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Assessment the effect of pile intervals on settlement and bending moment raft analysis of piled raft foundations

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Abstract. Application the pile group foundation to reduce overall settlement of the foundation and also avoid a very fruitful settlement of foundations, inconsistent was carried out. In such a case, in event that the Foundation, not as a mere pile group, which as a system consisting of a broad foundation with pile Group, economic design criteria will be provided in spite of high safety. A new approach in the design of the Foundation can be introduced as the piles are just a tool to improve the parameters of soil hardness; that it can work with detachable piles from raft. Centralized arrangement of piles as the most optimal layout of piles in reducing inconsistent settlement, which is the lowest value of resulting layout in this differential settlement. Using the combination of piles connected and disconnected to form the raft, bending moment created in the raft is reduced. It also concentrated arrangements have greatest effect in reducing amount of moment applied to the raft.

Keywords: pile intervals; numerical analysis; piled raft foundations; settlement of raft; bending moment

1. Introduction

Raft foundations are generally used to support buildings and structures, with or without basements, in dry or high water table conditions. When the shallow subsoil conditions are unfavorable (unsafe bearing capacity or excessive settlements) then load bearing piles can be used for transferring the total loads to more competent soil layers. In many cases, the maximum and differential settlements are the controlling factors to the selection of composite foundations systems including piles and raft. The piled raft foundation contains three elements of load-bearing; namely piles, raft and below soil mass. Matching their relative stiffness, raft foundation distributes the whole load transferred from the superstructure to the top soil and the connected piles. In conventional design of piled foundations, it was usually postulated that the overall load is supported by the piles. In composite foundation systems, raft contribution is taken to consideration for confirm the bearing capacity in ultimate moment and the serviceability of all over system. Piles using concept to reduce amount the settlement of raft was first time proposed via Burland *et al*. (1977) that located one pile beneath each shaft of structure. As reported by Solanki *et al*. (2013) many reports have been published on using the piles as settlement reducers. Zhuang and Lee (1994) have used a method of finite element to check the load contribution among the piles and foundation of raft. In this regard, observed that amounts of load sharing among the piles on system of composite piled-raft was affected via pile stiffness, rigidity of raft and length of pile to ratio of width. They also noticed that for example length of pile increases rigidity of pile decreases and be more uniform amount of load distribution. Ta and Small (1996) expanded a way, which was basis on method of finite layer, for composite piled raft system analysis in soil with layered structure. They found out that distribution of load among the shafts in composite system was efficacy via thickness and also soil layer stiffness. Ta and Small (1997) considered that load sharing via piles growths as the strata of bearing gets stiffer. Russo (1998) expanded numerical method to composite system, who observes nonlinearity of unilateral connection at the interface of raft-soil and nonlinear relationship of load-settlement. They declared as if nonlinear analysis must be considered to the raft and piles system since piles action as reducing the settlement and load capacity in ultimate point related to them may be achieved. Poulos (2001) developed a method with simplified analysis type as one tool on elementary design of composite foundation system. Poulos (2001) reported that until a raft foundation is lonely does not satisfy the requirements of design, using a bounded number the piles might to be better the performance of such foundations in terms of ultimate load capacity, total and differential settlements. Reul and Randolph (2004) by using the finite element method the composite piled-raft on clay soil with over consolidated conditions have modeled. Reul and Randolph (2004) observed than pile raft interaction results to an increase on the friction of skin with an increase the load or increase of the settlement.

Nakai *et al*. (2004) performed centrifuge model tests followed with a parameter survey according to the finite element analysis for structures supported by piled foundations and piled raft foundations. Nakai *et al*. (2004) showed that head of the pile effect connection condition

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upon the response characteristics of the superstructure is justly small until compared to kind of the foundation. They also showed that even since piles are not connected into the foundation of raft, the characteristics of load bearing in piles were not affected. Nakai *et al*. (2004) concluded that even for the case where shafts are not connected to the foundation of raft, significant contribution to the dynamic soil structure interaction were achieved to them.

El-Mossallamy *et al*. (2009) reported that the settlement and amount of sharing the load among the shallow foundation and shafts are the main factors that control the design of composite piles and raft foundations. Comodromos *et al*. (2009) observed the case of pile cap loaded with a non-uniform vertical load, the load is mostly carried by the piles in the proximity of the loaded area if the cap thickness is less than diameter of pile. They found that if the thickness of cap is greater than the diameter of pile, the kind and the place of the applied load have no efficacy in the load distribution to the piles. In traditional composite piles and raft systems, connection piles and raft is established and extend down into competent soil at depth. While these piles are impressive in reducing the settlement of raft foundation, they may cause to considerable shear forces and values of bending moments as if will affect in structural design of shallow foundation. In order to dominance problems of large stresses into the shallow foundation and piles, Cao *et al*. (2004) and Wong *et al*. (2000) proposed that the shafts be non-connected from the shallow foundation and to behave these piles as arming to the below soil rather than as structural members. Therewith, the gap among the non-connected piles and the shallow foundation can be filled by a cushion of structural fill matter. Liang *et al*. (2003) stated that the cushion, which is composed of a sand-gravel mixture compacted in layers among the top of piles and shallow foundation, has a significant role in mobilizing the capacity of bearing in the below soil and rectifying the mechanism of transfer of the load in piles. After that it has been explained via many authors, such as Lee *et al*. (2006), Eslami and Malekshah (2011) and Sharma *et al*. (2011).

Load sharing in pile group as embedded on soil of type the sand is studied in Fattah *et al*. (2017) study. And also the efficacy of interactions among the composite system elements and Soil on treatment of composite raft and piles Foundation is investigated by Lee and Moon (2016). Behavior piled rafts overlying a tunnel in sandy soil with ANSYS finite element program has been done (Al-Omari *et al.* (2016)). And also time dependent behavior of piled raft foundation in clayey soil by Fattah *et al*. (2012) is studied. Of course a research regarding the optimum pile arrangement in piled raft foundation by using simplified settlement analysis and adaptive step-length algorithm by Nakanishi and Takewaki (2013) is done.

2. Methodology of analysis

In fact, behavior of composite piled raft systems under axial loads is investigated by comparing conventional methods and the latest design methods with parametric analysis. It has been observed that the largest analysis of piled raft systems using boundary-component method approaches only considers the interaction between two piles at one time, and does not consider the presence of other candles in the group, which affects the calculated interaction. This function may lead to further sessions when the same foundation is measured by analyzing the finite element method. For this purpose, the 3D finite element Plaxis software for is used to analyze the foundation structure in this study, Plaxis 3D foundation manual (2006).

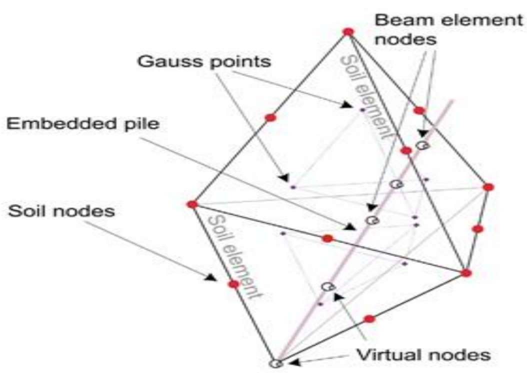

Fig. 1 Shape of embedded pile element with a 10-node tetrahedral Component

Certain types of elements have been used for model the treatment of piles and shallow foundation systems. In this evaluation, the plate element is used to model the raft foundation in software, Also the embedded pile element for model the piles is used. Element of embedded pile is a component of instrument developed by Plaxis and modeled as a beam element (Fig.1), Plaxis 3D foundation manual (2006).

2.1 Software results verification

For the accuracy of the software results, a wide investigation program relevant to piles within overconsolidated clay soil was conducted via Sommer and Hambach (1974) to optimize the foundation design related to a highway bridge in Germany. The equipment of Load cells at the base of pile to gauge the load amounts carried straightly via pile base was installed. Fig. 2 gives the pile load test array layout. The curves of the measured load settlement amount and the load distributions among basis resistance and friction of skin are shown at Fig. 2. The upper 4.5 m below soil including of silt followed via tertiary alluviums down to large depth soils. These tertiary alluviums are firm plasticclay analogous to the Frankfurt clay, by a changing overconsolidation degree. A pile load experiment is frequently used to confirm the numeral modeling of treatment of pile on clay soil with kind of Frankfurt overconsolidated by El-Mossallamy (2004).

Amount of groundwater table is on 3.5 m under the ground surface. Diameter of pile is 1.3 m and length of pile is 9.5 m. It is located completely in the clay with overconsolidated conditions. The system of loading consists of hydraulic jacks versus a reaction beam are worked. This beam is based on 16 anchors. Anchors as vertically about a depth among 15 and 20 m beneath the surface of ground at a distant about 4 m of the examined pile were installed, for

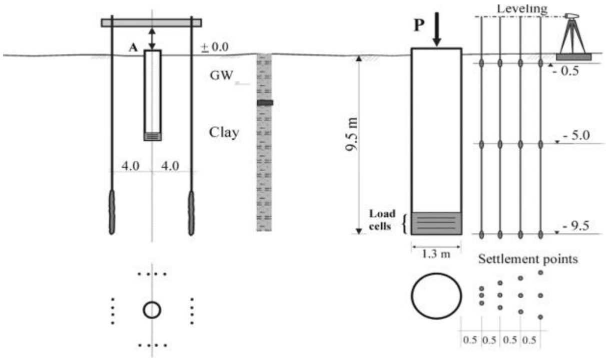

Fig. 2 Pile load test layouts and measurement points

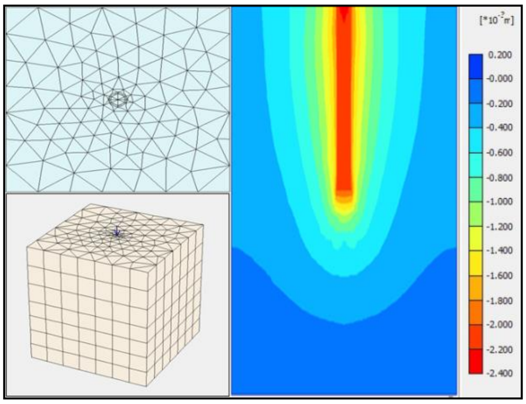

Fig. 3 Mesh generating in 2D, 3D, and deformation contour of a single-pile model

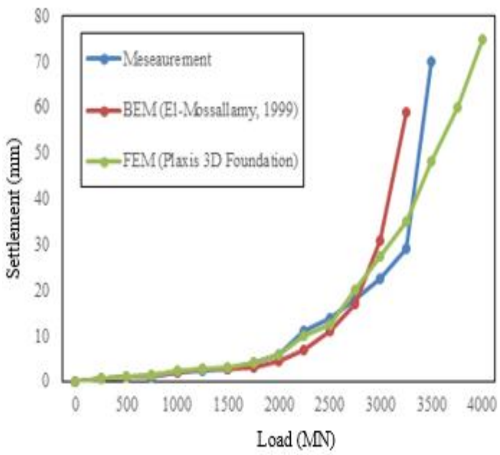

Fig. 4 Load-settlement diagram of torhaus building foundation

Table 1 Settlement values in sensitivity analysis of mesh dimensions parameter (unit: mm)

Mesh generation Height (m)	Mesh generation dimensions (length*width) (m)				
	10*10	15*15	20*20	25*25	30*30
15	9.03	7.21	6.16	6.34	4.7
20	10.12	7.62	6.66	5.98	5.95
25	11.4	8.11	7.01	6	5.99

minimize the efficacy of the reciprocal interaction among the examined pile and the response system (Fig. 2). Vertical and horizontal loading tests were carried out. The loads were applied in enhancements and holding constant than the rate of settlement was negligible. Both the applied loads and the corresponding movements at the tested head of pile location were measured. Additionally the soil displacements near the pile at different depths were measured using deep settlement points (Fig. 2).

Mesh network of finite element with dimensions 20 × 20 meters in length and 20 meters in depth is used. In center of the modeling soil, a pile with a length of 9.5 m and a thickness of 1.3 meters is modeled. Soil is modeled as a single pre-consolidated soft clay layer that matches the specific properties of materials. Groundwater level is located at 3.5 meters below the surface of the soil. Interface element is modeled along the length of the pile. This element has been developed up to 0.5 meters below the pile, to let for enough flexibility around of pile tip. Two-dimensional and three-dimensional mesh network as well as reshape the contour of the settlement obtained in the form of pile shown in Fig. 3.

The load-settlement curve of this case study using Plaxis 3D foundation software has shown that results obtained from the analysis of finite element present in the range of values obtained from other ways (Fig. 4). Therefore, the software results presented in the above instance are verified and can be used to conduct the main analysis of the research.

And also, in order to investigate the sensitivity analysis of the dimensional dimension to the settlement parameter, sum of the summation in various dimensions the boundary component is reviewed in accordance with Table 1. Based on resultant sum of results, the difference of results is less than 1%, which indicates that the network dimensions are not considered as an effective parameter in the modeling. As result, analysis the sum of results obtained without influence of above parameter is acceptable and correct.

2.2 Definition the model, geometry and loading

Composite foundations including pile and raft have been considered in this research. Knowing the performance of composite piled raft systems is important because of fact that the decreasing role of non-uniform settlement and piles plays the role of supporting the underlying soil and increasing the load bearing capacity of the soil. A case study has been used to analyzing the performance of piles and shallow foundation systems in this study by Lee and Moon (2016). Raft foundation with a thickness of 0.3 m and a dimension of 6 × 6 meters, which is located on a uniform sandy soil mass, and depth of raft from the soil surface is 2 m. Piles with a circular section of length 10 m and a thickness of 0.5 m and with 9 numbers below and within soil are located. Groundwater level is not considered, which actually indicates that the water level is outside of the 25 m thick layer of the sand.

Fig. 4 shows dimensions and specifications of this composite piled raft system. 3D picture of composite system is shown in Fig. 5. The distance between piles is 2 meters and their distance from the edge of the bridge is 1 meter.

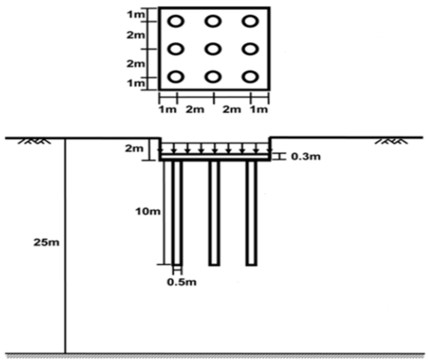

Fig. 5 Composite foundation dimensions and soil properties of investigation problem

Table 2 Geotechnical specification of soil

Character	Symbol	Sand soil	Unit
Material model	-	HS	-
Unsaturated specific weight	γ_{unsat}	9	kN.m^3
Saturation specific weight	γ_{sat}	18	kN.m^3
Reference Secant stiffness	E_{50}	5000	kN.m^2
Reference odometer stiffness	E_{oed}	5000	kN.m^2
Unloading / reloading stiffness	E_{ur}	15000	kN.m^2
Stress dependency power	m	0.5	-
Poisson's ratio for unloading-reloading	ν_{ur}	0.2	-
Cohesion	C	0.0001	kN.m^2
internal friction angle	ϕ	30	-
internal friction angle	ψ	0	-
K0-value for normal consolidation	K_0^{NC}	0.426	-
Ratio of over consolidation	OCR	1	-
Past overburden	POP	0	kN.m^2
Stiffness ratio in interface	R_{inter}	1	-
Layer thickness	D	25	m

Table 3 Raft specification in composite system

Character	Symbol	Raft	Unit
Material model	-	Linear elastic	-
Specific weight unit	γ	15	kN.m^3
Stiffness	E	$10^7 \times 3$	kN.m^2
Ratio of poisson	ν	0.2	-
Raft width	t	0.3	m
Raft dimension	W×B	6×6	m

Table 4 Pile specification in composite system

Character	Symbol	Sand	Unit
Material model	-	Linear elastic	-
Specific weight unit	γ	15	kN.m^3
Stiffness	E	$10^7 \times 3$	kN.m^2
ratio of poisson	N	0.2	-
Diameter of Pile	d	0.5	m

Table 4 Continued

Character	Symbol	Sand	Unit
Length of pile	l	10	m
Pile Numbers	-	9	-

For problem modeling, the parameters of composite system, including sand and raft and piles, are shown in Tables 2, 3 and 4, and the hardening behavior model for uniform sand is used. Raft Specifications used in the composite system are presented in Table 3, which are considered to be linear elastic behavior, with a dimension of 6×6 m and a thickness of 0.3 m. the specification of the embedded pile element used as model piles is given in Table 4. A total of 9 piles have been used under the raft. Based on the variation in the arrangement and location of the piles on the surface of the raft, it has been attempted to observe the behavior of the piles by changing their positions.

Pile Formations and composite piled raft systems used in this study is schematically depicted in Fig. 6. Check the placement of piles on the arrangement of Group and composite piled raft foundation system. Because using an optimized layout of piles within territory by virtue of positive results in the field of reducing the structure settlements and maximum using is achieved. Fig. 7 shows the layout of model test. Raft settlements are monitored with 8 linear displacement transducers (LVDTs) along 2 cross sections, A-A and B-B. The raft bending moments are monitored along profile A-A by strain guages connected to the raft bottoms. 4 shafts were used to repeat the point loads on the model of foundations. The exterior load is asymmetrically applied into the raft to make settlement of differential along the sections of A-A and B-B. The soil is loose silica sand soil with a relative density DR of almost 40%. The details of centrifuge tests can be achieved in Nguyen *et al*. (2014).

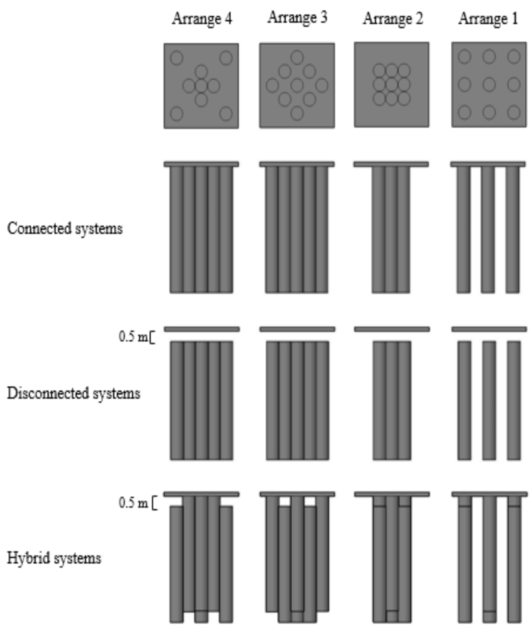

Fig. 6 Piles arrangement of piled raft foundation systems

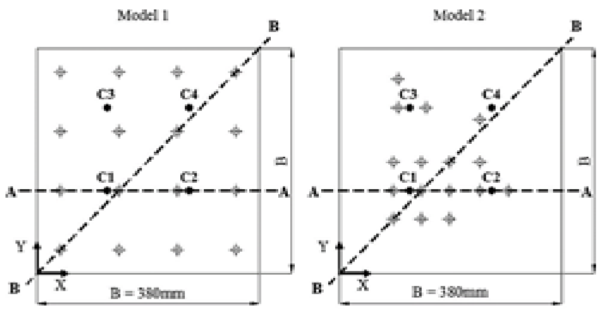

Fig. 7 Piles and columns, cross-sectional arrangements

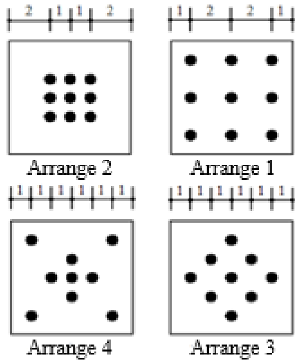

Fig. 8 Connected piled-raft systems (Unit: m)

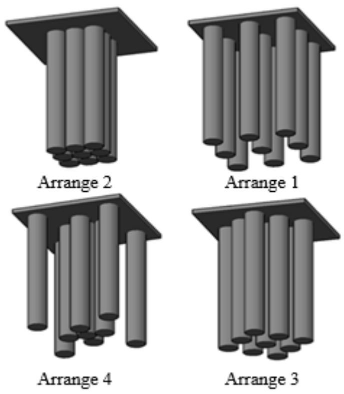

Fig. 9 3D view of connected piled-raft systems

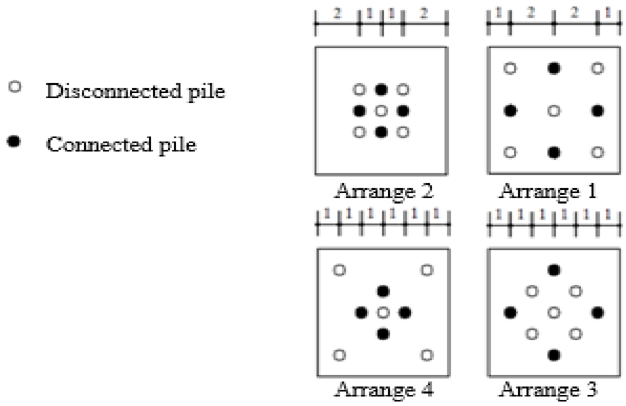

Fig. 10 Definition of hybrid piled-raft systems (unit: m)

Piles connected to the raft are in direct contact with the following piles and connection of the raft and piles continuously and without distances. Also, for the performance analysis of piled raft foundations, four types of arrangement for placing the piles within the soil are considered, as shown in Fig. 8, and three-dimensional view of the composite systems is shown in Fig. 9.

So far, and despite the fact that the idea of the use of piles in the form of disconnected from raft foundation recently became a current analysis method, various studies have been done on the operation of the disconnected piles. But there is no research about the combination of these piles and piles attached to the raft, as evidenced by it. Accordingly, considering that for the first time the effect of using the piles in shape of connected and disconnected from raft was mainly investigated in the present study, it has been attempted to combine this pile kinds with the various arrangement of piles, study and analyze. Also image related to that can be seen in Fig. 10.

3. Result and discussion

In this part of research, results of analysis of 3D foundation Plaxis software have been presented. Initially, four layouts for the arrangement of piles under the raft are considered. Piled raft systems with different arrangements in the connected, disconnected and combined pivot systems, calculating and analyzed. Then settlement and bending moment amount results of these three piled raft systems are compared**.**

3.1 Disconnected piled raft foundations

Fig. 11 shows the obtained diagrams about raft maximum settlement. As can be seen, the maximum settlement in the second alignment system (centralized arrangement of piles) with the value 66.2 mm has created the highest settlement capacity, Raft settlement in other layouts was less than 56 mm. From the resulting settlement levels, it appears that the arrangement of the spray scattering on the raft foundation surface and the majority of the area covered by the soil under the raft, their summation values were close to each other. But in arrangement no. 2, the piles concentrated in middle state of raft foundation, highest settlement has been created. To confirm this result, it can be noted that the arrangement no. 3, which is in some way a diamond-shaped concentrated arrangement, can be seen that its settlement was larger than the arrangements no. 1 and no. 4. Therefore, it is concluded that the concentration of the piles at least in the middle of small piled raft foundations (foundation with a low area), similar to the one used in the present study, increases the maximum settlement. Of course, this result cannot be cited in large piled raft foundations or piled raft foundations with more piles number, as discussed in the study (Nguyen *et al.* 2014). But it can certainly be said that the positive effect of the concentration of piles in the middle of the raft foundations in reducing the differential settlement and bending moment in both small and large piled raft foundations in present study, (Nguyen *et al.* 2014) and other studies has been proven.

Fig. 12 summarizes the results of the analysis in the

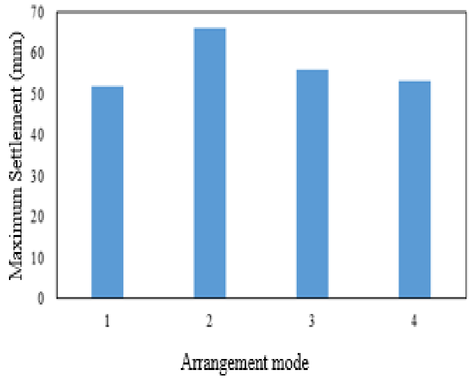

Fig. 11 Maximum settlement of raft in disconnected piled raft

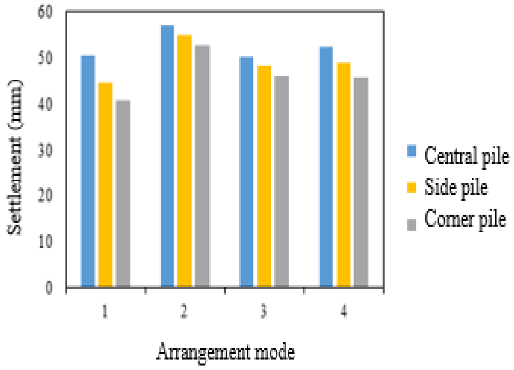

Fig. 12 Settlement amount in anywhere of the raft on disconnected piled raft

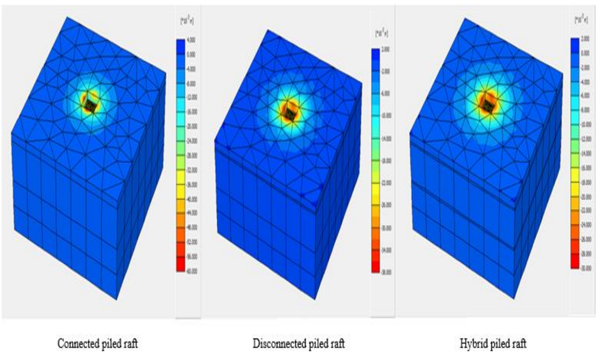

Fig. 13 Maximum settlement variation of piled raft systems

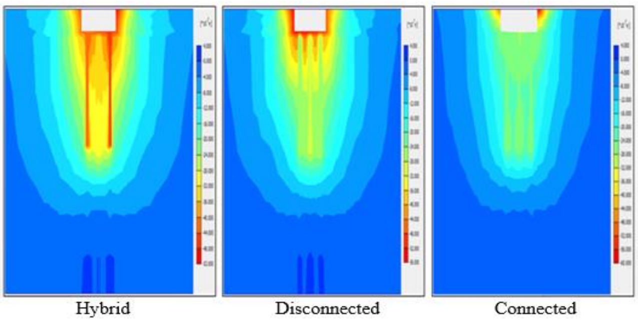

Fig. 14 Settlement contour of piled-raft systems

center, side by side and in corners of the system in a

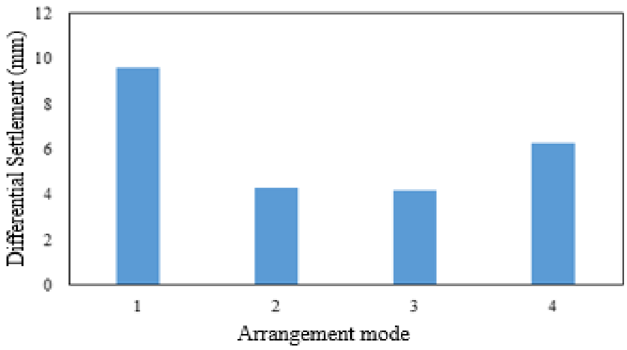

Fig. 15 Differential settlement of raft in disconnected piled raft foundation

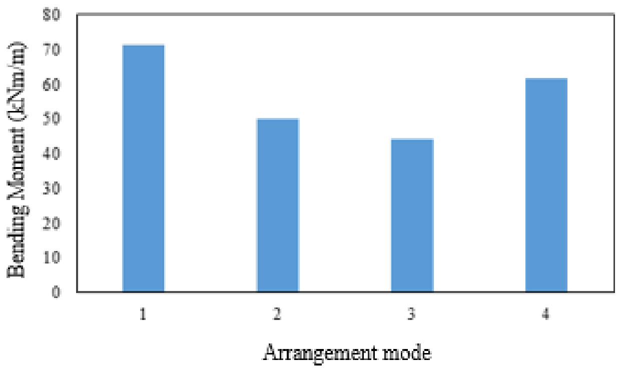

Fig. 16 Bending moment applied the raft in disconnected piled raft foundation

disconnected system with different arrangements, and shows the graphs derived from these values. In all of arrangements, settlement in the center of raft was more than anywhere, and this amount was greater than amount of settlement in corner of the pile. Of course, this difference in settlement rates was more pronounced in the arrangement of the first type (uniform arrangement) with scattered piles.

The maximum settlement variation of stress-induced of the raft on piled raft foundation systems as a contour of deformation is shown in Fig. 13.

Fig. 13 is a graphic contour of maximum settlement the connected, disconnected, and hybrid piled raft systems. Fig. 14 is added for a better view of the relationship between piles and raft foundation. This figure shows the maximum settlement created below the raft. With the disconnected piled raft foundations detached, the distance created between the raft foundation and the piles causes the piles to not directly tolerate the superstructure loads. When these piles are not connected to the raft foundation, can be much lower than the structural failure than the construction piles, while there are no violations of the various building codes, as they can assuming that the final geotechnical capacity is fully mobilized, the structural considerations of these piles are not critical. Also, since the piles are disconnected, the main members of the bearer are not loaded; one can ignore the differences and uncertainties in the loads and the strength of the materials. Therefore, to disconnected piles can be allowed to withstand large loads that make it economical than the piles attached to raft. Accordingly, with the above explanation and Fig. 14 considerations, it can be seen that in a separate and hybrid system, the bearing capacity increases and, as seen in the figure, it can tolerate more settlement.

In the second order arrangement (centralized arrangement) and third order arrangement (diamond arrangement), differential settlement was less and approximately equal (Fig. 15).

Fig. 16 shows the values of bending moment in a composite piled raft system with Separate piles from raft. The amount of moment created in raft foundation, in system with the third-pile arrangement, is less than other layouts, indicating that this type of layout is optimally aligned with the largest moment in the surface. As well as centralized piles (second mode), it also has a moment less than 50 kN. The most common moment in the composite system was the first-order arrangement.

3.2 Comparison of Piled Raft Foundation Systems

Maximum and differential settlement charts are presented in Figs. 17 and 18 arrangements are based on the previous definition of uniform, centralized, diamond, and diagonal layouts, respectively, with the first, second, third, and fourth arrangements Subjects**.** And also, the values of the bending moment on the raft in composite system are shown in Fig. 19.

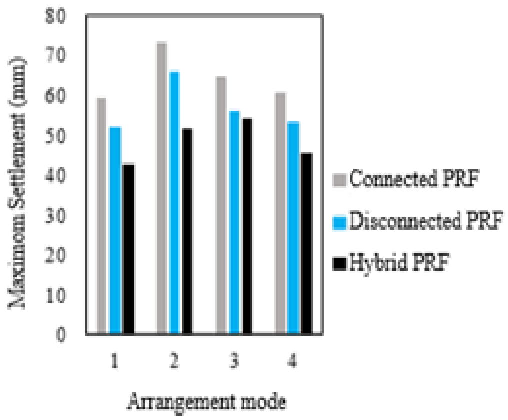

Fig. 17 Comparison of maximum settlement of composite systems

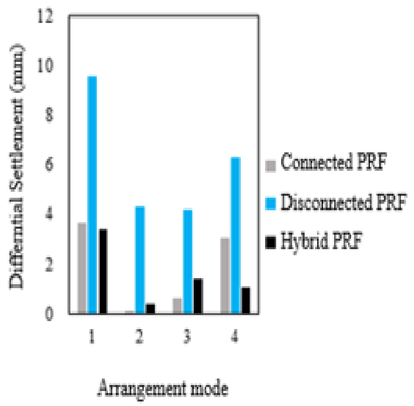

Fig. 18 Comparison of differential settlement of Composite systems

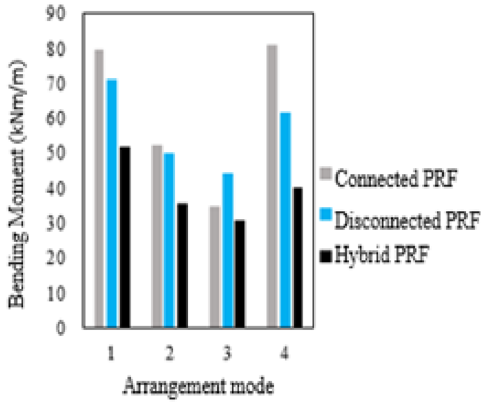

Fig. 19 Comparison of bending moment of composite systems

4. Conclusions

In this study, maximum settlement, differential settlement and bending moment of raft in the composite piled raft systems have been carefully analyzed.

In summing up the results of material modeling are as follows:

- Raft foundation with the initial arrangement of piles, which is common in the analysis of results as system of composite with the first arrangement (uniform arrangement), has lowest amount of maximum settlement, and with regard to the closeness of the sum of the maximum resulting from this layout and the fourth arrangement of the piles. In the composite system, it can be said that these two arrangements are useful for reducing the foundation settlement. As well as the combination of three connected, disconnected and combined systems, combination system with simultaneous use of the plugs connected to the raft and the detached from it, the summit has been reduced to a significant extent significantly. The maximum amount of sewage occurred at the maximum in the system with connected piles to the raft occurrence, and in the meantime, the function of the system in disconnected system was minimally connected to the system at a maximum potential.
- Average settlement of the mean of summation the points of center, side, and corner of the foundation are obtained. In fact, the location of the placement and pile arrangements under the raft foundation is a parameter that influences the amount of meeting occurring in different parts of the raft foundation. Raft foundation the first mode of pile, which shows the uniform arrangement of piles in the model, has a smaller settlement than other layouts.
- Bending moment parameter enters another important parameter affecting the positive performance of the piled raft system in the response of the instruments. As the bending moment acts on smaller values, structural stability increases and the risk of overturning decrease. The second-order composite system (centralized arrangement) and third-order arrangement (diamond arrangement) have significantly reduced bending moment applied to the raft foundation.

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