

Settlement Analysis of a Piled Raft

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Abstract

Recently the concept of settlement piles has been introduced in which the spacing could be large when the purpose of using piles is to mitigate the settlement rather than resisting the load. For large spacing the effect of cap soil contact on the bearing capacity may increase therefore the new system is usually referred to as piled raft. It is yet not clearly indicated what number of piles or spacing is enough to maintain tolerable settlements. This ambiguity is the main problem of the present research besides some other relations. The software ANSYS version 11 has been used to model and analyze the piled raft. The raft and piles are represented using the 8-node isoparametric brick element SOLID 65 while the surrounding soil is represented using the 8-node brick element SOLID 45. The raft dimensions are kept constants, as well as the cohesion and the angle of friction of the soil. The Drucker-Prager soil yield model has been employed. The results indicate that there is a limiting number of piles represented by the total piles area relative to the group area which in general amounts to 3 to 4% after which there will be no significant advantage of increasing the number of piles to reduce settlement. This relative piles area is slightly affected by the stress level relative to the bearing capacity so that the factor of safety. Accordingly the pile spacing may significantly be increased if the settlement is the major concern. The ultimate bearing capacity was found to moderately increase with increasing the relative pile area up to the narrowest spacing used of 3D which is in agreement with the conventional knowledge. For the conditions investigated the effect of raft-soil contact was found to be not very significant.

تحليل الهبوط لاسس الركائز الحصرية

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الخلاصة

لقد أُستحدث مؤخراً مفهوم المسافات الكبيره بين الركائز عندما يكون الغرض من استخدام الركائز هو التخفيف من الهطول بدلاً من مقاومة الحمل. بالنسبة للمسافات الكبيره فان تأثير اتصال العوامه بالتربة على سعة التحمل قد تزيد من هذه السعة و لذلك فان هذا النظام الجديد يشار اليه عادة بعوامة الركائز. ليس من الواضح لحد الآن ما هو عدد الركائز او المسافه بين الركائز التي تكون كافيه للحفاظ على هطول مقبول. هذا الغموض هو الموضوع الرئيسي لهذا البحث الى جانب بعض العلاقات الاخرى. حيث ان البحث العملي هو مكلف للغاية، فان هذه المشكله قد تم حلها بالطريقه العدديه. تم استخدام برنامج ANSYS 11 لتمثيل و تحليل عوامة الركائز . لقد تم تمثيل العوامه و الركائز باستخدام العنصر الطابوقي ذي الثماني نقاط (SOLID 65) كما تم تمثيل التربه المحيطه باستخدام العنصر الطابوقي ذي الثماني نقاط (SOLID 45). ابعاد العوامه بقيت ثابتة و هي 6.9 متر طول، 4.5 متر عرض و 0.5 متر سمك، فضلا عن التماسك وزاوية الاحتكاك للتربه التي ايضا بقيت ثابتة. و قد أُستخدم نموذج (Drucker-Prager) لتمثيل سلوك التربه. لقد أشارت النتائج الى وجود حد لعدد الركائز و يُمثل بنسبة مجموع مساحة الركائز الى مساحة المجموعه، و بعد ذلك الحد الذي يتراوح عموماً بين 3 و 4 % لن تكون هناك عموماً استفاده مهمه من زياده عدد الركائز لتقليل الهطول. ان هذه النسبة لمساحة الركائز تتأثر بنسبة مستوى الاجهاد الى سعة التحمل أي عامل الامان. في نهاية المطاف فقد وُجد ان سعة التحمل القصوى تزداد بشكل معتدل بزيادة نسبة مساحة الركائز الى حد استعمال أقل مسافه مستخدمه بين الركائز و هي ثلاثة امثال قطر الركيزه وهو ما يتفق مع المعارف التقليديه. كما وُجد ان تأثير الاتصال بين العوامه و التربه لا يكون مؤثراً جداً وهو ايضا ما يتفق مع المعارف التقليديه.

Introduction

Piled raft foundation provides an economical foundation option for circumstances where the performance of the raft alone does not satisfy the design requirements. Under these situations, the addition of a limited number of piles may improve the ultimate load capacity, the settlement and differential settlement performance, and the required thickness of the raft [1].

This type of foundation consists of a footing, usually a raft, and a relatively small number of friction/adhesion piles, this is referred to as a piled raft foundation. In this composite foundation, the load transfer mechanism is fairly complex because the load is transmitted to the soil through both the piles and the raft.

Piled Raft Philosophy

When the shear strength of soil is not adequate to support a shallow footing then the conventional approach is to adopt piled foundation where the piles only are considered to resist the applied load. However if the soil strength is fairly adequate but the immediate or consolidation settlement is deemed excessive then the concept of piled raft may be introduced in order to achieve economical savings.

It is known that the friction/adhesion resistance develops very much earlier than the bearing resistance as shown schematically in Fig. 1. Bowles [2] indicated that 5-10 mm penetration may be enough to develop full skin resistance in piles where about 10-30% of pile base diameter is needed to develop the full bearing resistance.

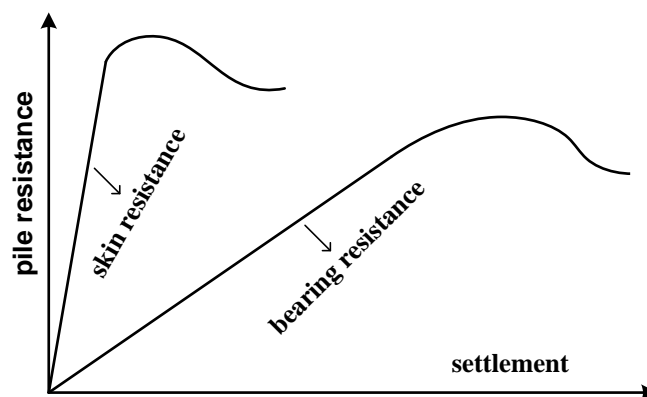


Fig.1 Schematic diagram of the rate of development of skin and bearing resistance of piles

Accordingly if a raft is fortified by some piles then upon loading the friction/adhesion of piles will resist the load until the development of certain settlement when the raft bearing will start contributing to the resistance, and the reaction to applied load will be shared by both the piles and the raft. The economical privilege of such a composite system is that the full ultimate capacity of piles is allowed to develop (piles safety factor =1) and the settlement may very much be reduced compared with the settlement of raft alone.

Further information on pile raft composite system may be reviewed in Poulos [1] and Reul and Randolph [3].

Piles Settlement Estimation Methods

The settlement of piles and pile groups is conventionally estimated by replacing the pile groups by a fictitious footing located at a certain depth below the surface mostly taken as two-third of the piles length. The settlement of this footing corresponds to the settlement of the pile group [4]. Alternatively the theory of elasticity may be employed through the Mindlin solution for a point load at the interior of an elastic solid [5, 2].

During the last decades, the finite element method has been initiated and rapidly developed. The method is applicable to many engineering fields including geotechnical engineering. The load-settlement relation of piled raft may be obtained using an elasto-plastic constitutive relation for the soil which yields more reliable results.

Finite Element Analysis of the Piled Raft

In this study a general finite element program "ANSYS 11.0" was selected to generate the solution for the analysis of piles under vertical loads. In this version, new features and enhancements are added, like the extension of the contact elements that provide robust simulation of general non-linear contact between rigid and deformed surfaces using three-dimensional elements.

In this work two types of elements are selected. The first one is Solid 65 to represent the concrete (raft and piles). The second one is Solid 45 to represent the soil under the raft. Both elements are three-dimensional brick elements.

Solid 45 element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions as shown in Fig. 2. The element has plasticity, creep, swelling, large deflection and large strain capabilities [6].

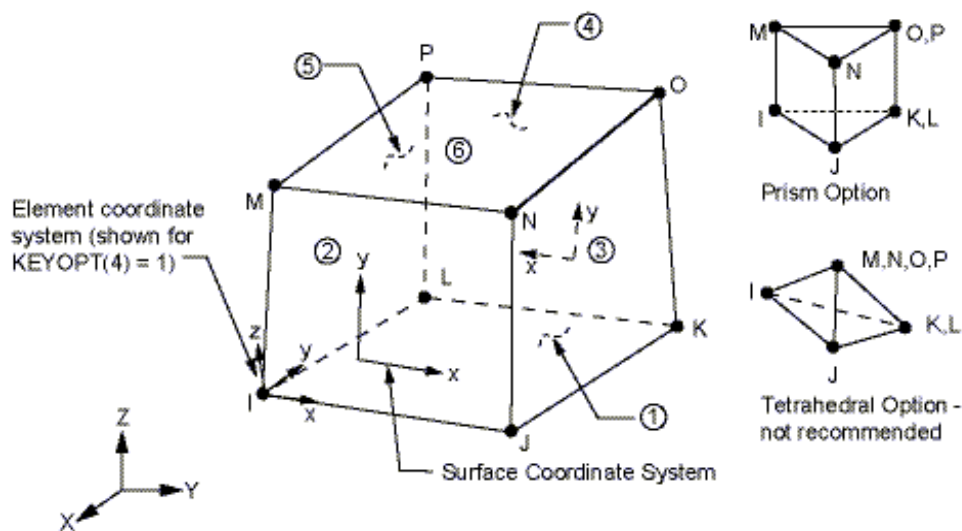


Fig. 2 Solid 45 three dimensional structural solid elements [6]

Solid 65 elements are used for the three-dimensional modeling of concrete solids without reinforcing bars. The solid is capable of cracking in tension and crushing in compression. The element is defined by eight nodes having three degrees of freedom at each node: translation in the nodal x, y and z directions. The concrete element is similar to the solid 45 element with the addition of special cracking and crushing capabilities [6].

The type of yield criterion used to characterize the behavior of the soil through this study is the Drucker–Prager model. The Drucker–Prager failure surface can be looked upon as a smooth Mohr–Coulomb surface or as an extension of Von-Mises surface for hydrostatic pressure–dependent materials such as soil.

In the combined-iterative procedure, a combination of the incremental and iterative scheme is used. For the incremental-iterative solution, Full Newton-Raphson procedure has been used in this study. The stiffness matrix is formed at every iteration. The advantage of this procedure is to give more accurate results, the disadvantage is that a large amount of computational effort may be required to form and decompose the stiffness matrix.

Table 1: Models of the numerically tested piled raft

Model no.	No. of piles	pile dia., D (m)	Raft-soil contact condition	Spacing between piles, s (m)	No. of elements	No. of nodes
1	4x6	0.4	Contact	3D	170200	41044
2	4x6	0.4	No contact	3D	167812	51072
3	3x5	0.4	Contact	3.75D	172348	41276
4	3x5	0.4	No contact	3.75D	178856	53052
5	2x4	0.4	Contact	5D	69056	17188
6	2x4	0.4	No contact	5D	61940	18984
7	2x3	0.4	Contact	7.5D	57584	15108
8	2x3	0.4	No contact	7.5D	52484	16764
9	0x0	-----	Contact	-----	11546	2764
10	2x4	0.6	Contact	3.2D	62652	16092
11	2x4	0.6	No contact	3.2D	56316	17160
12	2x3	0.6	Contact	4.8D	56632	14916
13	2x3	0.6	No contact	4.8D	52688	16172
14	2x3	0.8	Contact	3.5D	52832	14252
15	2x3	0.8	No contact	3.5D	48744	15353

In the present problem, the foundation consists of three parts: raft, piles and soil. The main goal of the present research is to explore the effect of piles and pile configuration on the settlement of raft, also to ascertain the effect of ignoring the raft-soil contact on the raft bearing capacity. Therefore, the program is set up to numerically analyze different models of a piled raft to fulfill the research goal. The size of the raft has been maintained constant at 4.5x6.9x0.50 m, as typically shown in Fig. 3, in order for the size effect not to interfere with effect of piles on the settlement. The pile length was not altered and kept at 15 m. The main parameters were the number and diameter of the piles. Table 1 presents the research program.

The material properties of the piled raft foundation are shown in Table 2. All models have the same material properties.

Table 2 Material properties of the models

properties material	Modulus of elasticity, E (MPa)	poisson's ratio, ν	cohesion, c (kN/m ²)	angle of internal friction, ϕ^0
concrete	25000	0.15	-----	-----
clay	25	0.35	35	0

In reference to the boundary conditions, all the models are fixed from all the sides, and the pressure is uniformly distributed on the top area of the raft. More details may be consulted in Hassan [7].

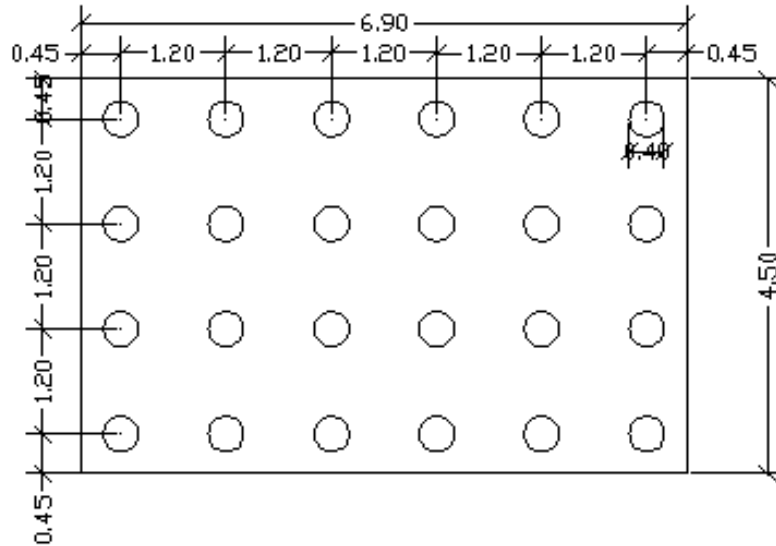


Fig. 3 A configuration of {4x6} piles (pile diameter=0.4m).

Determination of Ultimate Bearing Capacity

The ultimate capacity can, crudely, be defined as the load under which a rapid movement occurs under sustained or slight increase in the applied load. On most occasions, a distinct plunging ultimate load is not obtained in the field or numerical test as typically illustrated in the presently obtained pressure-settlement relations of Fig. 4. Therefore, the pile capacity or ultimate load must be determined by some methods based on the load-settlement data.

Fellenius [8, 9] presented nine different methods of pile capacity evaluation from load settlement records of a static loading test, the most important of which is the DeBeer Yield Limit method also known as the log-log method. Budhu [10] presented the Tangets method.

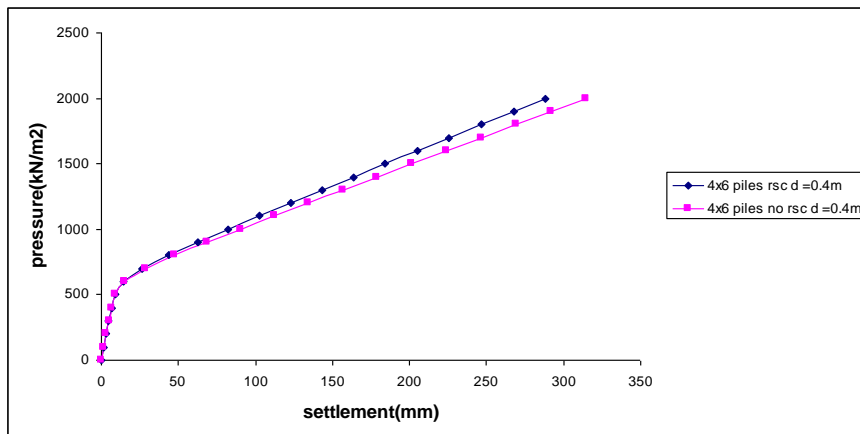


Fig. 4 Load-settlement curves for model 1 {4x6} piles (pile diameter=0.4m) [raft area=6.9x4.5m]

If a trend is difficult to discern when analyzing data, a well known trick is to plot the data to logarithmic scale rather than to linear scale and made use of the logarithmic linearity by plotting the load-settlement data in a double-logarithmic diagram. If the ultimate load was reached in the test, two line approximations will appear; one before and one after the ultimate load (provided the number of points allows the linear trend to develop). The slopes are meaningless, but the intersection of the lines is useful as it indicates where a change occurs in the response of the piles to the applied load. DeBeer called the intersection as the Yield Load. An example from the present work is given in Fig. 5.

When the pressure-settlement relation yields two almost linear portions as typically shown in Fig. 6, then in the tangent method the intersection of the tangents to those two portions represent the failure point.

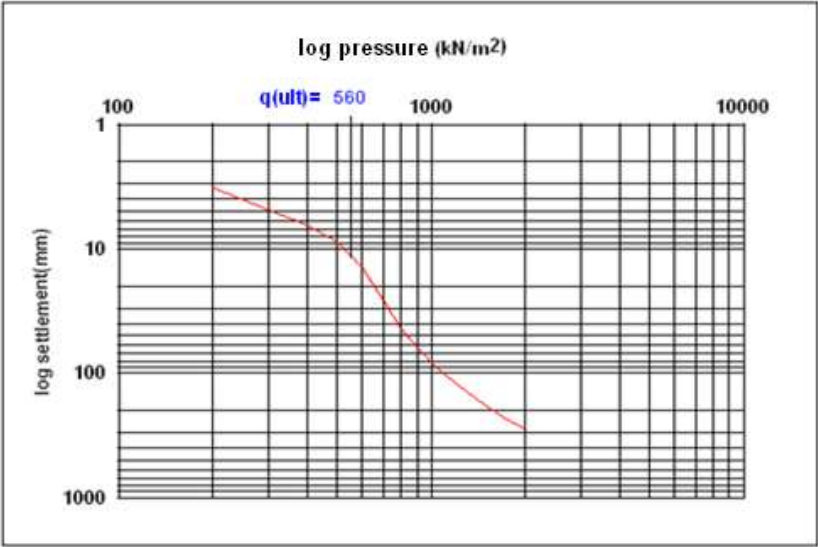
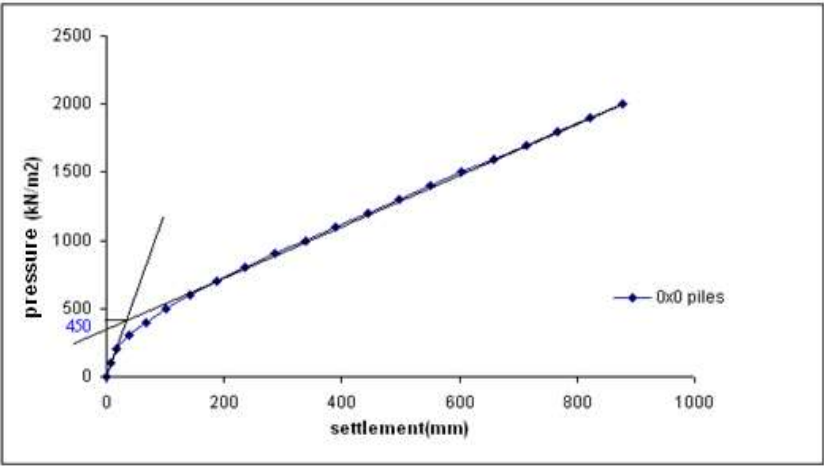


Fig. 5 Ultimate bearing capacity by log-log method for 4x6 piles with raft-soil contact (pile



diameter=0.4m).

Fig. 6 Ultimate bearing capacity obtained by tangents method for 0x0 piles.

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Table 3 Ultimate bearing capacities and settlements of the numerically tested piled raft

Model (No. of piles)	Dia. (mm)	Spacing	q_{ult} (kN/m ²) (log-log method)	q_{ult} (kN/m ²) (tangent method)	average q_{ult} (kN/m ²)	Settlement at working load (mm) [Tangent Method]	Settlement at ultimate load (mm) [Tangent Method]
4x6 rsc	0.4	3d	560	675	618	5.25	22
4x6 no rsc	0.4	3d	550	650	600	5.75	22.5
3x5 rsc	0.4	3.75d	530	630	580	4.75	22.5
3x5 no rsc	0.4	3.75d	530	630	580	4.75	23.5
2x4 rsc	0.4	5d	515	593	554	6	26
2x4 no rsc	0.4	5d	505	585	545	6.25	28
2x3 rsc	0.4	7.5d	520	625	573	6.75	38
2x3 no rsc	0.4	7.5d	500	610	555	7.5	45
2x4 rsc	0.6	3.2d	580	630	605	5.75	23
2x4 no rsc	0.6	3.2d	550	608	579	6	25
2x3 rsc	0.6	4.8d	530	605	568	6.25	28
2x3 no rsc	0.6	4.8d	520	583	552	6.5	28.5
2x3 rsc	0.8	3.5d	585	642	614	5.5	29.2
2x3 no rsc	0.8	3.5d	555	620	588	6.3	30.5
0x0	----	-----	-----	450	450	12.5	81

To determine the ultimate bearing capacity from the numerical models solved in the present work, the two aforementioned methods are employed. Table 3 presents the ultimate bearing capacities and settlements for each model.

In order to verify the bearing capacity results presently obtained from ANSYS, the results would be compared with Terzaghi Method commonly known as the Solid Block Method.

Assuming the pile cap is perfectly rigid and the soil contained within the periphery circumscribing all the piles behaves as a solid block, the entire block may be visualized as one deep footing. Naturally this assumption is valid for closely spaced piles therefore; the computer results would be compared with Terzaghi results for the case of 6x4 piles.

The parameters used are $c=35\text{kN/m}^2$, depth=15m, B=least dimension=4.5m. The calculated bearing at the tip is 297.5 kN/m^2 whereas the block shear resistance per area of group is 426.5 kN/m^2 . Thus, the total bearing capacity becomes 724 kN/m^2 .

Using the Tangents method, the numerical ultimate bearing capacity for (4x6) piles is 675kN/m^2 which is very close to that calculated using Terzaghi method. In finite element analysis the agreement of 93% with the limiting equilibrium method is usually considered to be very optimistic.

Settlement Results

The work is aimed at quantifying the advantage of using piled raft to reduce settlement and also to quantify the effect of pile spacing and pile diameter on settlement, also to assess the effect of raft-soil contact and the effect of the ratio of total piles area to group area.

According to the literature survey conducted, previous numerical research exhibited the load-settlement relations without performing the parametric studies required for taking

decisions in the design. Experimental investigations on this subject are of the utmost importance but they are expensive and require a good laboratory.

The load-settlement relationships are obtained for piled rafts with two cases: raft-soil contact, denoted by "rsc", and no raft-soil contact, denoted by "no rsc". Typical load-settlement relationships are shown in Figs. 4 and 6. All the load-settlement curves may be consulted in Hassan [7] where it appeared that the results are compatible and rational.

The working load is obtained by dividing the ultimate bearing capacity by (3) for all models. Then the results are marked on the load-settlement curves for each model to determine the settlement at working load. The settlement at ultimate load is also obtained by marking the ultimate bearing capacities on the load-settlement curves and determining the settlements. The obtained values are shown in Tables 3 using the Tangents method.

The effect of number of piles including implicitly the spacing between them and the raft-soil contact on the settlement at working and ultimate loads would be considered.

It appears that the settlement of the raft, in contact with soil, at ultimate load sharply drops with increasing the number of piles (n) from zero to 6 and this drop continues until n=8. Further increase in n would moderately increase the ultimate bearing capacity, Table 3, but would not significantly influence the settlement as demonstrated in Fig. 7. At working load, the settlement is reduced at n=6 and then the effect of increasing n almost vanishes.

If the raft is not in contact with soil then increasing n from 6 to 8 causes a sharp drop in settlement at the ultimate load after which the effect of increasing n diminishes as shown in Fig. 8. The effect of contact condition on settlement increases with decreasing n. The lack of contact decreases the bearing capacity but not to a considerable extent.

Table 3 indicate that the lack of contact increases the settlement both at working and ultimate loads by an average of 4.97% and 7.2% respectively using the Tangents method.

The results using larger pile diameter of 0.6m, although limited but give indications to the same conclusions, Table 3.

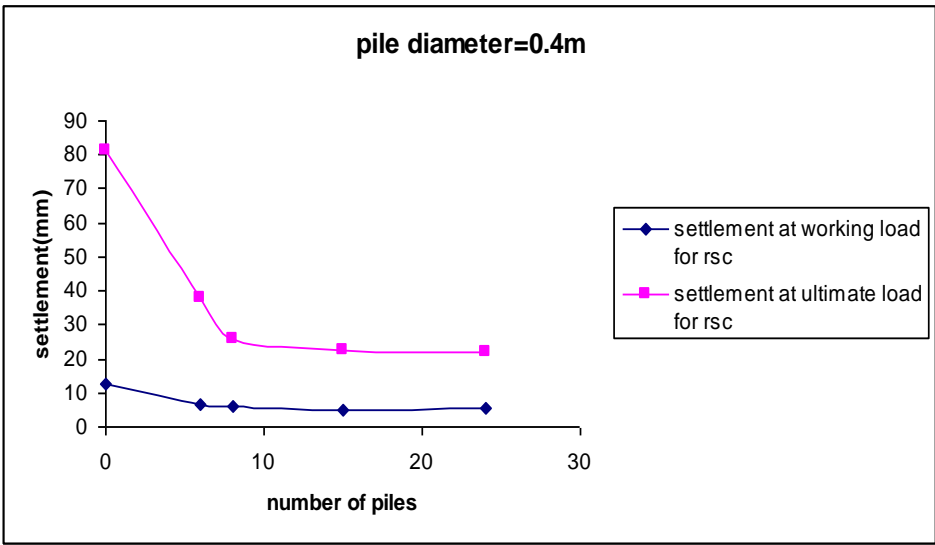


Fig. 7 Settlement at working and ultimate loads vs. number of piles using the Tangents method(rsc and pile diameter = 0.4m).

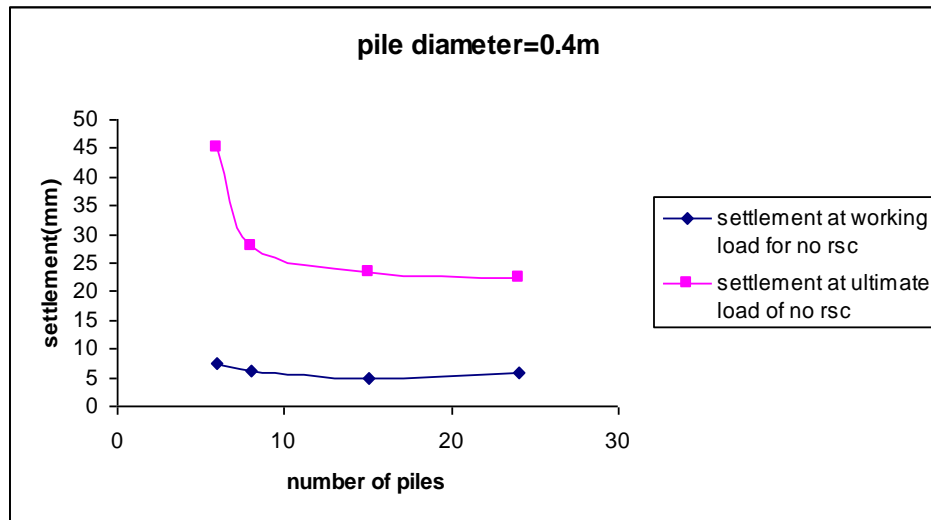


Fig. 8 Settlement at working and ultimate load vs. number of piles using the Tangents method (no rsc and pile diameter = 0.4 m).

These findings are interpreted on the bases that the skin resistance mobilizes very much earlier than the bearing or base resistance, Fig. 1, therefore a small number of piles can significantly reduce the settlement and that is why the skin resistance may reach its ultimate value while the bearing is at the beginning of progress. Therefore the skin resistance, when sufficient, may not give the chance to the full mobilization of raft bearing.

Foundation designers may sometimes suggest a large number of piles beneath structures subjected to low load like clarifiers. They argue that although the bearing capacity is adequate, the piles are needed to prevent excessive settlement. Great economical losses have been imposed due to such arguments. It is thought that small number of piles (large spacing) can sufficiently reduce the settlement which in turn greatly reduces the foundation cost.

In order to normalize the results so that the designers can make use of them irrespective of the area and shape of the cap, the settlement will presently be related to the ratio of total piles area to the area of the group. Figures 9 and 10 demonstrate the variation in settlement according to this ratio when the pile diameter is 0.4m. It is clear that increasing the piles area sharply reduces the settlement. Indeed a small pile area of generally 3 to 4% is enough after which there will be no further significant reduction in settlement. This small area slightly depends on the stress level relative to the bearing capacity of the piled raft, in other word every value for this limiting area corresponds to certain values of spacing and factor of safety. Figures 9 and 10 highlight the goal of the present work and indicate these values which would hopefully be useful for the foundation designers until more data can be obtained to revise the present data. However, not enough data are available when the pile diameter is larger than 0.4m, nevertheless the results given in Table 3 may lead to the same conclusions.

Although Figs. 9 and 10 are accomplished using certain soil properties and certain piled raft configurations and geometry, the results should be indicative for other cases.

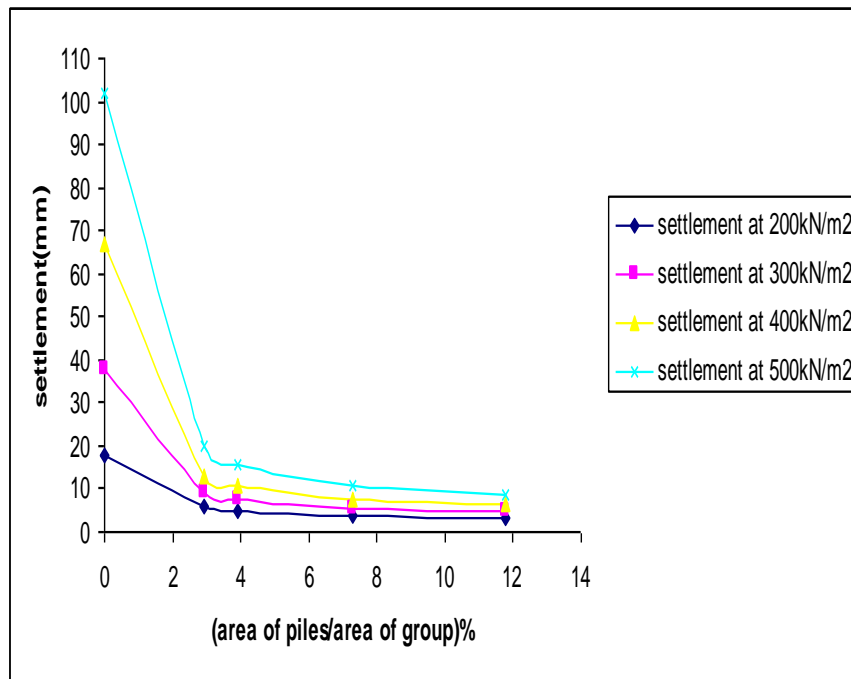


Fig. 9 Settlement at constant load vs. (area of piles/area of group)% for rsc (pile diameter = 0.4m)

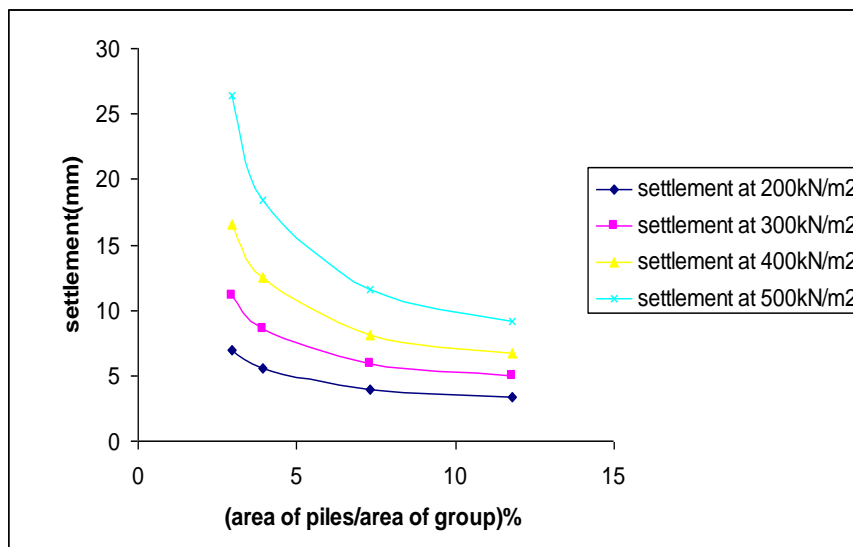


Fig. 10 Settlement at constant load vs. (area of piles/area of group) % for no rsc (pile diameter = 0.4m)

Conclusions

The three dimensional finite element software of ANSYS program has been used for the analysis of piled raft system including many parameters like number of piles, diameter of piles, and raft-soil contact condition. The following conclusions are drawn;

- 1- The number of piles, or the spacing, under the same raft has been set up in the form of the ratio of total piles area to group area and diagrammatically presented against the settlement. It has been noticed that there is a limiting small value of this relative piles area which amounts to 3 to 4% after which the settlement, in general, does not significantly decrease with increasing the number of piles. This limiting ratio is influenced by the adopted factor of safety. This is thought to be an important finding to significantly reduce the foundation cost of many structures.
- 2- As far as the present research is concerned it has been revealed that the log-log method and the Tangents method are the most suitable methods to estimate the ultimate bearing capacity from the load-settlement relations of the piled raft foundation.
- 3- Increasing the relative piles area over the limiting value for settlement moderately increases the ultimate bearing capacity.
- 4- With reference to the effect of pile diameter, it has been noticed that whenever the diameter increases the settlement at ultimate load decreases.
- 5- The advantage of raft-soil contact in increasing bearing capacity is noticeable but not significant, it presently reached up to 4% whereas the same effect on settlement at ultimate load is more pronounced and it reached up to 15%.

Acknowledgment

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