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# Numerical Analysis of Piled Raft Foundation using Fem with Interaction Effects

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**Abstract:** In modern construction, a piled-raft foundation is a composite construction which consists of piles and raft is one of the alternatives over conventional pile or raft foundations. It is used not only for reducing the settlement of soil, but also can handle large eccentric loading. The analysis of piled raft foundation is very tough and the design of piled raft with soil interaction effect is one of the major problem as the behavior of a structure is highly affected not only by the response of the superstructure, but also by the behaviour of the foundation and the soil as well. In this study, the piled raft foundation is analyzed using ANSYS (2D analysis), a popular finite element software to study the load displacement response in a sand medium of various relative densities (loose, medium dense and dense) with interaction effects.

Three different pile spacing - 3d, 4d and 5d were considered for the study (where d is the pile diameter) with three different pile configuration (3x3, 4x4 and 5x5) with an objective of finding the optimum number of piles and pile spacing for various relative densities of sand. The results show that the ultimate load and settlement corresponding to ultimate load increases with the relative density. Lesser settlement is observed when the frictional angle of the sand is increased and increases when the number of piles are increasing. The rate of settlement decreases with the increase in relative density of the soil. The load settlement response of medium and dense sand is almost identical. The performance of a 4 x 4 pile group is observed to optimum.

**Key Words:** eccentric loading, pile raft foundation, ANSYS, settlement, relative density.

## Introduction

The piled raft foundation is a composite structure which consists of three bearing parts – the piles, mat and underground soil. The overall load from the superstructure is partly carried by the mat through the effect of subsoil and the remaining load only carried by the piles under the effect of negative skin friction(1). The piled raft foundation is mainly used to reduce the settlement – particularly the differential settlement. It is an economical design without affecting the safety criteria. The behavior of piled raft foundation mainly depends on the complex soil structure interaction effects and an understanding of these effects is necessary for the reliable design of such foundation (2).

In a pile foundation the contribution of pile cap that functions as a raft is completely neglected. It is used only for the supporting the structure. The piles alone carry the loads and transmit the load to the deep stratum. On the other hand, in a raft foundation the total building load is carried only by the raft demanding a very thick raft, which thereby increases the cost of the foundation as well as it undergoes a large settlement. Piled raft foundation is therefore a best alternative for carrying more load and also containing settlement to a smaller degree (3). It also allows shorter length of piles and lesser thickness of raft in the design, thereby proving highly economical.

The present study highlights the change in the load carrying capacity and their corresponding settlements for the various combination of spacing between the piles and the number of piles in different relative densities of sand – loose, medium dense and dense [4]. Finite element analysis using ANSYS 12.0 is used to evaluate the effect of some parameters such as the spacing between the piles and the number of piles on the load settlement behavior of the piled raft foundation. The analysis is done for three different spacing and three different group of piles.

It is necessary to consider the effect of various interactions which are present within the piled raft foundation: pile-pile interaction, pile-raft interaction, and raft-raft interaction. These effects are generally ignored in most of the common structural analyses, so it might seriously underestimate Piled raft foundations have the capacity to provide economical foundation systems [5]. Piled raft foundations are most suitable for foundations of high rise buildings in weak soil also. The analysis of piled raft foundation is very tough and time consuming, so computers are often used. When a large number of piles or a large size of raft is involved, then more computing time is need for the analysis. The only disadvantage is that all the elements in the mat foundation should be square shaped and to be equal size [6].

Increasing the thickness of raft gradually decreases the total and differential settlement but increases the induced bending moment. There is a limit for thickness of the raft that reduces the differential settlement. But this option does not fulfill economical design concepts and very sensitive. Rising the length of the pile gradually decreases the total and differential settlements but does not decreases the induced bending moments. The maximum carrying moment of soft clay are higher than that of silty sand and stiff clay [7].

The ultimate settlements are affected only lesser amount by the type of soil. Ultimate Moment carrying capacity is a function of type of Soil, Diameter of piles, Pile configuration and Amount of concrete [8]. Provide larger inner pile diameters with smaller outer pile diameter will give better results. Pile length does not have more impact on the maximum load carrying capacity. If the pile diameter increases then the maximum load carrying capacity increases gradually [9].

## Methodology

Two dimensional plane strain analysis using finite element software ANSYS to find the ultimate load carrying capacity and settlement of a piled raft foundation. It is one of the non-linear analysis and in this project only deals with vertical loads. Here, pile and mat are taken as linear and isotropic while the soil-raft interface and soil-pile interface are treated as non-linear. Drucker-Prager model is used for representing the soil.

The following properties are taken for the analysis of pile and mat, i) Young's modulus (E), ii) Poisson's ratio (μ) and iii) Density for pile and raft [10]. Soil is treated as elasto - plastic and having the linear material properties and properties that describe non-linear behaviour are material cohesion strength (c), angle of internal friction (φ) and flow angle (ψ) are explained. For the design of piles, mat and underground soil, PLANE 82 is used as the type of element and the behavior of the element is taken as plane strain behaviour.

The interface behaviour is designed as non- linear behaviour. The Contact elements CONTA 172 and TARGET 169 at soil-pile interface and soil-raft interface for soil and raft respectively provides complete analysis. On the boundary conditions, nodes which present in the bottom of the soil zone is fixed against movement in both vertical and horizontal directions on the other way the zone away from pile raft (the vertical surface of underground soil at the boundary) is restricted only against the horizontal movements. The horizontal boundary (H) is fixed at 5 times the width of the piled raft cluster (5D) and the vertical boundary (V) is fixed at 3 times the width of the piled raft cluster (3D).

The load is applied on the center of the upper raft surface for the analysis. After giving all the inputs the model can be solved for the given boundary and loading conditions. The results will be in the form of contour diagram for the study on the settlement behaviour until failure under various loads. The nodal solutions and the contour graphs describe the results of the analysis indicating the load-settlement response of the structure.

This process should be tried for various combinations of spacing of pile (3d, 4d and 5d), where d is the pile diameter and for various number of piles (3x3, 4x4 and 5x5) in square configuration in different relative densities of sand (loose sand, medium sand and dense sand) by changing the material properties. The results for the various combinations are compared for the optimum results.

**Values Of The Parameters**

A brief summary of the parameters selected for the study are given below:

- Pile diameter=0.5 m
- Pile length=5 m
- Pile spacing: 3 d, 4 d and 5 d where d – diameter of the pile
- Number of piles: 9, 16 and 25
- Configuration : square - 3x3, 4x4 & 5x5
- Thickness of the raft= 0.5m
- Type of Soil: loose sand , medium sand and dense sand

## Material Properties

The properties of the piles, raft and soil are given below in tables 5.1 and 5.2. The pile and raft is made up of concrete. Hence, properties of concrete are used to model the pile and raft. The pile and raft show linear isotropic behaviour.

**Table 1 Properties of the Materials**

| Description | Piled &raft | Soil |
|---|---|---|
| **E** (kPa) | 2.5*10^7 | 2*10^4 |
| **μ** | 0.15 | 0.2 |
| **γ** (kg/m³) | 2500 | 2000 |

The Drucker Prager model is used to model soil for non-linear behaviour.The soil selected for the study is sand. A minimal cohesion for all the relative densities selected in this study.

**Table 2 Properies of Soil**

| Description | Loose sand | Medium sand | Dense sand |
|---|---|---|---|
| **c** | 5 kPa | 5 kPa | 5 kPa |
| **φ** | 15° | 30° | 42° |
| **ψ** | 6° | 6° | 10° |

Three different relative densities – loose, medium dense and dense are modelled by varying the angle of internal friction and by assigning an appropriate dilatancy (i.e.) flow angle.

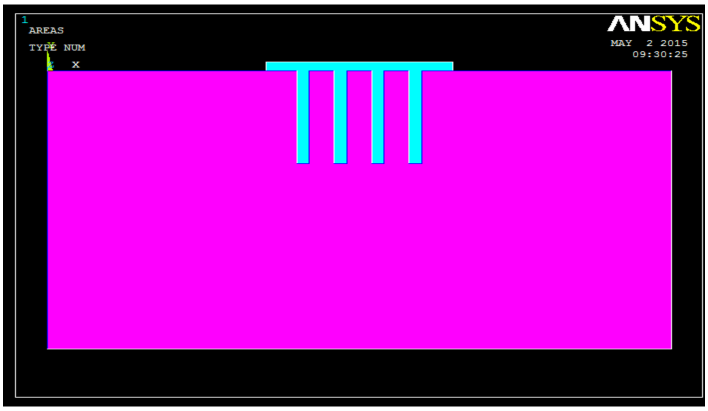


**Figure 1:Ansys Model of 4x4 Pile Group**

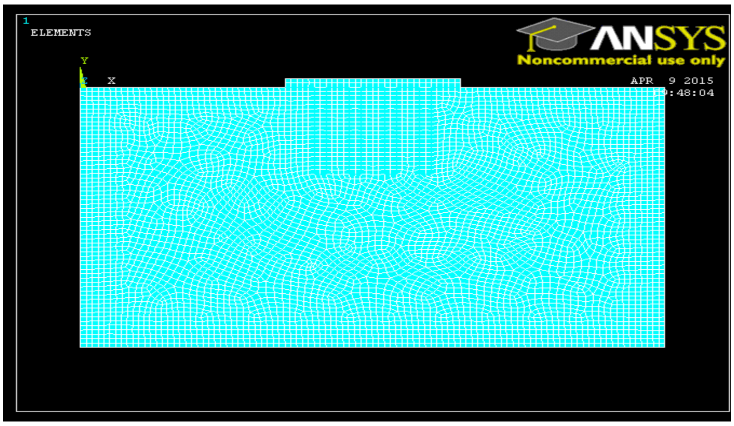


**Figure 2: Meshed Model of 4x4 Pile Group**

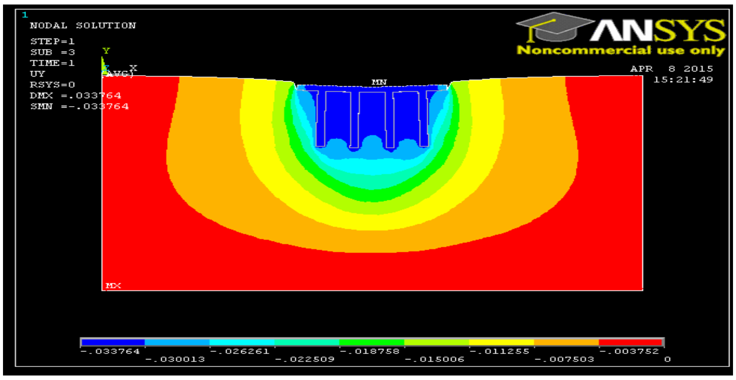


**Figure 3: Contour Diagram of 4x4 Pile Group**

## Results and Discussions

### 1.Load Vs Settlement

The response of the piled raft foundation system for various load, with different spacing of piles and number of piles are studied with special interest on its load settlement behaviour. For the constant value of 5 loads the settlements are calculated for various combinations.

**Case (i): 9 piles (3x3)**

This is for 9 pile groups. The procedure is done for 3 different spacing and for three different types of soils. From the table the settlement increases with the increase in spacing between the piles and decreases with the increases in angle of internal friction.

**Table 3: Load Vs Displacement for 9 Piles**

| Load (kN) | 3d spacing | | | 4d spacing | | | 5d spacing | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15° | 30° | 42° | 15° | 30° | 42° | 15° | 30° | 42° |
| 100 | 2.96 | 2.08 | 1.96 | 3.38 | 2.15 | 2.03 | 3.84 | 2.32 | 2.11 |
| 300 | 11.46 | 10.57 | 9.15 | 15.62 | 14.54 | 13.45 | 16.32 | 12.65 | 11.87 |
| 500 | 23.11 | 17.23 | 14.19 | 35.16 | 27.56 | 22.86 | 37.24 | 24.14 | 21.24 |
| 700 | 46.56 | 21.22 | 18.95 | 45.17 | 38.90 | 32.03 | 60.40 | 36.73 | 30.96 |
| 900 | 75.45 | 29.53 | 24.62 | 53.49 | 46.26 | 40.79 | 86.65 | 51.30 | 40.90 |

**Case (ii) 16 piles (4x4):**

Here the number of piles changes from 9 to 16. The spacing and the relative density of the soil of various combinations are continued by the same way of 9 piles. The same way of increase in the settlement like 9 pile group.

**Table 4: Load Vs Displacement for 16 Piles**

| Load (kN) | 3d spacing | | | 4d spacing | | | 5d spacing | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15° | 30° | 42° | 15° | 30° | 42° | 15° | 30° | 42° |
| 100 | 3.21 | 2.31 | 2.11 | 4.28 | 3.56 | 3.22 | 4.17 | 3.63 | 3.34 |
| 300 | 14.25 | 11.27 | 10.95 | 15.08 | 12.94 | 12.65 | 16.14 | 14.53 | 12.73 |
| 500 | 31.51 | 21.29 | 18.73 | 33.76 | 24.10 | 22.09 | 35.12 | 27.09 | 26.34 |
| 700 | 52.38 | 32.04 | 27.18 | 56.54 | 36.47 | 30.61 | 60.02 | 40.43 | 35.97 |
| 900 | 77.58 | 38.54 | 34.15 | 81.23 | 48.15 | 39.37 | 85.68 | 53.59 | 42.84 |

**Case (iii) 25 piles (5x5):**

In this test instead of 16 piles 25 piles are used. The remaining procedure is almost similar. For this also three different spacing and three different soil conditions are used.it is observed that when the number of piles increases the settlement also increases.

**Table 5: Load Vs Displacement for 25 Piles**

| Load (kN) | 3d spacing | | | 4d spacing | | | 5d spacing | | |
|---|---|---|---|---|---|---|---|---|---|
| | 15° | 30° | 42° | 15° | 30° | 42° | 15° | 30° | 42° |
| 100 | 3.42 | 2.51 | 2.14 | 5.84 | 4.67 | 4.55 | 8.24 | 7.12 | 6.97 |
| 300 | 13.98 | 12.43 | 12.21 | 15.48 | 14.39 | 14.18 | 17.25 | 16.98 | 16.82 |
| 500 | 30.51 | 22.81 | 18.13 | 33.08 | 26.24 | 24.53 | 36.05 | 28.71 | 26.42 |
| 700 | 54.30 | 32.23 | 25.16 | 57.19 | 39.11 | 35.23 | 61.78 | 41.04 | 38.71 |
| 900 | 70.78 | 37.59 | 33.37 | 87.35 | 53.27 | 47.97 | 92.18 | 55.28 | 52.93 |

## 2. Ultimate Load And Ultimate Settlement

The maximum load which can be carried by the structure is called its ultimate load and the corresponding settlement corresponding to the ultimate load is called the ultimate settlement. Here the effect of ultimate load is analysed for the different combination of pile raft foundation. The ultimate load is calculated from the load settlement graph using the above tabulated values

**Case (i): 9 number of piles**

For a 3 x 3 pile group the ultimate load increases when there is some increase in pile spacing. There is minimal change in the case of loose sand which can be attributed to load compacting the surrounding soil rather than carrying it. But in dense though on increasing the spacing from 3 d to 4 d the change is not appreciable (only 4 %), there is considerable increase in the ultimate load by 19 % on increasing the spacing from 4 d to 5 d. the ultimate settlement increases with the increase in ultimate load for all the spacing and number of piles of all types of soils and vice versa

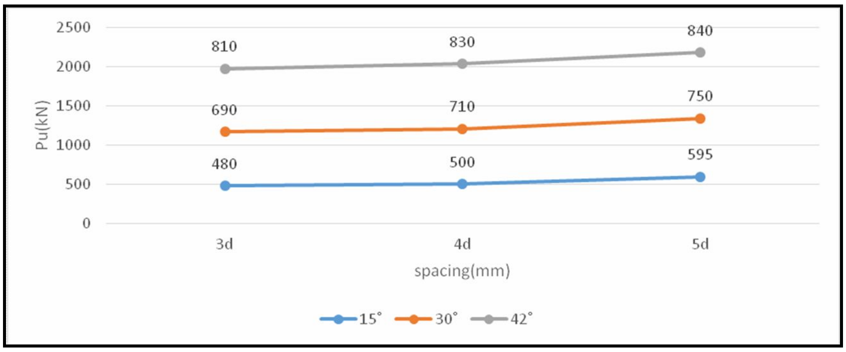


**Figure 4: Ultimate Load Vs Spacing between Piles for 3x3 Piles**

**Case (ii) 16 number of piles:**

Figure shows the ultimate load variance with the pile spacing for the 4 x 4 pile group. The ultimate load increases when the spacing increases to 4 d but on increasing the spacing to 5 d, even though the spacing is increased, the ultimate load decreases.

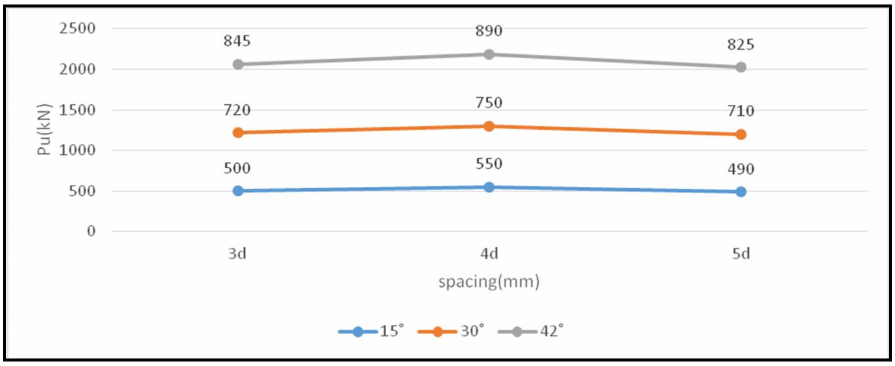


**Figure 5: Ultimate Load Vs Spacing between Piles for 4x4 Piles**

**Case (iii): 25 number of piles:**

Figure 6.17 shows the ultimate load behaviour of 5 x 5 pile group for the various spacing. The ultimate load starts to decrease with the increase in spacing and the trend is similar in all relative densities of sand.

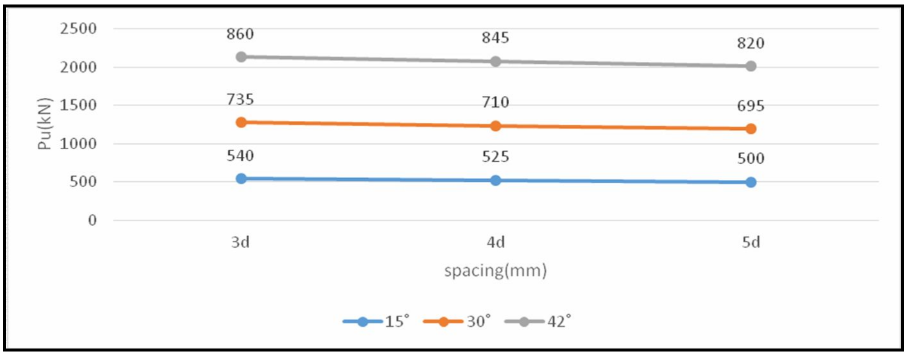


**Figure 6: Ultimate Load Vs Spacing between Piles for 5x5 Piles**

**3.Normal Load Vs Ultimate Load And Normal Settlement Vs Ultimate Settlement**

The ratio of $P/P_u$ and $\delta/\delta_u$ is one of the major factor to determine the load response criteria. From the ultimate load it is seen that16 group of piles show some good results when compared to 9 and 25 number of piles since that combination consist of higher ultimate load with lesser settlements. Hence we are discussing the behaviour of 16 number of piles alone

**Case (i):3d spacing**

The figure represents the behaviour of 4x4 piles of 3d spacing and this is very similar to that of 3x3 piles. For loose soil the curve is concave and for medium and dense the curve is convex.

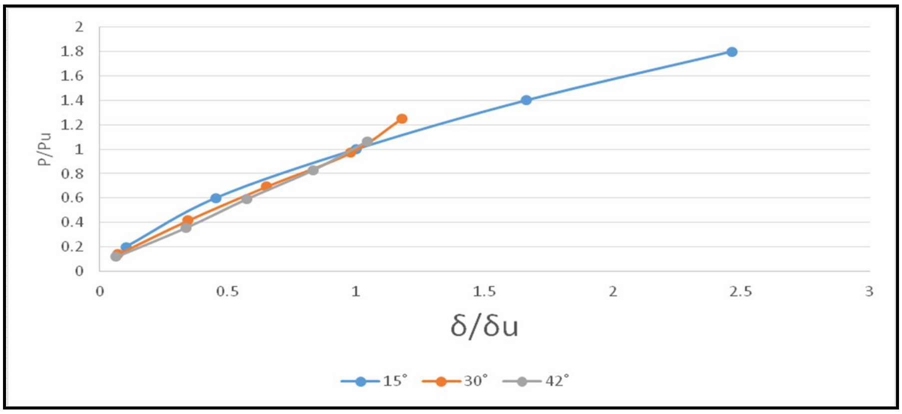


**Figure 7: P/P$_u$ Vs Δ/Δ$_u$ for 4x4 Pile-3d Spacing**

**Case (ii): 4d spacing**

The figure 6.23 shows the normalized load – settlement behaviour for the pile of 4 x 4 of 4 d spacing. It is also similar to that of 3 x 3 pile group. For all the types of sand the curve is concave behaviour and there is no sudden change.

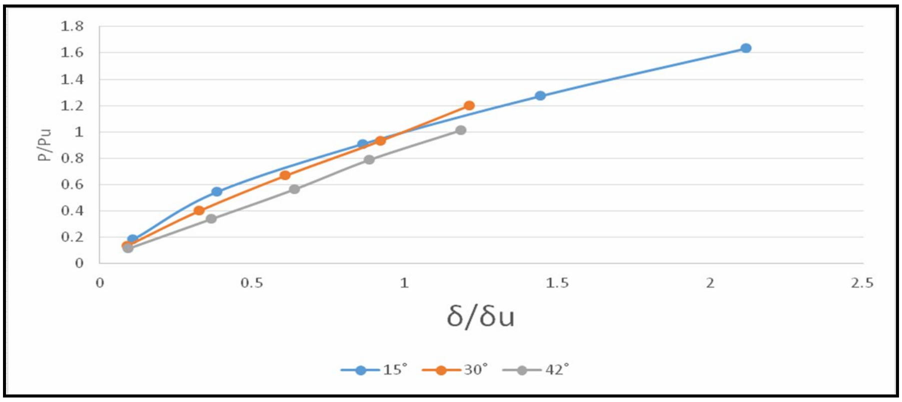


**Figure 8: P/P$_u$ Vs Δ/Δ$_u$ for 4x4 Pile-4d Spacing**

**Case (iii): 5d spacing**

Figure 6.24 shows the trend of 4 x 4 piles of 5 d spacing. This is also similar to the graph of 3 x 3 piles of 5d spacing. All the curves are convex in nature but the magnitude varies for the relative densities. For loose soil the curve extends upto the value of P/P$_u$ is 2.2 but for medium it is reduced to 1.4 and for dense sand it is decreased to 0.9

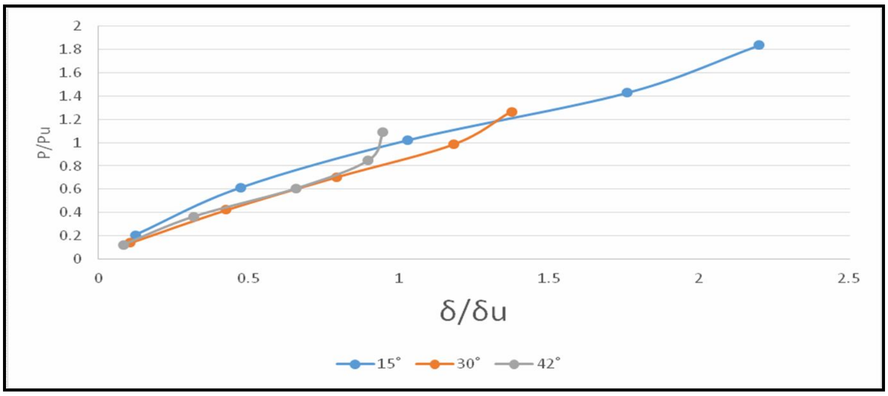


**Figure 9: P/P$_u$ Vs Δ/Δ$_u$ for 4x4 Pile-5d Spacing**

From the figures 6.22 to 6.24, for 4x4 piles t the curves for all spacing is different but it is very similar to that of 3 x 3 pile. The behaviour is almost same but the magnitude only changes in gradual manner

## Discussions

### On spacing between the piles

When the pile spacing alters then the load carrying capacity also varies. For the 3x3 pile group the ultimate load is increased by 4% when the spacing between the piles increased to 4d and 5d.for 4x4 pile group the ultimate load is increased by 10% when the spacing is increased to 4d but decreased by 12% when the spacing increased to 5d.for 5x5 pile group the ultimate load decreased by 2% when the spacing increased to 4d and 5d.

Regarding settlement when we changes the spacing there is much change in the settlement also. If we alters the spacing to 4d and 5d there is nearly 40% increase in the settlement.

### On number of piles

If the number of piles increases there is some increment in the load carrying capacity as well as the reduction in settlement. When the number of piles increases from 9 to 16 the ultimate load increases by 4% and settlement decreases by 4% and if the number of piles changes from 16 to 25 the ultimate load increases by 5% and the settlement reduces by 8%

### On soil conditions

When the soil turns from loose to medium the load carrying capacity increases by 43% and the settlement decreases by 5%.in similar way when soil moves from medium to dense the load carrying capacity increases by 17% and settlement decreases by 1%

From the overall analysis the graphs are linear only for the lesser number of piles and for the lesser spacing. The medium and dense sand shows some similarity and give normal results. The loose sand give some dissimilarity and abrupt values. When compared with 3x3 and 5x5 piles 4x4 shows some good results and it carry maximum ultimate load with the lesser settlements. So it provides optimistic values

## Conclusions

From the analysis the following results are obtained. The solutions are completely analytical in nature and may have some small practical variations depending on the nature of the structure and the loading pattern / type of load.

1. Pile spacing affects greatly the maximum settlement, the ultimate settlement and the load carrying capacity of the piles
2. The spacing between the piles should be within the permissible range that depend upon the loading conditions also. If the load acts at the centre of the mat structure then we have to provide lesser pile spacing.
3. Increasing the number of piles decreases the total and ultimate settlement and increases the load carrying capacity upto certain limit that depend upon the loading condition
4. The number of piles also depend upon the loading conditions. But the cost of construction will increase if the number of piles increased. So the optimum number of piles should be used.
5. From this analysis 16 number of piles is more optimised when compared to 9 and 25 number of piles because it produces the combination of higher load carrying capacity with the lesser settlements.
6. The soil type is also one of the major factor that affect load settlement behaviour. Dense sand produces better results when compared to the loose and medium sand.

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