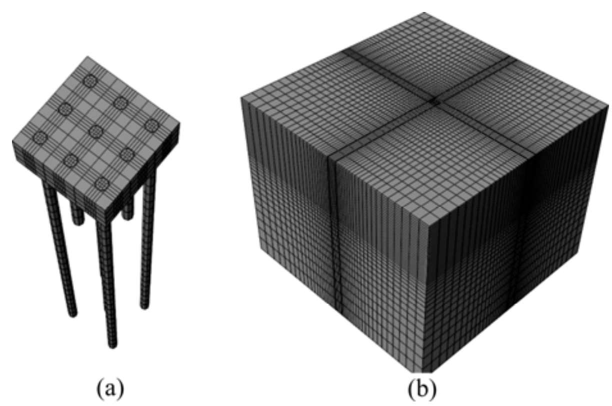

Fig. 6 Finite element mesh of model: (a) Composite piled raft; (b) Subsoil

2.2 FE analysis

Six different pile patterns were determined for arrangement of the short and the long piles under the raft. The patterns are illustrated schematically in Fig. 7, named as A, B, C, D, E and F. As it is shown in Fig. 7, patterns A and D represent simple piled raft foundations with similar pile lengths. These patterns were set to compare the effects of using composite piled raft on reducing settlements with simple pile raft. The patterns A and D are expected to have minimum and maximum raft settlements, respectively. In fact, these patterns define the limits of possible maximum and minimum raft settlements, in such a way that the settlements of other patterns (i.e. B, C, E and F patterns) would lie between these two limits. Patterns B and C represent the composite piled raft with nine dissimilar piles, having five and four long piles in each pattern, respectively. In addition, two economical patterns (E and F) with five dissimilar piles were determined to investigate the effect of reducing the number of piles used under the piled raft. These six patterns were subjected to three normal stress levels of 100 kPa, 200 kPa and 300 kPa to evaluate the effect of various stress levels on efficiency of the each piles pattern in reducing settlements of the raft. Note that all of these models have been analyzed using static type of analysis. As it was discussed before, the lengths of the short and long piles are assumed to be 5 m and 25 m, respectively.

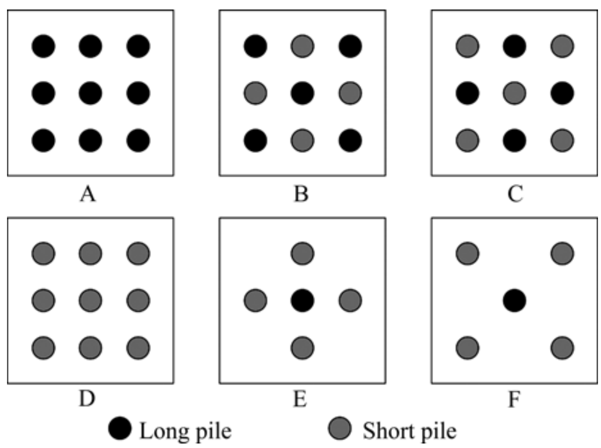

Fig. 7 Long−short piles arrangements studied in this work

2.3 Validation

The 3D finite element modeling approach was validated against the results of experimental study carried out by WANG et al [14]. For the validation, the particular case of composite piled raft described as "steel pipe pile and sand column" was considered which showed the least settlement among other cases. The characteristics of 3D finite element model were considered exactly according to the test condition. For the subsoil, the modified Drucker-Prager plastic yield criterion (cap model) was occupied. The cap model parameters of subsoil are listed in Table 2. Further details of the experimental study can be found in Ref. [14].

Table 2 Cap model parameters of subsoil

Property	Magnitude
d/kPa	125.6
β/(°)	48.0
Initial yield surface size/kPa	0.0
Cap eccentricity	0.4
Flow stress ratio	1.0

Comparison of obtained load−settlement curve from laboratory and from numerical modelling is illustrated in the Fig. 8. As shown in Fig. 8, the results of 3D FE modelling are in a well agreement with those observed in the laboratory.

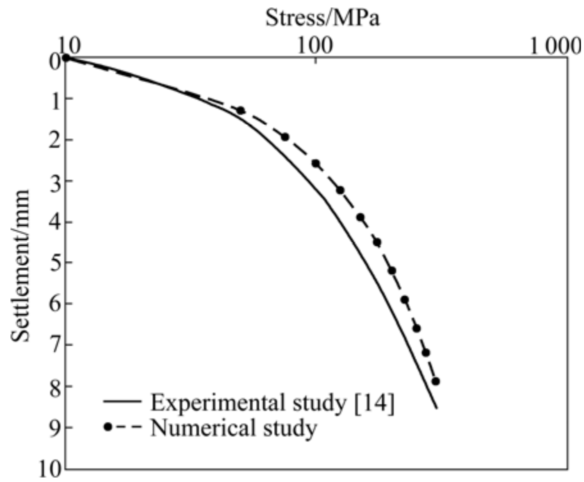

Fig. 8 Laboratory data vs 3D FE results for load-settlement curve

3 Results and interpretation

3.1 Raft settlement

After all of the analyses have been carried out, the settlements of the raft under three vertical stresses of 100 kPa, 200 kPa and 300 kPa in all pile arrangements are monitored. The observed settlements are shown in the Fig. 9. It is important to note that all the settlements are obtained from the position of A-line which is shown in Fig. 5. The horizontal axis in Fig. 9 represents normalized coordinate on the raft. At the first look at all settlement which are plotted in Fig. 9, it is clear that in all pile arrangements and under all vertical stresses, no differential settlement has occurred along the raft center line (i.e. A-line). This might be a result of high rigidity of the raft (due to high modulus of elasticity and 1 m thickness) and placing the piles at a relatively close spacing.

As it was mentioned before, patterns A and D are

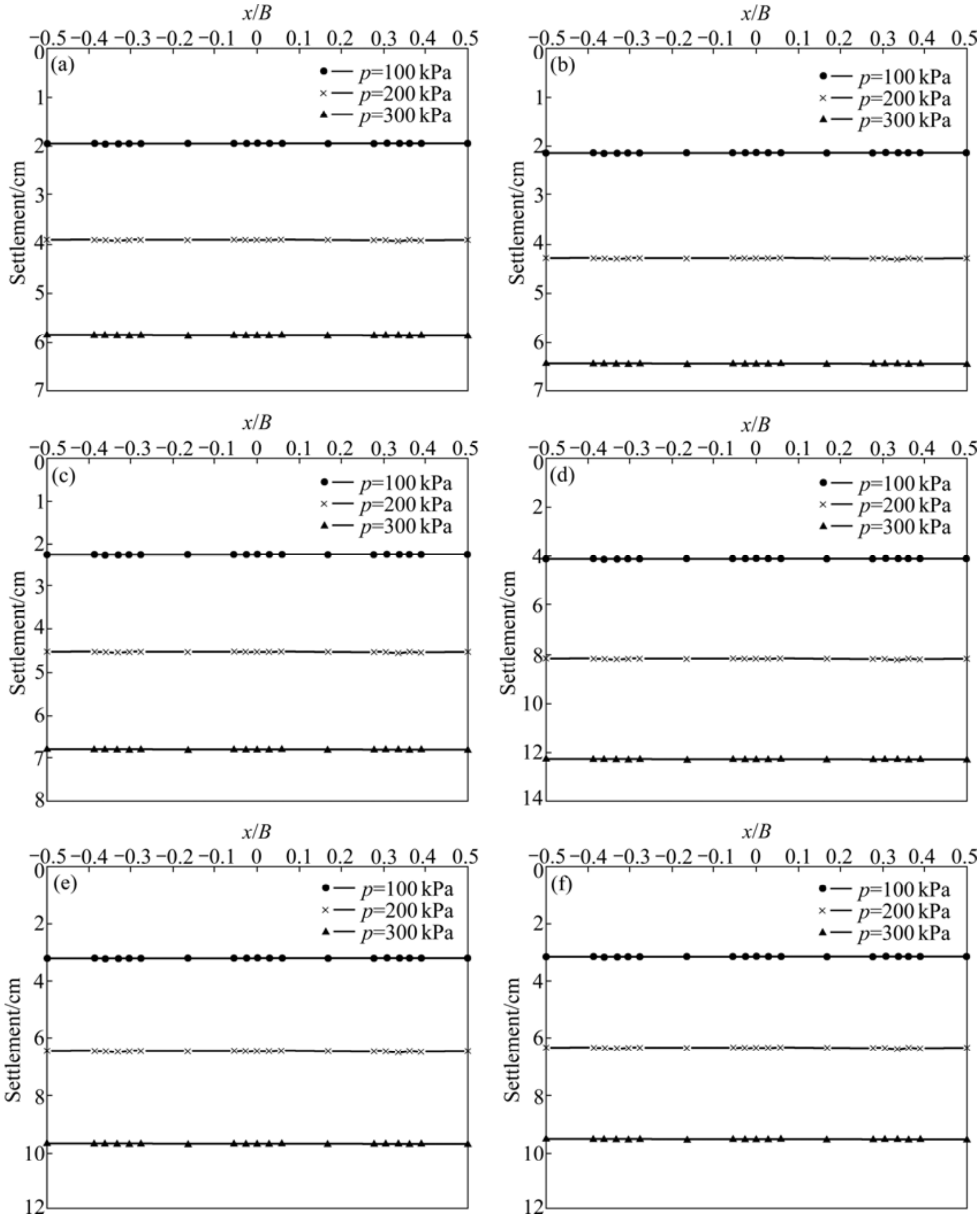

Fig. 9 Settlements of raft for different long−short pile arrangements: (a) Pattern A; (b) Pattern B; (c) Pattern C; (d) Pattern D; (e) Pattern E; (f) Pattern F

expected to have minimum and maximum raft settlements. For the pattern A, raft settlements of 2.0 cm, 3.9 cm and 4.8 cm are observed for stress levels of 100 kPa, 200 kPa and 300 kPa, respectively. These are the least settlements that have been monitored with regard to other patterns. In the patterns B and C, with five and four long piles in each, respectively, the monitored raft settlements are slightly larger than those monitored in pattern A. However, the settlement differences are negligible. Regarding the reduced magnitude of concrete and the related costs for drilling and construction in the patterns B and C, it can be deduced that using composite piled raft foundation using patterns B or C can be an economic option for lowering raft settlements to a minimum value.

On the other hand, for the pattern D, raft settlements of 4.1 cm, 8.2 cm and 12.2 cm are observed for stress levels of 100 kPa, 200 kPa and 300 kPa, respectively, which are the largest among the other patterns. From the plots of raft settlements in Fig. 9, it is clear that using patterns E or F for long−short pile arrangement leads to lowering the magnitude of settlements by about 1 cm. It should be noted that the overall pile lengths for all D, E and F patterns are the same (45 m in each pattern) and this shows how using composite piled raft foundation could be effective and economic in reducing raft settlements. While the difference between the observed settlements in patterns E and F are very negligible, the settlement in pattern E is a little larger than the settlement monitored in pattern F. Since the net spacing between the short piles in the pattern E is less than its counterpart in pattern F, pile arrangements in pattern F is less influenced by the stress interference phenomenon.

Evaluating the settlements of a composite piled raft system could be discussed using the concept of dimensionless stiffness of composite piled raft parameter K ($=P/(\delta\times E_s\times d)$), where P is the uniform vertical stress acting on the raft, δ is the average settlement of the raft and E_s is the elastic modulus of subsoil. To reach a better understanding about the effects of various long−short pile arrangements introduced previously, on K (composite piled raft stiffness parameter) and the raft settlements at different stress levels, Fig. 10 is illustrated. It is important to note that K is in inverse proportion to δ. As it is shown in Fig. 10(a), patterns E and F have significant effect on reducing settlements of the raft with respect to D pattern. On the other hand, the settlements monitored in patterns B and C are very close to those yielded by pattern A which is the minimum boundary for the raft settlement. In addition, all the observed settlements grow with increase in the vertical stress in a linear trend. All the data interpreted in Fig. 10(a) are in well agreement with the data shown in Fig. 10(b). Close magnitudes for parameter K are obtained for patterns A, B and C. The obtained magnitudes of K for E and F patterns increased by 27% with respect to pattern D. Furthermore, Fig. 10(a) shows that with the increase in the vertical stress, the range between the maximum raft settlement (monitored from pattern D) and the minimum raft settlement (monitored form pattern A) becomes wider. This means that the effect of using different piles arrangement in reducing raft settlements becomes more obvious with increasing the vertical stress acting on the raft.

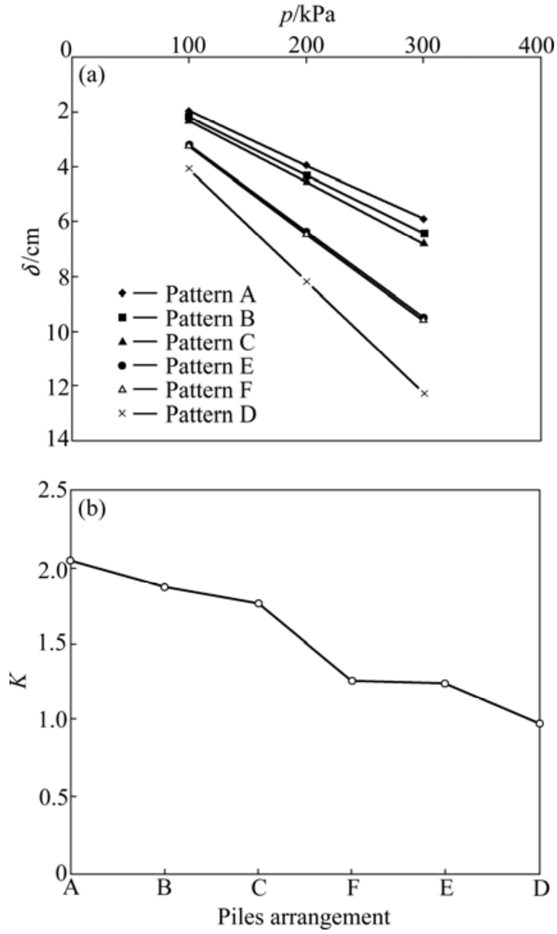

Fig. 10 Raft settlement at different vertical stresses (a) and dimensionless stiffness of composite piled raft for different pile arrangements (b)

3.2 Axial stresses of long and short piles

Settlements of any vertically loaded piled raft system (composite piled raft or simple piled raft) definitely depend on the axial stresses that piles undergo. In a vertically loaded simple piled raft (with similar pile lengths), depending on stiffness of subsoil, vertical stress acting on raft and rigidity of piled raft, the axial stresses of piles usually are the same or have minor differences. However, these differences among the piles in a composite piled raft system become more visible due to dissimilar lengths of short and long piles. Therefore, studying the axial stresses of a vertically loaded composite piled raft is a point of interest in assessment of settlements of composite piled raft foundation.

As mentioned above, composite piled raft is a new and economic type of foundation designed for reducing settlements and its performance is usually compared with simple piled rafts. Therefore, at first, the axial stresses of simple piled rafts (patterns A and D) are evaluated and then the axial stresses of composite piled rafts (patterns B, C, E and F) are studied. Figure 11 shows the axial stress distribution of piled raft along the piles length in patterns A and D. Results show that in both A and D patterns, the piles which are located at the center of the raft take the least axial stresses compared to other piles. On the other hand, the piles located at the corner of the raft take the largest axial stresses among other piles. This trend also has been found in the recent research works [13]. Thus, the range of minimum and maximum axial stresses is simply determined by indicating axial stresses of center and corner pile at each stress level in Fig. 11. The difference between minimum (center pile) and maximum (corner pile) axial stresses of piles becomes

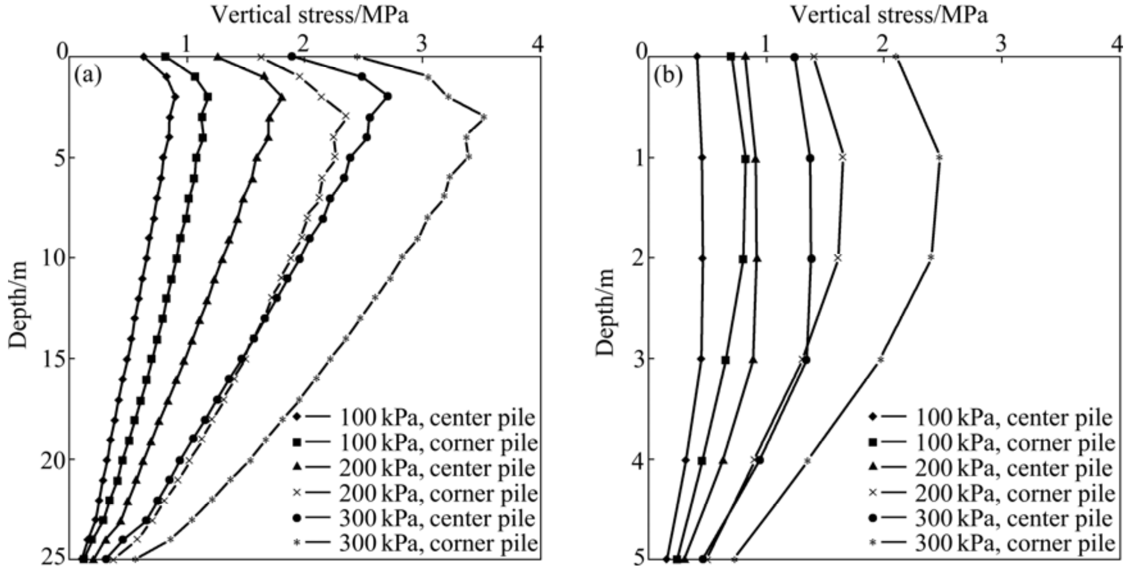

Fig. 11 Axial stress distribution of simple piled raft with cushion: (a) Pattern A; (b) Pattern D

larger with the increase in the magnitude of vertical stress acting on the raft.

From Fig. 11, it is clear that in all piles under different stress levels, the location of the piles in which the maximum axial stress occurs is placed at shallow depths. This is because of considering the cushion beneath the raft. Conversely, in piled rafts without cushion, the point of maximum axial stress for piles usually shifts up to the head of piles, as shown in the Fig. 12. In Fig. 12, distribution of axial stress of piles in pattern A in the case of considering cushion is compared with the case that no cushion element is considered under the raft. A similar trend has been seen for all of pile arrangement patterns under different stress levels. It can be deduced that using cushion underneath the raft causes the load undertaken by subsoil to increase under the adjustment of cushion, the axial stresses of piles to decrease along the pile length, and the displacements of subsoil to be larger than that of piles in range of certain depth along piles shaft. And then, the negative skin friction is generated by the relatively larger settlements of shallow subsoil. However, with further increase in depth, displacements of piles become larger than those of subsoil, and the friction along piles will become positive and axial stress of piles decreases with the depth again. Pile and subsoil deformations which are shown in Fig. 13, completely confirm the interpretations of axial stresses of piles. This trend also is observed in recent research works [12].

Figure 14 shows the axial stress distribution of composite piled rafts (patterns B, C, E and F). In pattern B, the corner and the center long piles had a very close axial stress distribution in each normal stress, therefore to make the plots simpler, the mean axial stress of corner and center long piles were calculated and shown in

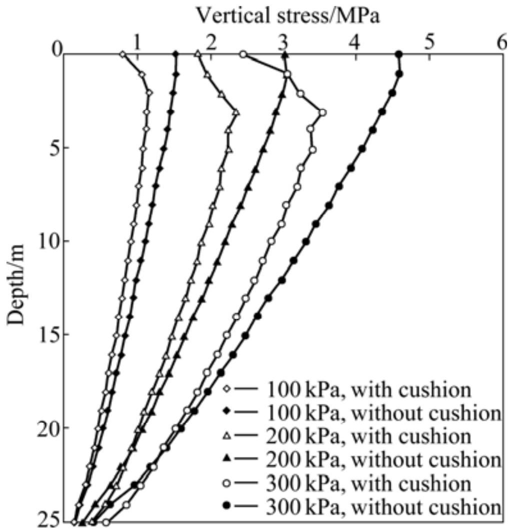

Fig. 12 Effect of cushion on axial stress distribution of piles for pile pattern A

Fig. 14(a). Also, a similar procedure has been performed for pattern C in Fig. 14(b) for corner and center short piles. Again here, in composite piled rafts due to considering cushion beneath the raft, the maximum axial stress of piles shifts lower from the head of piles to a certain depth (compared with composite piled rafts without cushion). As it is shown in Fig. 14, the axial stress of long piles in pattern C is slightly larger than that of pattern B, and axial stress of short piles in pattern B is a little larger than that of pattern C. In other words, the difference between axial stress of long and short piles in pattern B is lower than pattern C. This means a composite piled raft having a long−short pile arrangement similar to pattern B, makes a better use of the bearing capacities of short piles compared to piles arrangement used in pattern C, and as a result, it will show smaller raft settlement. The related monitored settlements described in Section 3.1, conforms well to the interpretations of the axial stress of piles for patterns B and C.

The plots of axial stress of piles in Figs. 14(c) and (d) show that the axial stresses of short and long piles in patterns E and F are very close to each other. This is

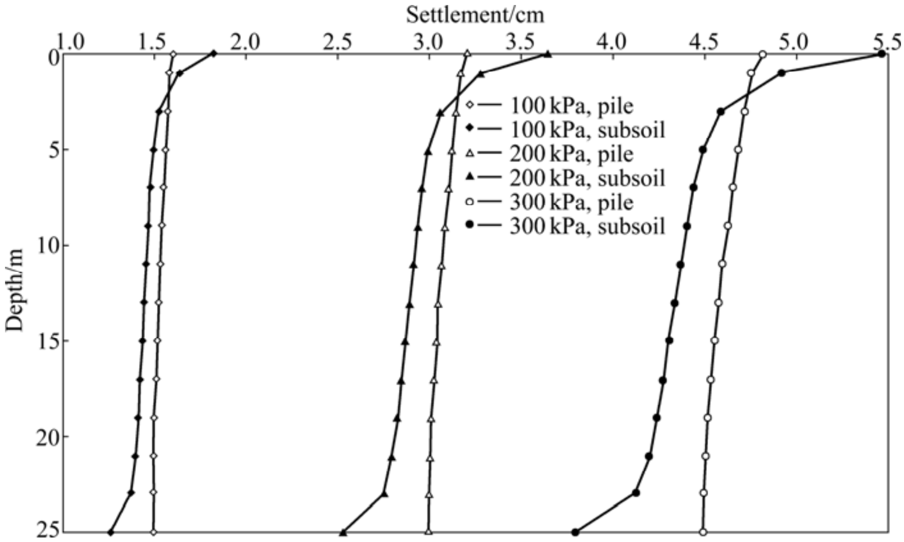

Fig. 13 Settlements of pile and subsoil of piled raft with pattern A

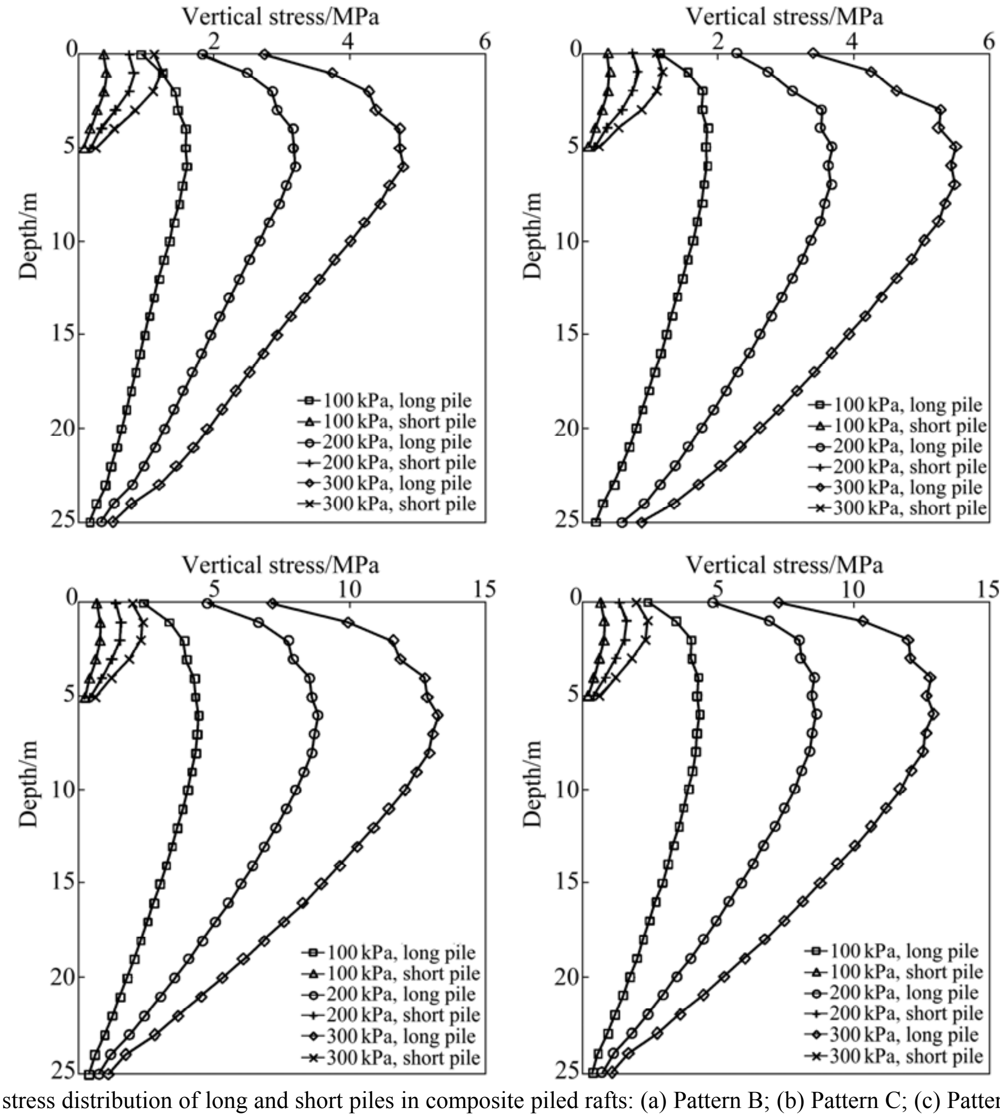

Fig. 14 Axial stress distribution of long and short piles in composite piled rafts: (a) Pattern B; (b) Pattern C; (c) Pattern E; (d) Pattern F

expected because piles arrangements in patterns E and F are very similar. The only difference between the piles arrangements in these two patterns is the locations of the short piles. However, the axial stress of short piles in pattern F is a little larger than that of pattern E, and the axial stress of long piles in pattern F is a little smaller than that of pattern E. It should be emphasized again that, the difference between axial stresses of piles in patterns E and F is very negligible which can be attributed to the axe-to-axe distance of short piles in each pattern.

3.3 Composite piled raft efficiency

From the aforementioned points, it can be deduced that the more axial stress the short piles support, the more the reinforcing effect they have. In other words, the most effective long−short pile arrangement is the one in which the difference between axial stresses of long and short piles is minimized. On this account, we have developed the concept of composite piled raft efficiency (CPRE) ratio. CPRE ratio is defined by

$$R_{\text{CPRE}} = \frac{\sigma_{\text{sh}}}{\sigma_{\text{l}}} \tag{1}$$

where σ_{sh} is the mean of maximum axial stress of short piles and σ_{l} is the mean of maximum axial stress of long piles. According to the literature review in Section 1.3 and the results of this work, it can be deduced that many factors like piles length, number of short piles and long piles, piles stiffness, cushion characteristics, magnitude of vertical stress acting on raft, raft characteristics etc, could affect the settlements of a composite piled raft system. However, all of the mentioned factors are part of input parameters which usually exist in any problem. Predicting the performance (or settlement) of a piled raft system using the input parameters is very difficult. A very comprehensive parametric study should be carried out to determine how every parameter affects the raft settlements, and it might be difficult, troublesome, energy and cost consuming, and in some cases impossible. But using an output parameter, which is already influenced by all input parameters, is a simple and advantageous way to assess the efficiency of a composite piled raft foundation.

CPRE ratios are calculated for all pile arrangements of composite piled rafts. The computed CPRE ratios for different patterns under different vertical stresses show that unlike the dimensionless stiffness of composite piled raft (*K*), CPRE ratio is not a function of magnitude of vertical stress (Fig. 15). From Fig. 15 it is clear that pattern B has the best performance among other pile patterns, and pattern E is the least efficient pile pattern.

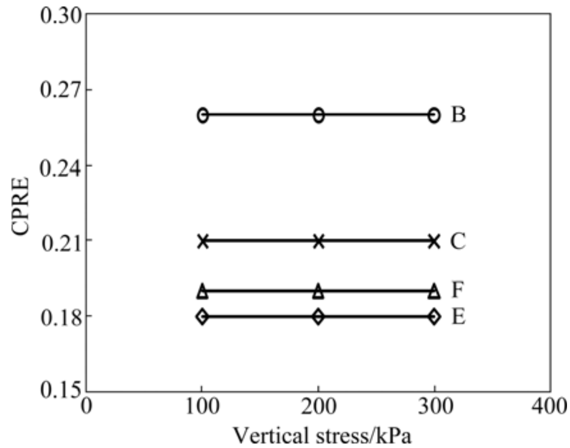

Fig. 15 CPRE ratios for different pile pattern of composite piled rafts under different vertical stresses

4 Conclusions

1) Two simple piled rafts with similar pile lengths of 5 m and 25 m (patterns D and A, respectively), under all stress levels, define the maximum and minimum ranges of possible raft settlements. The settlements of all composite piled rafts are laid within this range. The observed raft settlements of composite piled rafts with pile patterns of B and C are very close to each other. However, the observed settlements of piled raft in the pattern A are slightly smaller than those of patterns B and C. By comparing the pile lengths, magnitude of used concrete and the related costs for excavation and construction in the pattern A with their counterparts in patterns B and C, it will be easily understood that how using a composite piled raft foundation can be economic and effective on reducing the raft settlements. There is also a similar explanation for the raft settlement for pile patterns of D with E and F. The piles arrangements in patterns E and F improve the raft settlement by about 40% compared to the monitored settlement from pile pattern D, which is considered high. Note that with the increase in the magnitude of normal stress acting on the raft, the range of maximum and minimum settlements (observed from pile patterns D and A, respectively) becomes wider. In other words, the influence of using an effective long−short pile arrangement in reducing raft settlements becomes more apparent when the raft stress increases.

2) The monitored axial stress of piles shows that the location of the piles in which the maximum axial stress occurs is placed at shallow depths. This is a result of considering cushion beneath the raft. Conversely, in piled rafts without cushion, the point of maximum axial stress for piles usually shifts up to the head of piles. In addition, the plots of displacements of pile and adjacent subsoil confirm that displacements of subsoil are larger than

those of piles in shallow depths along the piles shaft. And with further increase in depth, displacements of piles become larger than those of subsoil. This phenomenon causes the axial stress of long piles to be smaller, and axial stress of short piles to be larger compared to the case in which cushion is not used underneath the raft.

3) Comparisons of long and short pile distributions of composite piled rafts with their settlements show that when the difference between axial stresses of long and short piles is minimized, the composite piled raft shows smaller settlement and in fact, it performs effectively under the vertical stresses. Among the different pile patterns for composite piled raft in this study, the pile pattern B has the most pronounced effect on reducing raft settlements. Moreover, the plots of axial stresses of long and short piles for the pattern B confirms that the difference between axial stress of long piles and axial stress of short piles are the least magnitude among other pile patterns.

4) Based on the information about the settlements and axial stress of piles, the concept of composite piled raft efficiency (CPRE) ratio is developed which is defined by the mean of maximum axial stress of short piles to that of long piles. Results of calculation of CPRE ratio for the considered pile patterns of composite piled raft in this work show that the magnitudes of CPRE ratio exactly follow the trend that in the monitored raft settlements have been found. Also, it is found that unlike the dimensionless stiffness of composite piled raft (K), CPRE ratio is not a function of magnitude of vertical stress.

Acknowledgement

Grateful acknowledgment is given to Imam Khomeini International University (IKIU) for providing financial support during the research undertaken in the Civil Engineering Department at IKIU, Iran. Also authors are so thankful to the reviewer's useful and constructive comments.

References

[1] POULOS H. Pile raft foundations: Design and applications [J]. Geotechnique, 2001, 51(2): 95−113.

[2] DAVIS E, POULOS H. The analysis of piled raft systems [J]. Australia Geotechnique Journal, 1972, (2): 21−27.

[3] BURLAND J, BROMS B. Behavior of foundations and structures [C]// Proceeding 13th International Conference on Soil Mechanics and Foundation Engineering. Tokyo, 1977: 495−546.

[4] COOKE R. Piled raft foundation on stiff clays—A contribution to design philosophy [J]. Geotechnique, 1986, 36(2): 169−203.

[5] CHOW Y, THEVENDRAN V. Optimisation of pile groups [J]. Computers and Geotechnics, 1987, 4(1): 43−58.

[6] RANDOLPH M. Design methods of pile group and piled rafts: State-of-the-art report [C]// Proceeding 13th International Conference on soil Mechanics and Foundation Engineering. New Delhi, 1994: 61−82.

[7] HORIKOSHI K, RANDOLPH M. Centrifuge modeling of piled raft foundation on clay [J]. Geotechnique, 1996, 46(4): 741−752.

[8] TA L, SMALL J. Analysis of piled raft systems in layered soils [J]. International Journal for Numerical and Analytical Method in Geomechanics, 1996, 20(1): 57−72.

[9] KIM K, LEE S. Optimal pile arrangement for minimizing differential settlements in piled raft foundation [J]. Computers and Geotechnics, 2001, 28(2): 235−253.

[10] SHAHU J, MADHAV M, HAYASHI S. Analysis of soft ground-granular pile-granular mat system [J]. Computers and Geotechnics, 2001, 27(1): 45−62.

[11] ZHAO M, ZHANG L, YANG M. Settlement calculation for long-short piled raft foundation [J]. Journal of Central South University of Technology, 2006, 13(6): 749−754.

[12] LIANG F, CHEN L, SHI X. Numerical analysis of composite piled raft with cushion subjected to vertical load [J]. Computers and Geotechnics, 2003, 30(6): 443−453.

[13] LIANG F, CHEN L, HAN J. Integral equation method for analysis of piled rafts with dissimilar piles under vertical loading [J]. Computers and Geotechnics, 2009, 36(3): 419−426.

[14] WANG X Z, ZHENG J J, YIN J H. On composite foundation with different vertical reinforcing elements under vertical loading: A physical model testing study [J]. Journal of Zhejiang University: Science A (Applied Physics & Engineering), 2010, 11(2): 80−87.

[15] ZHENG J, ABUSHARAR S W, WANG X. Three-dimensional nonlinear finite element modelling of composite foundation formed by CGF-lime piles [J]. Computers and Geotechnics, 2008, 35(4): 637−643.

(Edited by DENG Lü-xiang)