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Numerical Analysis of Pile Foundation Subjected to Axial and Combined Axial and Lateral Loading

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Abstract

Construction of structures on soft soils having high compressibility, low bearing capacity and low shear strength would cause vertical and differential settlement of structures. Using deep foundation like piles may reduce both the vertical and differential settlements by transferring loads coming from superstructure to hard bearing stratum of soil through friction and/or end bearing action. In current work, numerical analysis is carried out using different mesh configurations available in Plaxis 3D giving input from literature. The mesh configuration which gives reasonable results is compared to field test results available in literature. Further, the same mesh configuration is adopted for present study. To verify the numerical analysis the field load test of 4-piled raft system was modelled and analyzed, and then the analysis results are compared to reported field load test results from available literature. Piles often subjected to axial loads, lateral loads and moments therefore, behaviour of 2-Pile group is numerically analyzed by applying axial and combined axial and lateral loads in finite element program Plaxis 3D. Results from the analysis will be discussed further in detail.

Keywords: *Mesh configuration, Model validation, Two pile group, Axial loads, Lateral loads and Plaxis 3D.*

1.0 Introduction

All engineered structures transferring load to the foundation or substructure are commonly referred to as superstructure. Particularly buildings and bridges are significant superstructures that transfer all imposed and dead loads to the foundation. Foundations may also be subjected to carry only machinery parts in industry, support industrial equipment, pipes, tanks, towers and perform as sign bases, etc. Therefore, from all these reasons foundation is described as part of engineered system that interconnects the load carrying components to the ground. A foundation is a type of interface component which supports every structural element built on the ground surface. The foundation would transfer its self-weight and all loads which come from overlying structure to the underlying soil layer or hard stratum. When the buildings are constructed on edge of hilly areas, due to environmental impacts such as rain, earthquakes and rise of water table etc, there may be chance of landslide which leads to collapse of building, if loads are not transferred properly to hard stratum.

1.1 Pile Foundation

Piles are columnar components of a foundation that can carry weight from superstructure to stiffer, more compacted, less compressible soils and rock through water or weak compressible layers. Piles may need to carry uplift loads if they supporting tall structures that are vulnerable to wind or wave forces that could lead them to topple. Two

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sources of lateral loads that may have an influence on the behaviour of piles used in maritime constructions are the impact of berthing ships and the power of waves. Piles are usually used to carry heavy loads such as those from bridge piers, abutments and multistoried buildings.

Wang et al[2]., reported series of field load test results on instrumented driven pipe piles, examined contribution of diameter at pile base, when subjected to lateral loads. Pile load tests were conducted on piles of different diameter 273 mm and 457 mm. Field load test data that was already available used as input and performed numerical analysis. Concluded that base diameter of pile has negligible effect on lateral response of pile. Aswin Lim[1] carried out field static load test and numerical analysis of the real scale field load test using Plaxis 2D. From the back analysis results, given empirical equations to be adopted to obtain good matching of results between field load test and numerical analysis. Those empirical equations consist of relation between undrained shear strength and SPT (N) values and Young's modulus and N values to be adopted as input for numerical analysis at Northern Jakarta coastal area.

The findings of the Youngho Kim and Sangseom Jeong[4] using nonlinear 3D finite element analysis were validated by considering parameters such as pile deflection, bending moment, and p-y curves over the length of the pile with field load test in marine clay. To investigate effect of lateral load transfer factor, many parametric tests were conducted. Authors conducted study and concluded that results from 3D FE results were significantly more accurate than those acquired from analysis using existing methods. Compared p-y curve generated from numerical analysis with the results of the field load test, found that the 3D FE analysis gives matching results when pile is subjected to lateral loading.

Kourkoulis[5] by using a method developed by them examined the slope stabilizing piles and pile groups. Investigated the variables that affect behaviour of piles and pile groups, including pile spacing, stable soil mass thickness, pile embedment depth, pile diameter, and pile group arrangement. The authors came to conclusion that soil arching between the piles occurs when the pile spacing is less than or equal to 4D. The piles would act like single pile when the distance between them exceeded 5D. They investigated and came to the conclusion that shear modulus-related soil inhomogeneity was irrelevant. Additionally, they came to the conclusion that using single piles is insufficient for stabilizing deep landslides. In such cases, pile groups were the most efficient solution[9,10,11,12] studied behaviour of a square-piled raft on clay soil using numerical analysis by varying pile placements, pile numbers, length of pile and type of loading etc. The authors concluded that by employing the same number of piles in each pile group, average settlement of pile group may be reduced by widening the gap between piles. In order to decrease differential settlement, the Ag/Ar ratio should also be raised. An increase in the load level would result in an increase in differential settlement[7]. Studies carried out on pile in a soil deposit subjected to axial loads under axis-symmetric conditions by varying different values of L/D ratio of the pile using FE program Plaxis 2D. From the results, it was shown that the pile having larger length among the lengths they had considered has the greater bearing capacity in clay layer underlain by sand and in sand layer underlain by clay layer there also the bearing capacity increased with increase in length upto certain length but after there was no significant increase in bearing capacity of pile. Madhusudan[8] conducted an experimental study to understand behaviour of pile in a sand layer under independent and combined uplift and lateral loads. Modelled aluminum pile of inner and outer diameters are 19 mm and 25.4 mm respectively. To compare behaviour of stiff and flexible piles, authors modified several lengths to diameter ratios (18, 28 and 38) by varying the length of the pile. The combined effect of uplift and lateral load has no impact on ability of long flexible piles to withstand lateral loads, according to the authors. However, for short-length piles (L/D=18 and 28), coupled loading led to an increase in the pile's uplift capacity.

Through 3D finite-element analysis, S. Karthigeyan[6] conducted numerical studies to examine the lateral response of piles subjected to independent lateral load and combined axial and lateral load in both clayey soil and sandy soil. Depending on magnitude of axial load, the presence of axial load might enhance lateral load capacity of piles in sandy soils by up to 40%. For axial loads more than 0.6 times ultimate axial load, lateral load capacity of piles in clayey soils affected by up to 20%. Authors concluded that lateral load capacity increased substantially due to vertical stresses in sandy soils and somewhat decreased it in clayey soils. Piles subjected to combined loading also studied by the authors[12,13,14].

2.0 Objectives of Study

Employing numerical analysis, objective of present study is to analyze a soil-two pile group system. Investigating the behaviour of a 2-pile group under axial loads and combined axial and lateral loads is analyzed using 3D FE modelling.

To analyze 2-piled group behaviour by varying diameter of piles and spacing between piles subjected to vertical loading.

To study the 2-pile group behaviour by varying diameter of piles and pile spacing subjected to axial load and, combined axial and lateral load.

3.0 Methodology

The FE method is a numerical technique for getting reasonably precise solutions to integral and partial differential equations (FEM). The removal of differential equation entirely (for steady state problems) or transformation of the partial differential equation into an approximating system of ordinary differential equations, which is later numerically integrated using conventional methods like Euler's method, were the two main numerical approaches to problem solving. Elasto-plastic analysis, which simulates model using FE approach, is carried out in this research using geotechnical programme PLAXIS 3D, which is commercially accessible. Steps involved in analysis are as follows,

- Geometry input
- Material data sets
- Definition of structural elements
- Mesh generation
- Selecting nodes for generation of curves
- Performing calculations
- Viewing calculation results

4.0 Verification of the Model

4.1 Soil Investigation

To validate full scale field load test results, only two layers were considered in numerical study. The groundwater table is at 15m below the surface of ground.

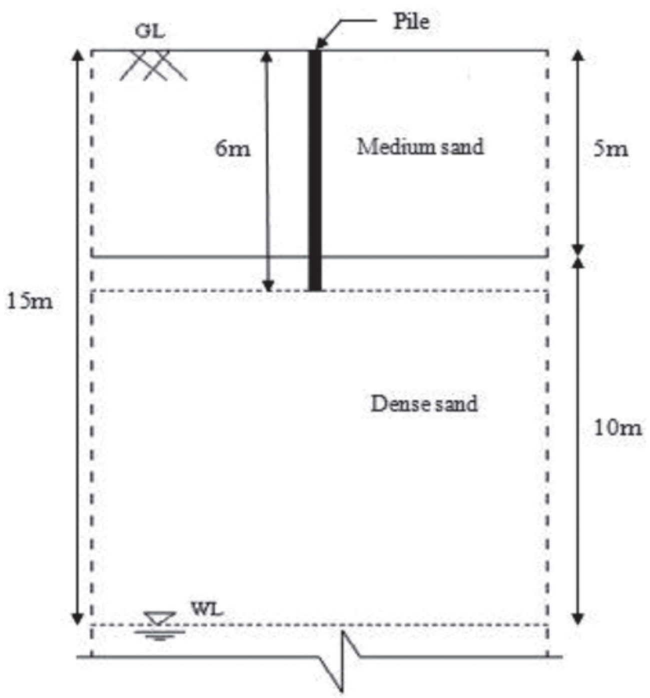

Figure 1: Soil profile at location of site

The Figure 1 shows profile of soil present at location of site.

To validate the model, field load tests carried out by Hussein[3] and location of site was at Karbala, Iraq, which was 100 km southwest of Baghdad according to ASTM D1143 (2007). Jacks with a capacity of single jack upto 500 tons, was used to compress the load on a raft. Load-settlement curve from the field load test is as shown in Figure 2.

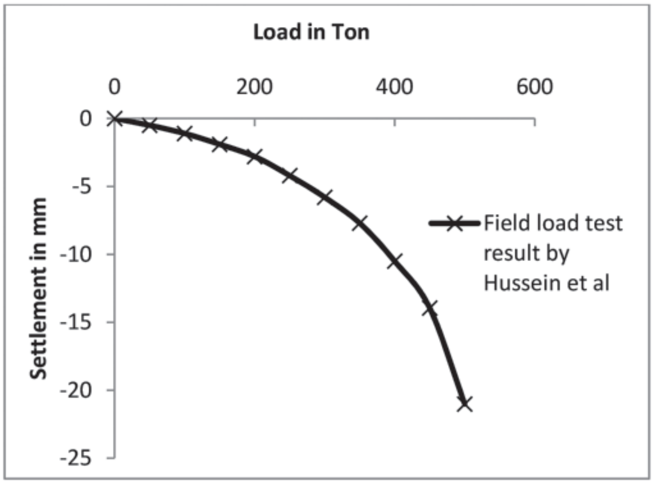

Figure 2: Field load test result (load settlement curve)

4.2 Details of the 3D FE Model

Piled-raft foundation systems are 3D complex problems which require 3D FE method for solving the problem. Therefore, in present study PLAXIS 3D is chosen to analyze the 2-pile group system.

Three material elements are considered in defining geometry of numerical model:

1. Soil and Interfaces,
2. Embedded Piles and
3. Plate element.

Only one fourth of whole model was created in order to decrease computing time and efforts as Plaxis 3D is symmetrical about the *x* and *y* axis. Thus, by modeling only quarter of the whole model numbers of elements are reduced in calculation, which may save computation time without affecting the results. Created model is shown as shown in Figure 3.

The embedded pile special element available in Plaxis 3D program is used, to model four (2×2) pile-group models, where piles are expected to act like slender beam elements as shown in Figure 4.

Pile cap was modeled using plate element because embedded pile and plate element in Plaxis 3D have six degrees of freedom; they may be connected in a perfectly compatible approach.

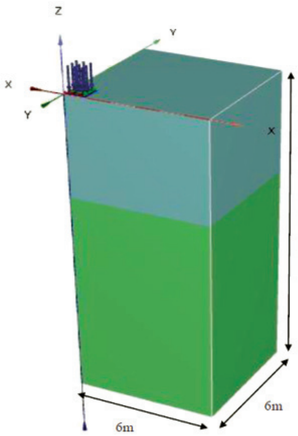

Figure 3: 3D soil model generated by using plaxis 3D

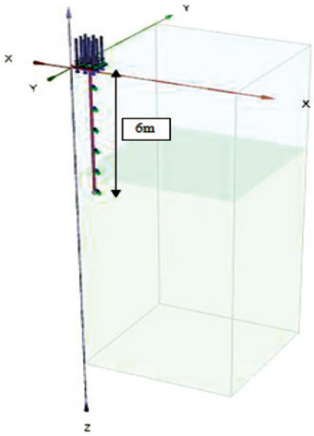

Figure 4: Embedded pile and Pile cap model

4.3 Soil Parameters Adopted in Validation Study

Details of soil parameters used in validation study are given in Table 1. Also the embedded pile and pile parameters used in study are given in Table 2 and Table 3 respectively.

Table 1: Soil properties

Property	Layer 1: very dense sand	Layer 2: medium dense sand
Unit weight γ (kN/m^3)	20	17
Drainage type	Drained	Drained
Secant stiffness, $E_{50.ref}$ (kPa)	60000	35000
Tangent stiffness for primary oedometer loading, $E_{oed.ref}$ (kPa)	60000	35000
Unloading/reloading stiffness, $E_{ur.ref}$ (kPa)	180000	105000
Power for stress-level dependency of stiffness, m	0.4	0.5
Poisson's ratio, v_{ur}	0.15	0.2
Reference pressure (kPa), P_{ref}	100	100
$Y_{0.7}$ Shear strain at which G_s=0.722G_0	0.15E-4	0.15E-4
Shear modulus at very small strains, $G_{0.ref}$	130000	100000
Cohesion c (kPa)	0.1	0.1
Friction angle, Ø	41	35
Dilatancy angle, ψ	11	5
Tension cut-off (kPa)	0	0
K_{0NC} =1- sinØ	0.344	0.426
K_{0ini} = K_{0NC}	0.344	0.426

Table 2: Pile parameters of 300 mm diameter pile

Parameter	Value	
Young's Modulus, E (kN/m^3)	2E+07	
Unit weight, γ (kN/m^3)	25	
Pile type	Massive circular type	
Diameter, D (mm)	300	
Skin resistance	Multi-linear	
	L(m)	T(kN/m)
	0	0
	5	144
	6	120
Skin resistance, F_{max} (kN)	1296	

Table 3: Pile Cap Parameters

Young's modulus (E), kN/m^2	2×10^7
Unit weight (γ), kN/m^3	25
Diameter (d), m	0.6

4.4 Pile Parameters used for validation study

Once the configuration of mesh size was confirmed, validation of model was carried out using field load test data of Hussain et al., (2017).

Also for comparative study, the numerical studies of Elshehahwy et al., 2018 considered which was carried on pile group using same field load test data given by Hussain[3], 2017. The results of the analysis and the data from the field load test exhibit good agreement, as can be shown in Figure 5. As a result, Plaxis 3D is used to do additional analyses.

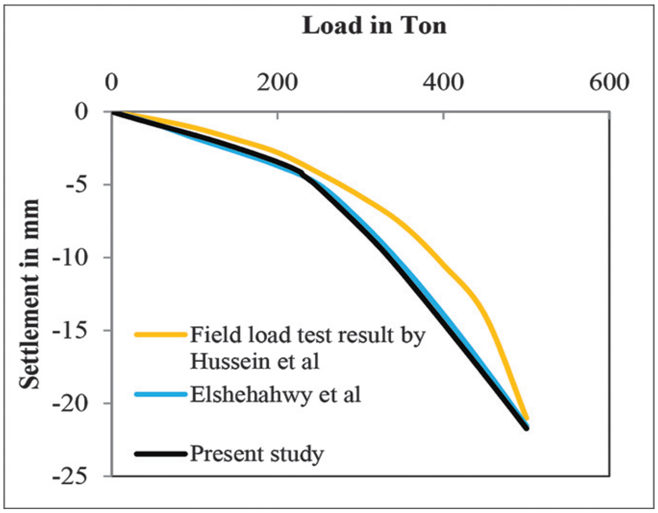

Figure 5: Load settlement curve of previous studies and present study

5.0 Details of the Present Study

In present analysis, two layered soil deposit is adopted and details of same are shown in Figure 2. All the input parameters of sand for analysis are taken from literature[3] given in Table 1. Pile and pile cap details used in analysis are given in Table 2 and Table 3 respectively.

In present study we carried out the study on 2-pile group subjected to axial and combined axial and lateral load with varying pile diameters and pile spacing. The spacing between centre to centre diameters of the piles is taken as 2d, 2.5d, 3d, 3.5d, 4d, 4.5d and 5d respectively. Projection of pile cap is taken as 150 mm from face of the piles. The 3D model of soil-pile system generated by using plaxis 3D is shown in Figure 6.

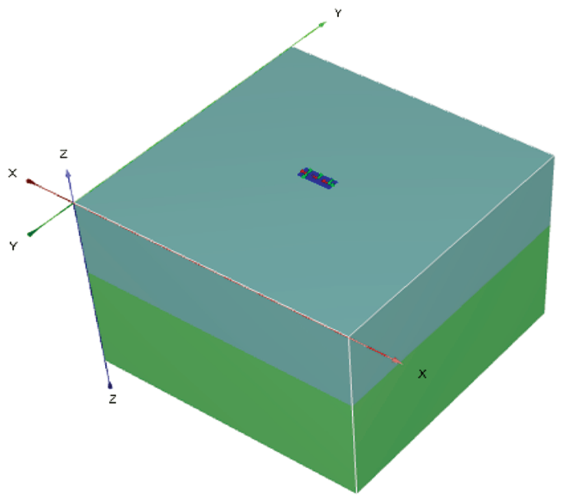

Figure 6: Soil-pile model

6.0 Results and Discussion

6.1 Two Piled Group Subjected to Axial Loading Corresponding to Settlement of 20 mm

In the plaxis 3D we have option that allows us to input prescribed displacement. To compare load settlement curves by varying pile spacing in the present study the prescribed settlement of 20 mm is applied for all the studies and load carrying capacity corresponding to 20 mm settlement of 2-pile group by varying pile spacing is analysed.

Load settlement curves for different pile diameter are given in Figures 7, 8, 9 and 10.

When 2-pile group subjected to only axial loading, it is observed from the load settlement curves that varying pile spacing does not have any considerable effect on the load carrying capacity of pile group for different diameters such as 300 mm, 400 mm, 500 mm and 600 mm respectively.

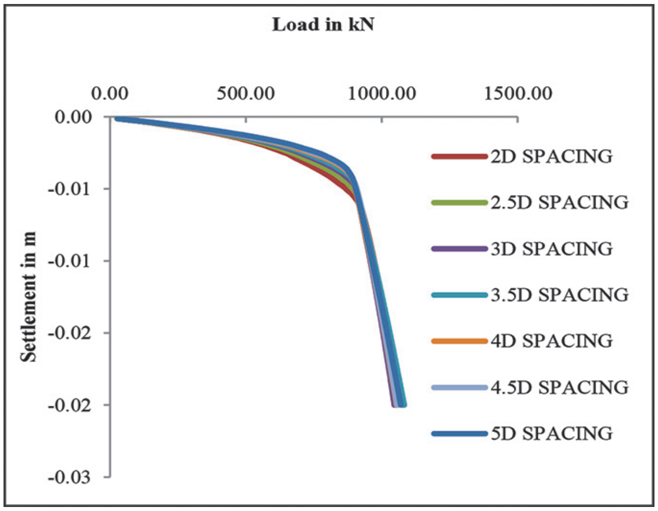

Figure 7: 2-pile group of diameter 300 mm

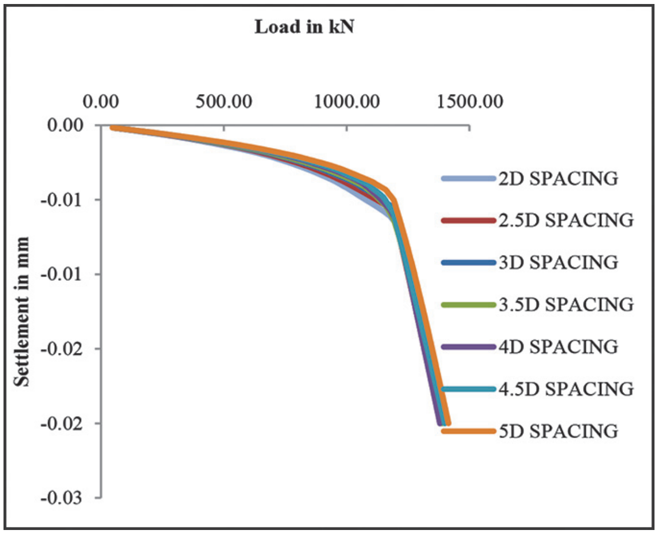

Figure 8: 2-pile group of diameter 400 mm

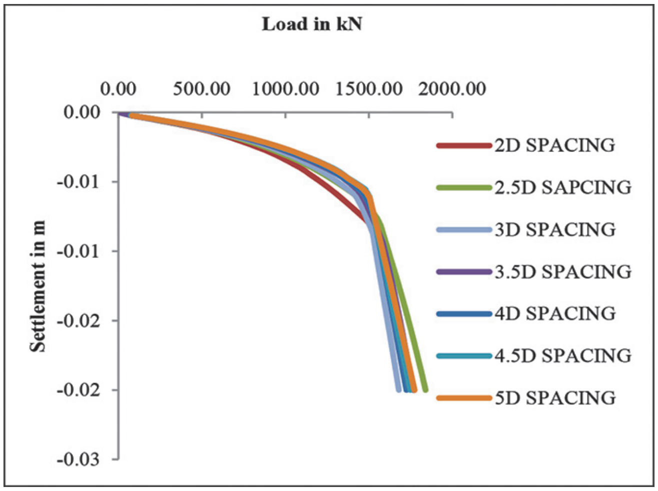

Figure 9: 2-pile group of diameter 500 mm

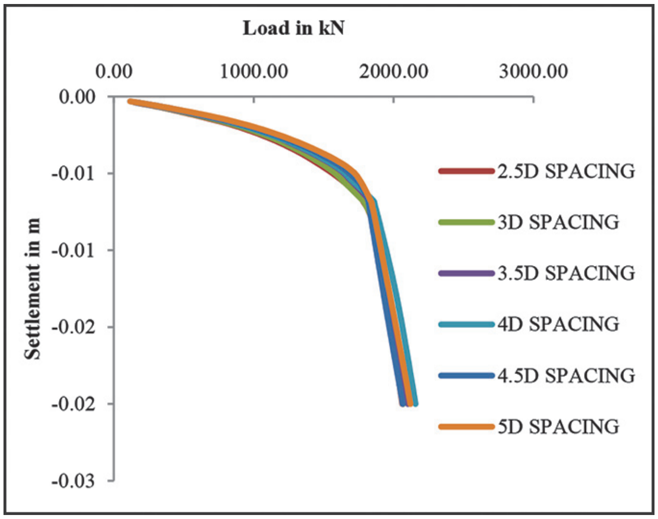

Figure 10: 2-pile group of diameter 600 mm

6.2 Two Piled Group Subjected to Combined Axial and Lateral Loading

The axial load corresponding to 20 mm prescribed settlement as obtained from previous section in this paper is applied along with lateral load of 10% of the diameter of pile. As time concern 2-pile group subjected to combined loading is analysed only for pile spacing of 3d with different diameter of pile such as 300 mm, 400 mm, 500 mm and 600 mm. These analysis results are compared to results of pile group subjected to axial loading.

The load settlement curves for different pile diameters are shown in Figures 11, 12, 13 and 14 respectively.

From curves it was observed that for pile group of diameters 300 mm and 400 mm the load carrying capacity was not affected by lateral load.

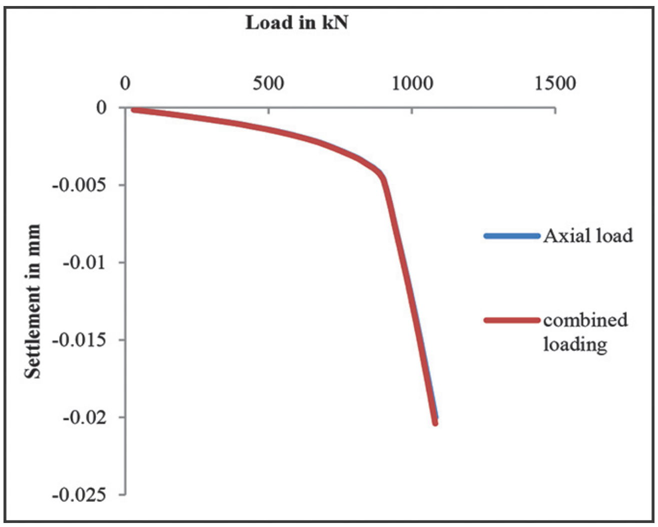

Figure 11: 2-pile group of diameter 300 mm

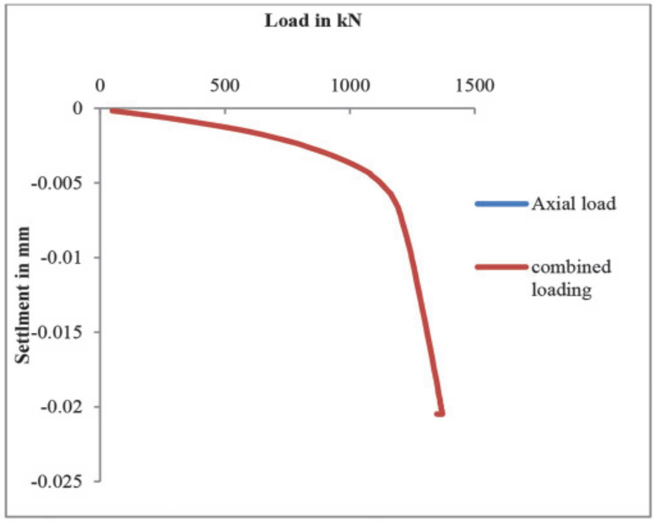

Figure 12: 2-pile group of diameter 400 mm

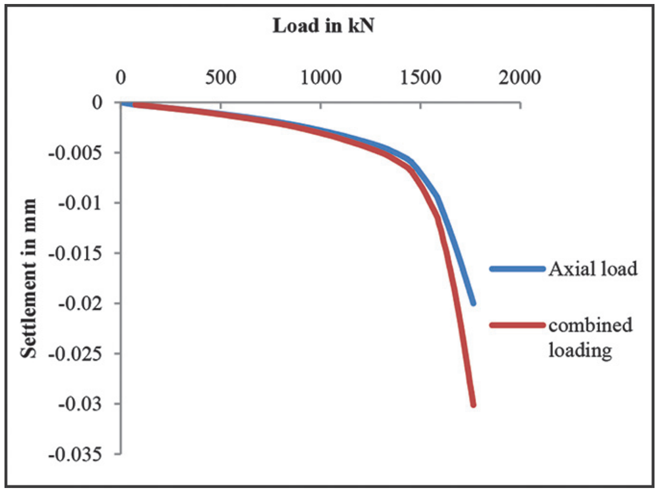

Figure 13: 2-pile group of diameter 500 mm

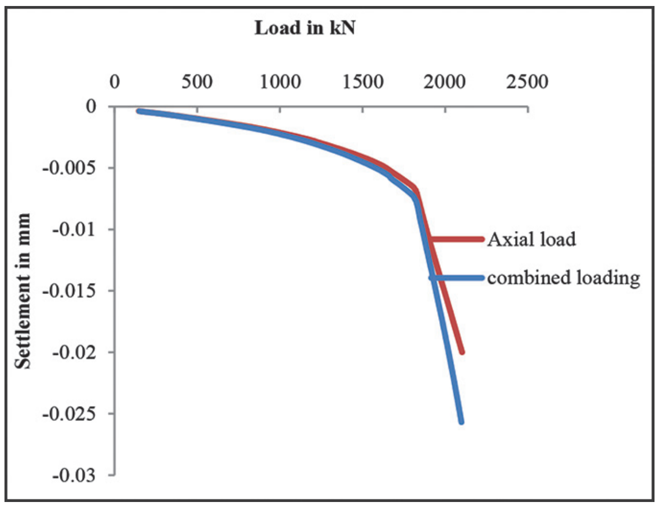

Figure 14: 2-pile group of diameter 600 mm

But for pile diameters of 500 mm and 600 mm the curves were shown slight variation and also the settlement was increased when pile group is subjected to combined loading compared to pile group subjected to only axial loading. It is might be because of formation of gap between pile and surrounding soil which leads to decrease in friction capacity of pile.

7.0 Summary and Conclusions

Model is validated using input parameters available in data given by Hussain[3]. Analysis is performed on 2-piled group subjected to axial load and, combined axial and lateral load embedded in two layered soil varying pile diameter of 300 mm, 400 mm, 500 mm and 600 mm respectively. Also, numerically analyzed pile group by varying pile spacing in each pile group as 2d, 2.5d, 3d, 3.5d, 4d, 4.5d and 5d respectively. Based on the analysis, the following conclusions are drawn,

- From results it is observed that the pile spacing does not have any significant effect on load carrying capacity of pile group. Also when pile group subjected to axial loading is compared to combined axial and lateral loading for 300 mm and 400 mm there is no significant effect but for 500 mm and 600 mm diameter pile group there was a increase in settlement of pile group in case of combined loading.
- From the model validation study, it is concluded that results from numerical study using Plaxis 3D are in good matching with field load test results, one can use results with confidence in real structural design by inputting appropriate parameters in model.
- Increase in pile diameter increases load carrying capacity of 2-pile group when subjected to both axial and, combined axial and lateral load.

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