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Settlement analysis of pile cap with normal and under-reamed piles

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Abstract. The use of pile foundations has become more popular in recent years, as the combined action of the pile cap and the piles can increase the bearing capacity, reduce settlement, and the piles can be arranged so as to reduce differential deflection in the pile cap. Piles are relatively long, slender members that transmit foundation loads through soil strata of low bearing capacity to deeper soil or rock strata having a high bearing capacity. In this study analysis of pile cap with considering different parameters like depth of the pile cap, width and breadth of the pile cap, type of piles and different types of soil which affect the behaviour of pile cap foundation is carried out by using Finite Element Software ANSYS. For understanding the settlement behaviour of pile cap foundation, parametric studies have been carried out in four types of clay by varying pile cap dimensions with two types of piles namely normal and under-reamed piles for different group of piles. Furthermore, the analysis results of settlement and stress values for the pile cap with normal and under-reamed piles are compared. From the study it can be concluded that settlement values of pile cap with under-reamed pile are less than the settlements of pile cap with normal pile. It means that the ultimate load bearing capacity of pile cap with under-reamed piles are greater than the pile cap with normal piles.

Keywords: pile foundation; under-reamed pile; settlement analysis; finite element method; clay soils; bearing capacity

1. Introduction

One of the most important aspects of any Civil Engineering project is the foundation system. Designing the foundation system carefully and properly will surely lead to a safe, efficient and economic project. To carry the excessive loads that come from the superstructures like high-rise buildings, bridges, power plants or other civil structures and to prevent excessive settlements, piled foundations have been developed and widely used in recent decades.

In urban areas, people are concentrating on expansion of buildings vertically rather than horizontally due to high cost of land, limited space and scarcity of land. Pile foundations are being increasingly used for multi-storied buildings, with or without basement, in subsoil conditions such as thick clay deposits even with a high-water table. If the clay shear strength is very low, long load-bearing piles are introduced to transfer the entire load to deeper and stiffer soil layers. Even if the clay shear strength is adequate for giving the required bearing capacity of a pile foundation, the settlement may be very large. For situations where it becomes necessary to reduce settlements, a pile foundation can be opted. The total and differential settlements can be minimized by providing the piles at specific locations under the pile cap. In this study, pile cap with normal and under-reamed piles with different piled group combinations on four different types of clayey soils are analyzed by Finite Element Method.

2. Review of literature

Poulos (2001) studied the philosophy of using piles as settlement reducers, and outlines the key requirements of design methods for rafts enhanced with piles. It is essential to take account of the various interactions which exist within a piled raft foundation: pile-pile, pile-raft, raft-pile, and raft. Lianga *et al*. (2003) introduced the concept of composite piled raft and incorporated the effect of unequal length and moduli of piles as well as the action of cushion in consideration. In this new type of foundation, the short piles are used to strengthen the shallow soft soil, the long piles are used to reduce the settlement and the cushion is used to redistribute and adjust the stress ratio of piles to subsoil. Lee (2007) studied modified boundary element method to analyse the behaviour of under-reamed piles in elastic homogeneous soils. Abate (2009) analyzed pile raft foundation and concluded that both the stiffnesses of the raft and pile group have a major role in determining the total and differential settlement of the piled raft system. Yilmaz (2010) presented two different concepts and design procedures namely settlement reducing piles and piled raft

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foundations have been studied independently. A laboratory study is conducted on model rafts with differing number of model settlement reducing piles. Pile length, pile diameter, type of soil and size of raft are kept constant and settlements are measured under sustained loading. Shukla *et al*. (2011) studied different parameters like size of the raft, thickness of the raft, diameter of the piles, length of piles, configuration of piles, stiffness of raft and piles etc., which affect the behaviour of piled raft foundation and its interdependency is also reviewed. Cho *et al*. (2012) investigated the behaviour of a square piled raft subjected to vertical loading. In this study, the 3D elasto-plastic FE analyses with slip interface model of pile-soil contact were carried out with drained shear parameters and no consolidation effect for a clay layer. Bajad *et al*. (2012) proposed that by using small scale model tests, the interference effect on the load-deformation and time settlement behaviour of rafts and piled rafts placed on the artificially consolidated soft clay were investigated. The effect of spacing (s) among foundations on the results was explored. Karim *et al*. (2012) analyzed the numerical modelling of the piled raft problem considering the load effect using the finite element method. Singh *et al*. (2013) researched on elastic analysis of piled raft foundation in clay soils, the load sharing behaviour of piles and raft has been studied by varying soil modulus, pile spacing, pile length and raft thickness. Shah (2013) conducted an analytical research on simplified method for analysis of piled raft with use of SAFE software considering all the interactions. The flexible raft is modelled as thin plate elements and the piles as elastic beam elements. These two element models are combined via the nodes at the pile heads. Srilakshmi *et al*. (2013) studied the analysis of piled raft foundation by using finite element software ANSYS. For understanding the behaviour of piled raft foundation, parametric studies have been carried out in medium sand by varying pile diameters and pile lengths in different combinations. Joy *et al.* (2014) analysed a Combined piled raft foundation using Finite Element Software Plaxis 3D with permuted arrangement of piles. Three different Pile diameters and its combinations were modelled and analysed. Venkatesh *et al.* (2014) studied different parameters like size of raft, diameter of piles, length of piles, configuration of piles etc., which affect the behaviour of piled raft foundation. And its interdependency is also reviewed for *G*+14 storey building. Alkinani *et al*. (2014) studied the distribution of the load under piled raft foundation considering the effect of piled raft geometry, length and diameter of piles, and other factors. Patil *et al*. (2014) investigated the load-settlement behaviour and load sharing between the piles and raft. From the results of this study, it has been concluded that the load bearing capacity of piled raft increases as the number of piles beneath the raft increases. Rajashekhar *et al*. (2015) considered an example for the software assessment and studied different parameters like size of the raft, thickness of the raft, diameter of the piles, length of piles that affect the behaviour of piled raft foundation, analysis is carried out by using Finite Element Software ANSYS. Square rigid raft of 15 m×15 m and 16 piles of 0.3m diameter and 30m length are attached to it and placed on a deep deposit of soft clay. Settlement analysis of piled raft by Finite Element Method under vertical load is carried out using ANSYS15.0 to determine settlement of foundation. Kumar (2015) analysed the piled raft foundation using ANSYS (2D analysis) to study the load displacement response in a sand medium of various relative densities (loose, medium dense and dense) with interaction effects. Thomas *et al*. (2015) analysed plaza like structures wherein the raft thickness as well as pile length can be varied depending upon the capacity requirements, it becomes necessary to understand the effect of variation in pile length on settlement reduction and load sharing behaviour of piled raft. Keiji and Takewaki (2013) studied on the Optimum pile arrangement in piled raft foundation by using simplified settlement analysis and adaptive step-length algorithm. Chetchotisak *et al*. (2017) developed an interactive strut-and-tie-model for shear strength prediction of RC pile caps. de Souza *et al*. (2007) analysed the four-pile caps supporting columns subjected to generic loading by Non-linear finite element analysis. Kumara and Choudhury (2018) developed a new model for prediction of capacity of combined pile-raft foundations. Mali and Singh (2018) studied the behavior of large piled-raft foundation on clay soils. Hamderi (2018) developed a formula for determination of comprehensive group pile settlement based on 3D finite element analyses.

From review of literature, it is observed that little literature is available on settlement comparison of normal and under-reamed pile groups. It is also observed that simple available equations are available for determination of the settlement of pile caps. However, they can be adopted for pile caps with a fewer number of piles. Piled raft foundation consists of a greater number of piles and hence these simple equations do not give accurate solution. Further, the settlement given by these equations does not include axial deformation of the piles. Analysis by FEM overcomes these limitations and gives the results with reasonable accuracy.

3. Objectives and scope of the study

The main objective of this investigation is to compare the settlement behaviour of the pile cap with normal and under-reamed piles with different pile group combinations on four different types of clayey soils using Finite element analysis. The scope of the study is limited to pile cap with Single, two, three, four, five, six and eight group of piles on four different types of clayey soils. The model specifications, modelling of pile cap with normal and under-reamed piles, analysing various pile group combinations by using FEM are presented in the Section 4 (Methodology).

4. Methodology

4.1 Geometrical configuration of pile foundation

Table 1 and Table 2 show the geometrical parameters of

Table 1 Dimensions (in mm) of pile cap with different normal pile groups

Pile Cap Type Parameter	1 Normal Pile	2 Normal Piles	3 Normal Piles	4 Normal Piles	5 Normal Piles	6 Normal Piles	8 Normal Piles
Length	1350	2475	3600	2475	3260	3600	4725
Width	1350	1350	1350	2475	3260	2475	2475
Depth	300	300	400	600	600	750	750

Table 2 Dimensions (in mm) of pile cap with different under-reamed pile groups

Pile cap type Parameter	1	2	3	4	5	6	8
Length	1140	2660	4180	2660	4140	4180	5700
Width	1140	1140	1140	2660	4140	2660	2660
Depth	300	300	400	600	600	750	750

Table 3 Material Properties of the Soil and Piled cap

Model	Density (kg/m^3)	Poisson's ratio	Young's Modulus (N/m^2)
Very soft clay	1600	0.35	13×10^6
Soft clay	1900	0.30	15×10^6
Medium clay	2050	0.25	20×10^6
Hard clay	2130	0.15	50×10^6
Piled cap	2500	0.15	27.5×10^9

pile cap with normal and under-reamed piles for different group of piles.

For the pile cap considered for normal pile group, Length of pile is 10000 mm, Diameter of pile is 450 mm. For the pile cap considered for under-reamed pile group, Length of pile is 10000 mm, Diameter of pile is 380 mm with three under-ream bulbs. Under-ream bulb diameter is 760 mm.

4.2 Material properties

Table 3 presents the material properties of pile cap and different types of clayey soils for which the analysis has been done to determine the settlement behavior of various pile group combinations. Material properties of soil are referred from Foundation Analysis and Design (Fifth Edition) by Joseph E. Bowles (Page No. 125).

4.3 3D Model view of different piled groups

The Section 4.3 presents models of normal and under-reamed pile groups considered in this study (Fig. 1).

4.4 Ultimate load bearing capacity of pile

The ultimate load bearing capacity of a pile is the maximum load that it can carry without failure or excessive settlement of pile. The bearing capacity of a pile depends primarily on three factors

1. Type of soil through which pile is embedded.
2. Method of pile installation.
3. Pile dimension (cross-section and length of pile).

While calculating pile load capacity for cast-in-situ concrete pile using static analysis, it is necessary to use soil shear strength parameter and dimension of pile.

Load carrying capacity of pile using static analysis

The pile transfers the load into the soil in two ways. Firstly, through the tip in compression termed as end-bearing or point bearing. Secondly, by shear along the surface termed as skin friction.

Load carrying capacity of piles in cohesive soil

The ultimate load carrying capacity (Q_U) of pile in cohesive soil performed by static analysis by the formula

$$Q_U = A_b N_c C_b + \alpha\, C_s\, A_s \quad (1)$$

Where the first term represents the end bearing resistance (Q_b) and the second term gives the skin friction resistance (Q_s).

Where

Q_U = Ultimate load capacity in kN

A_b=Cross-sectional area of pile in m^2

N_C = Bearing capacity factor, taken as 9

α = Adhesion factor, depends upon the undrained shear strength of the soil

C_b= Cohesion of soil at pile base level -76 kN/m^2

C_s = Cohesion of soil along the pile surface -76 kN/m^2

A_S = Surface area of pile in m, α=0.6

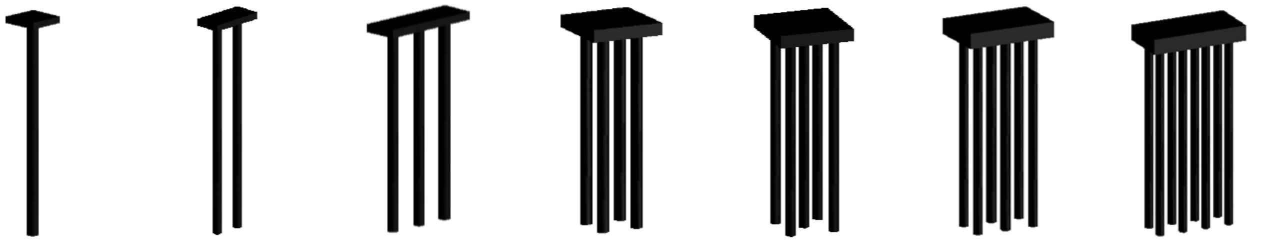
From the Eqs. (1), by considering the factor of safety, the ultimate load bearing capacity of single pile is 376 kN. Calculating the load bearing capacities of two, three, four, five, six, eight piles are as 752 kN, 1128 kN, 1504 kN, 1880 kN, 2256 kN and 3008 kN. By fixing the same load bearing capacity to under-reamed piles, the stem diameter as 380 mm and bulb diameter as 760 mm are obtained and same loads were applied on the pile cap with under-reamed piles.

4.5 Finite element modelling and analysis procedure

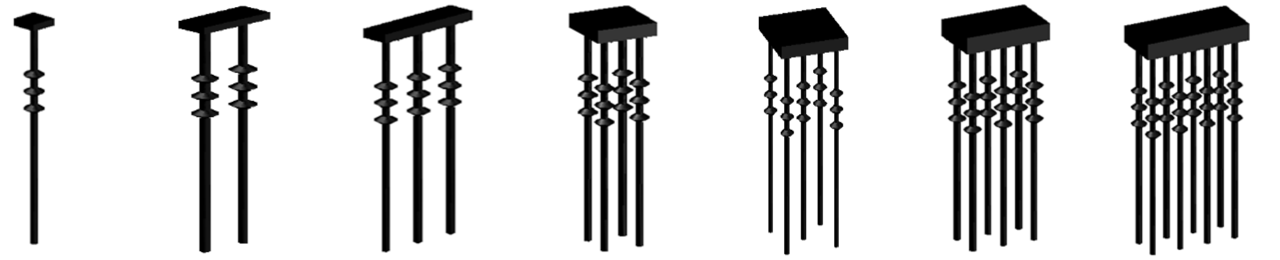
Settlement analysis of pile cap by finite element method under vertical load is carried out using finite element software ANSYS 16.0. Here, pile and pile cap are treated as linear, soil-pile cap and soil-pile interface as non-linear and Drucker-Prager constitute model is used for soil. Pile and pile cap are modelled as linear isotropic and the properties considered for analysis are Young's modulus (E), Poisson's ratio (μ) and density for pile and pile cap. Soil is modelled as an elasto-plastic and in addition to linear material properties. Properties like material cohesion strength (c) and friction angle (Φ) is given.

Pile cap with normal and under-reamed piles are modelled in AutoCAD and exported to ANSYS for analysis by the following procedure.

1. In the tool box, static structural analysis system is selected, and then a column with data required such as engineering data, geometry, model, setup, solution and



(a) Single Normal Pile (b) Two Normal Piles (c) Three Normal Piles (d) Four Normal Piles (e) Five Normal Pile (f) Six Normal Pile (g) Eight Normal Pile



(h) Single Under-Reamed Pile (i) Two Under-Reamed Piles (j) Three Under-Reamed Piles (k) Four Under-Reamed Piles (l) Five Under-Reamed Piles (m) Six Under-Reamed Piles (n) Eight Under-Reamed Piles

Fig. 1 Isometric view of pile cap with normal piles and under-reamed piles

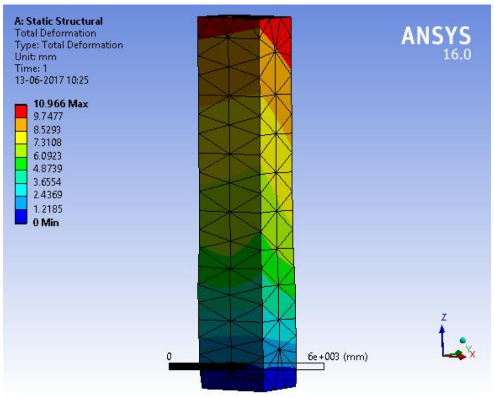


Fig. 2(a) Contour diagrams for settlement of pile cap with six normal piles in very soft clay

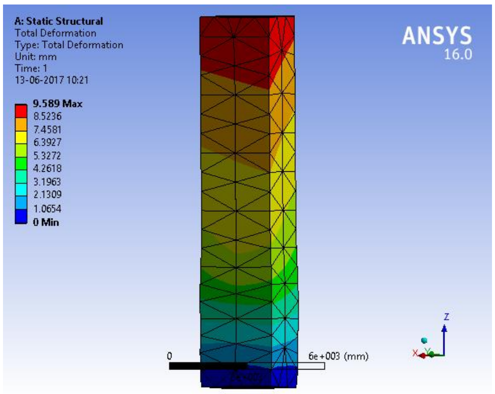


Fig. 3(a) Contour diagrams for settlement of pile cap with sixNormal Pilesin soft clay

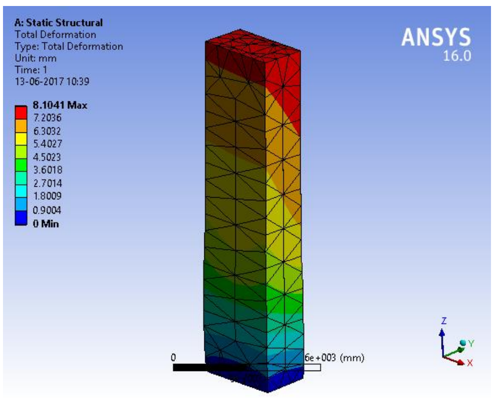


Fig. 2(b) Contour diagrams for settlement of pile cap with six Under-reamed pilesin very soft clay

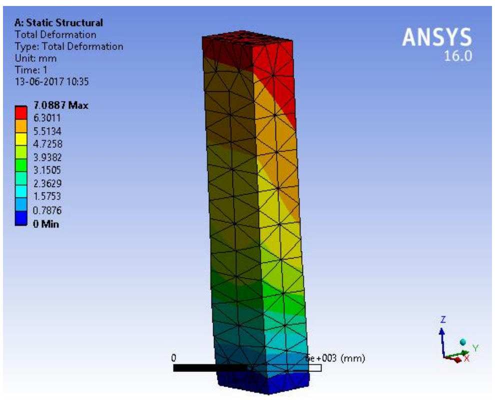


Fig. 3(b) Contour diagrams for settlement of pile cap with sixUnder-reamed pilesin soft clay

results is seen.

2. The material properties such as density, Poisson's ratio, and young's modulus of piled cap and different types of clayey soils are entered in engineering data.

3. In the geometry part, a soil model of specified dimension is created enclosing the piled cap and soil model; this separates the piled cap and soil in same region.

4. In the model part, meshing is done.

5. In the setup part, elastic support and fixed supports are given to the sides and bottom of the model. Vertical

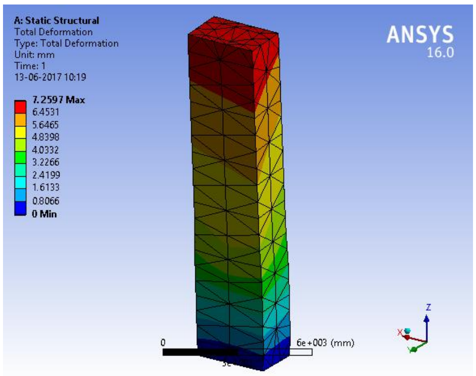


Fig. 4(a) Contour diagrams for settlement of the pile cap with six Normal Pilesin medium clay

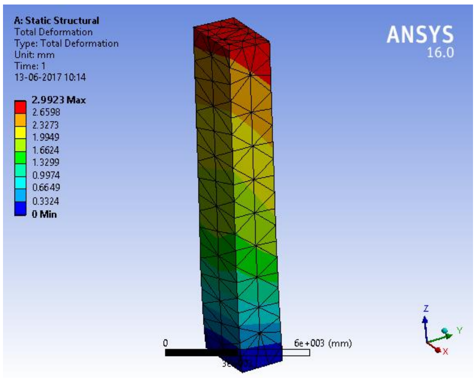


Fig. 5(a) Contour diagrams for settlement of pile cap with six Normal Pilesin hard clay

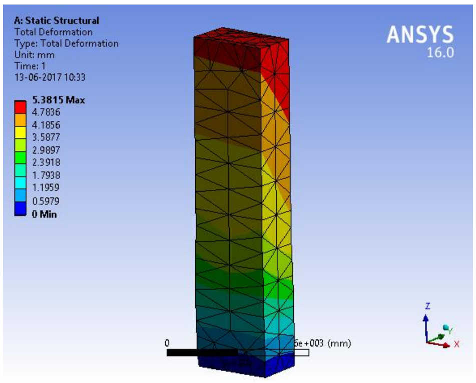


Fig. 4(b) Contour diagrams for settlement of pile cap with six Under-reamed piles inmedium clay

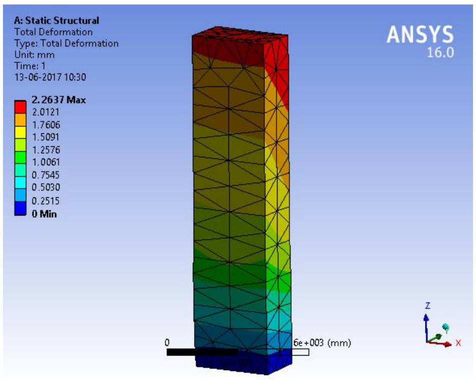


Fig. 5(b) Contour diagrams for settlement of pile cap with sixUnder-reamedpiles in hard clay

loads of 376 kN, 752 kN, 1128 kN, 1504 kN, 1880 kN, 2256 kN and 3008 kN are applied at the centre of the pile cap.

6. By analyzing with the above data, the deformation and stress contours are obtained

4.6 Contour diagrams for settlement and stress analysis of pile cap with six normal and under-reamed piles

Fig. 2 to Fig. 9 shows the contour diagrams obtained from ANSYS 16.0 for settlement and stresses of the pile cap with six normal piles and under-reamed piles in very soft clay, soft clay, medium clay and hard clay.

The settlement behaviour and stress values of pile cap with six normal and under-reamed piles are tabulated in Table 9 based on contours obtained from ANSYS 16.0 (Fig. 2 to Fig. 9).

4.7 Validation

Different models are available for calculating the settlement of a piled raft subjected to a central point load. The approximate settlement of piled raft under point load as proposed by Poulos (2001) is given by Eq. (2).

$$S = \frac{\omega\,(1-\nu_s^2)\,P}{(E_s.a)} \tag{2}$$

Where,

ω=Settlement factor;

ν_s=Poisson's ratio of Soil;

P=Load acting on Piled raft

E_s=Young's modulus of soil;

E_r=Young's modulus of raft;

a=characteristic length of raft given by Eq. (3);

t=Thickness of raft.

and

$$a = t \times \left[\frac{E_r \times (1-\nu_s^2)}{6 \times E_s \times (1-\nu_r^2)}\right]^{\frac{1}{3}} \tag{3}$$

To validate the settlement analysis by FEM with this model, pile cap with two normal piles on very soft clay is considered with the following data.

ν_s=0.35;

ν_r=0.15;

P=752 kN;

E_s=13 MPa;

E_r=27500 MPa;

t=300 mm;

a=2044; (as calculated from Eqs. (3))

ω=0.44.

After substituting the above data in Eq. (2), Settlement of Pile Cap (Poulos 2001)

S=12.17 mm.

Settlement of Pile Cap (FEM Approach adopted in this paper)=9.8 mm

The result shows reasonably good agreement.

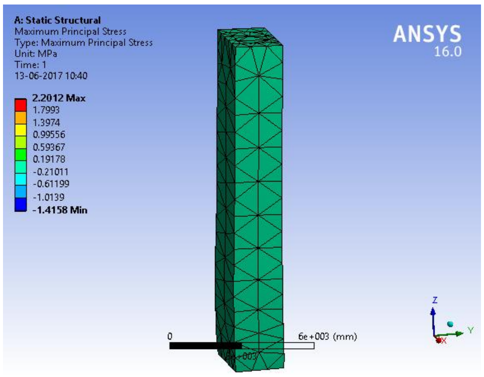


Fig. 6(a) Contour diagrams for stresses of pile cap with six Normal piles in very soft clay

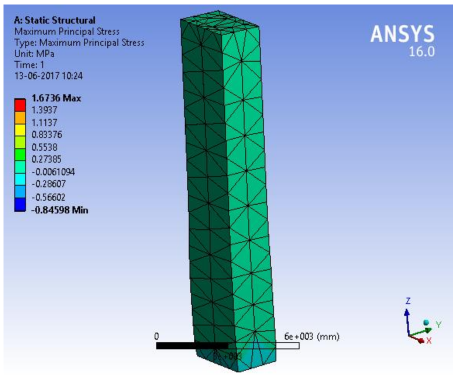


Fig. 6(b) Contour diagrams for stresses of pile cap with six Under-reamed piles in very soft clay

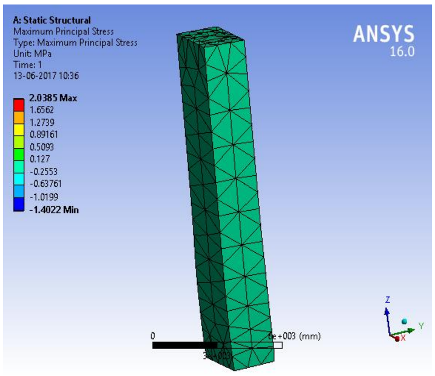


Fig. 7(a) Contour diagrams for stresses of the pile cap with six Normal piles in soft clay

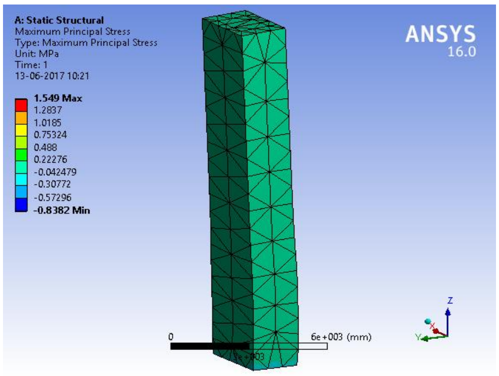


Fig. 7(b) Contour diagrams for stresses of the pile cap with six Under-reamed piles in soft clay

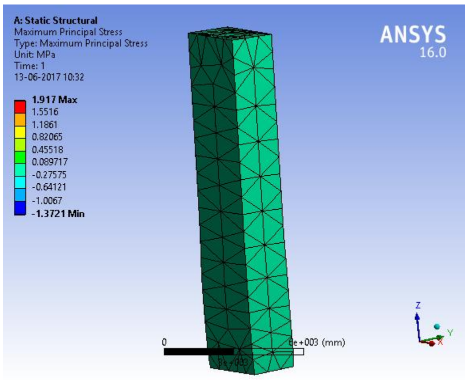


Fig. 8(a) Contour diagrams for stresses of the pile cap with six Normal Pilesin medium clay

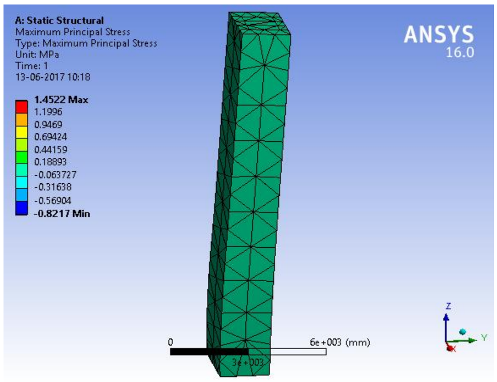


Fig. 8(b) Contour diagrams for stresses of the pile cap with six Under-reamed pilesin medium clay

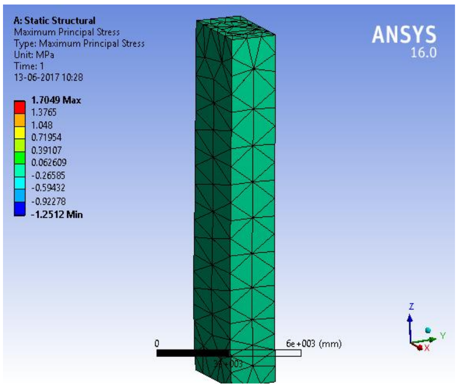


Fig. 9(a) Stress contour for settlement of pile cap with six Normal pilesin hard clay

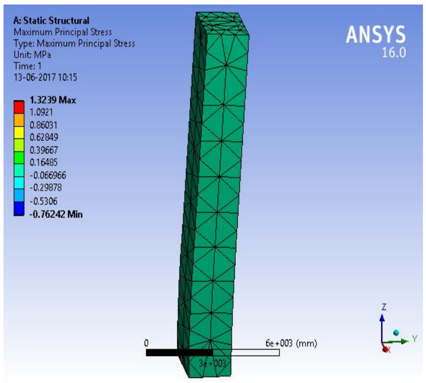


Fig. 9(b) Stress contour for settlement of pile cap with six Under-reamed pilesin hard clay

Table 4 Analysis results of the Pile cap with Single Normal Pile and Under-reamed Pile

Type of soil	Settlement (mm)		Stress (MPa)	
	Piled cap	Under-Reamed Piled Cap	Piled cap	Under-Reamed Piled Cap
Very Soft Clay	8.9	7.1	1.60	1.24
Soft Clay	7.8	6.2	1.48	1.16
Medium Clay	5.9	4.7	1.40	1.10
Hard Clay	2.5	2.1	1.23	1.01

Table 5 Analysis results of the Pile cap with Two Normal Piles and Under-reamed Piles

Type of soil	Settlement (mm)		Stress (MPa)	
	Two Piled Cap	Two Under-Reamed Piled Cap	Two Piled Cap	Two Under-Reamed Piled Cap
Very Soft Clay	9.8	7.7	1.60	1.38
Soft Clay	8.5	6.7	1.50	1.28
Medium Clay	6.5	5.1	1.41	1.21
Hard Clay	2.8	2.2	1.35	1.08

Table 6 Analysis results of the Pile cap with Three Normal Piles and Under-reamed Piles

Type of soil	Settlement (mm)		Stress (MPa)	
	Three piled cap	Three under-Reamed piled cap	Three piled cap	Three under-Reamed piled cap
Very Soft Clay	10.0	8.9	1.98	1.45
Soft Clay	8.8	7.8	1.83	1.33
Medium Clay	6.7	6.0	1.72	1.24
Hard Clay	2.8	2.6	1.54	1.09

Table 7 Analysis results of the Pile cap with Four Normal Piles and Under-reamed Piles

Type of soil	Settlement (mm)		Stress (MPa)	
	Four Piled cap	Four under-Reamed Piled cap	Four Piled cap	Four under-Reamed Piled cap
Very Soft Clay	7.7	5.9	2.04	1.46
Soft Clay	6.7	5.1	1.88	1.32
Medium Clay	5.0	3.9	1.75	1.22
Hard Clay	2.2	1.7	1.50	1.07

Table 8 Analysis results of the Pile cap with Five Normal Piles and Under-reamed Piles

Type of soil	Settlement (mm)		Stress (MPa)	
	Five Piled Cap	Five Under-Reamed Piled cap	Five Piled Cap	Five Under-Reamed Piled cap
Very Soft Clay	7.0	4.2	1.72	1.51
Soft Clay	6.0	3.7	1.63	1.40
Medium Clay	4.6	2.8	1.60	1.33
Hard Clay	2.0	1.2	1.48	1.28

Table 9 Analysis results of the Pile cap with Six Normal Piles and Under-reamed Piles

Type of soil	Settlement (mm)		Stress (MPa)	
	Six Piled cap	Six Under-Reamed Piled cap	Six Piled cap	Six Under-Reamed Piled cap
Very Soft Clay	11.0	8.1	2.20	1.67
Soft Clay	9.5	7.0	2.0	1.54
Medium Clay	7.3	5.4	1.90	1.45
Hard Clay	3.0	2.3	1.70	1.32

Table 10 Analysis results of the Pile cap with Eight Normal Piles and Under-reamed Piles

Type of soil	Settlement (mm)		Stress (MPa)	
	Eight Piled cap	Eight Under-Reamed Piled cap	Eight Piled cap	Eight under-Reamed Piled cap
Very Soft Clay	11.2	7.9	2.0	1.75
Soft Clay	9.7	6.9	1.90	1.65
Medium Clay	7.4	5.2	1.75	1.51
Hard Clay	3.1	23	1.49	1.42

5. Results and discussion

The results from the study of contours on the settlement behaviour between the pile cap with normal pile and under-reamed pile on four different types of soils, as well as stresses developed when loads are applied on pile cap are presented and discussed in this Section.

5.1 Settlement and stress analysis of piled cap

Tables 4, 5, 6, 7, 8, 9 and 10 present the analysis results of the pile cap with single, two, three, four, five, six and eight normal and under-reamed piles obtained from ANSYS 16.0 for very soft clay, soft clay, medium clay and hard clay types of soils respectively. Table 4 presents the analysis results of the pile cap with single normal and under-reamed pile in four different types of clayey soils.

From the Fig. 10, for a point load of 376 kN applied on a single piled cap, a 20% decrease in settlement value in single under-reamed piled cap is observed when compared to single normal piled cap in very soft clay, soft clay and medium clay soil. In case of hard clay soil there was 16% decrease in settlement value.

ANSYS 16.0 for very soft clay, soft clay, medium clay and hard clay types of soils respectively. Table 4 presents the analysis results of the pile cap with single normal and under-reamed pile in four different types of clayey soils.

From the Fig. 10, for a point load of 376 kN applied on a single piled cap, a 20% decrease in settlement value in single under-reamed piled cap is observed when compared to single normal piled cap in very soft clay, soft clay and medium clay soil. In case of hard clay soil there was 16% decrease in settlement value.

From the Fig. 11, for a point load of 376 kN applied on a single piled cap, a 22% decrease in stress value in single under-reamed piled cap is observed when compared to single normal piled cap in very soft clay, soft clay and medium clay soil. In hard clay soil there was 18% decrease in stress value.

Table 5 presents the analysis results of the pile cap with

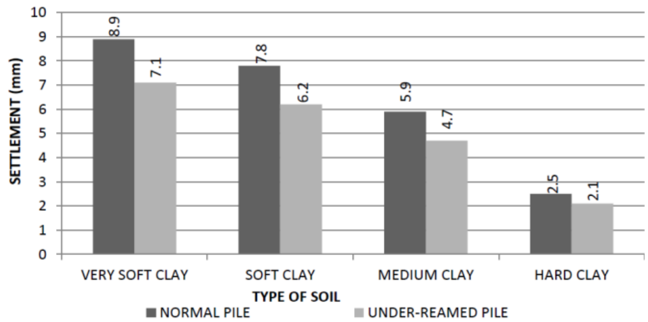


Fig. 10 Settlement values of the pile cap with single normal pile and under-reamed pile

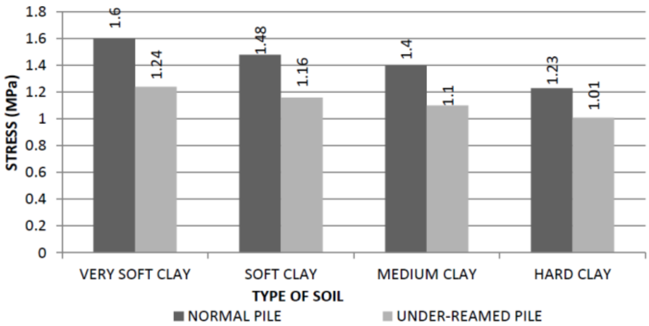


Fig. 11 Stress values of the pile cap with single normal pile and under-reamed pile

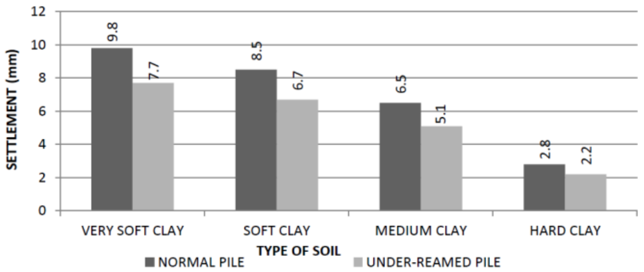


Fig. 12 Settlement values of the pile cap with two normal piles and under-reamed piles

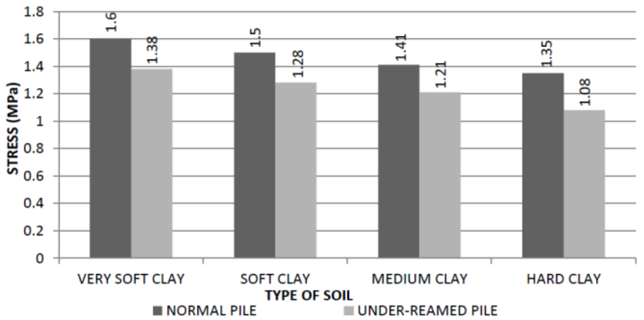


Fig. 13 Stress values of the pile cap with two normal piles and under-reamed piles

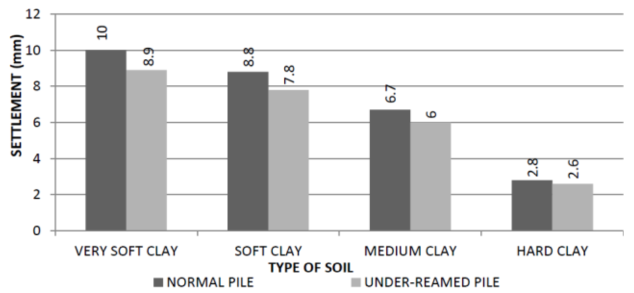


Fig. 14 Settlement values of the pile cap with three normal piles and under-reamed piles

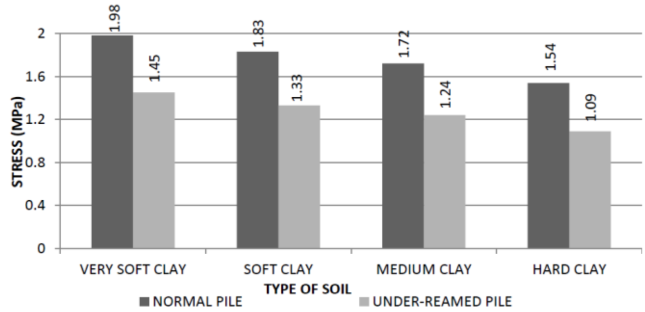


Fig. 15 Stress values of the pile cap with three normal piles and under-reamed piles

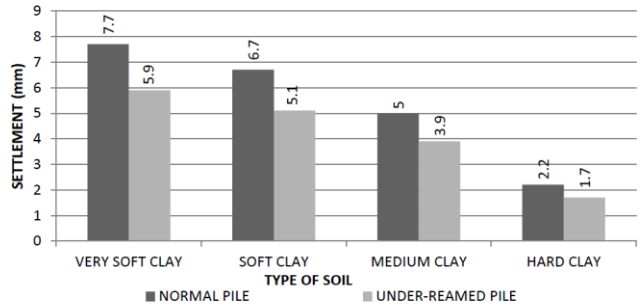


Fig. 16 Settlement values of the pile cap with four normal piles and under-reamed piles

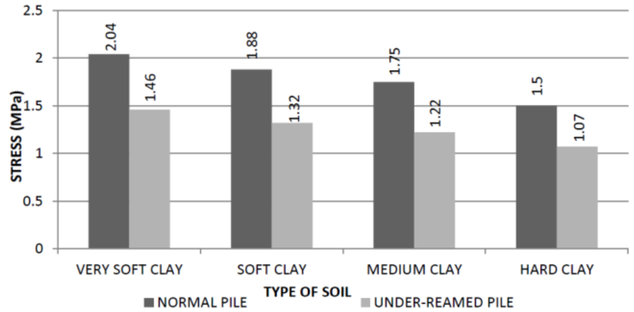


Fig. 17 Stress values of the pile cap with four normal piles and under-reamed piles

two normal and under-reamed piles in four different types of clayey soils.

From the Fig. 12, for a point load of 752 kN applied on a two piled cap, a 21% decrease in settlement value in two under-reamed piled cap is observed when compared to two normal piled cap in very soft clay, soft clay, medium clay and hard clay soil.

From the Fig. 13, when a point load of 752 kN is applied on a two piled cap, a 14% decrease in stress value in two under-reamed piled cap is observed when compared to two normal piled cap in very soft clay, soft clay and medium clay soil. In hard clay soil there was 20% decrease in stress value.

Table 6 presents the analysis results of the pile cap with

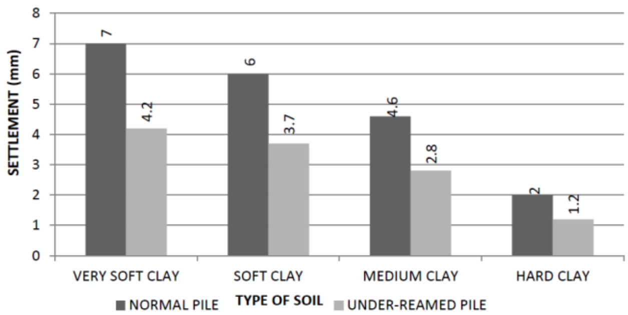


Fig. 18 Settlement values of the pile cap with five normal piles and under-reamed piles

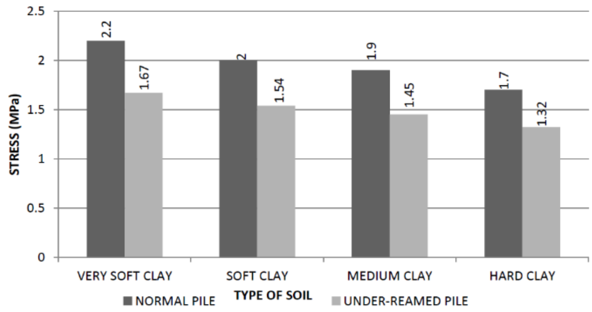


Fig. 21 Stress values of the pile cap with six normal piles and under-reamed piles

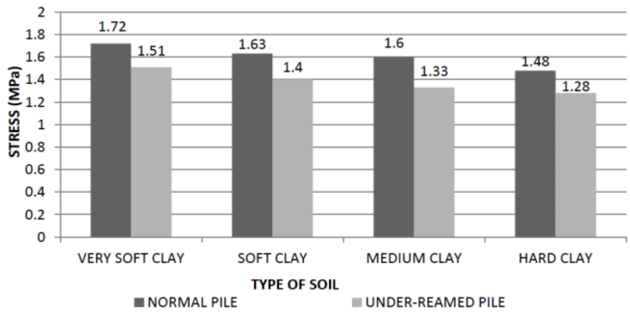


Fig. 19 Stress values of the pile cap with five normal piles and under-reamed piles

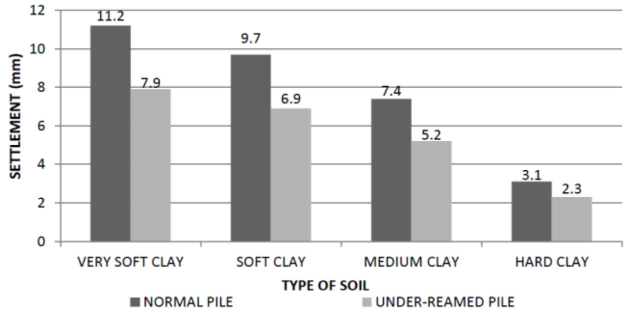


Fig. 22 Settlement values of the pile cap with eight normal piles and under-reamed piles

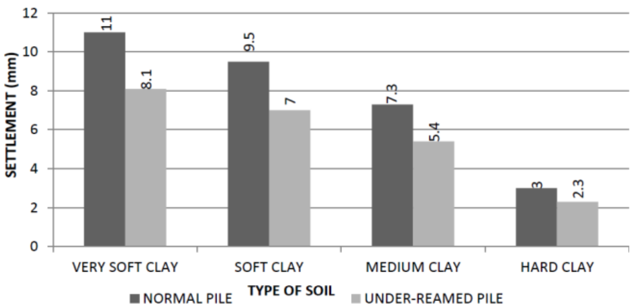


Fig. 20 Settlement values of the pile cap with six normal piles and under-reamed piles

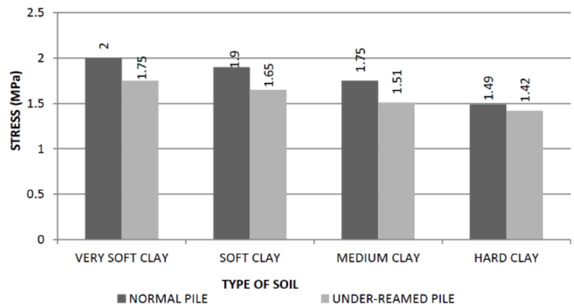


Fig. 23 Stress values of the pile cap with eight normal piles and under-reamed piles

three normal and under-reamed piles in four different types of clayey soils.

From the Fig. 14, for a point load of 1128 kN applied on a three piled cap, a 11% decrease in settlement value in three under-reamed piled cap is observed when compared to three normal piled cap in very soft clay, soft clay and medium clay soil. In hard clay soil there was 7% decrease in settlement value.

From the Fig. 15, for a point load of 1128 kN applied on a three piled cap, a 27% decrease in stress value in three under-reamed piled cap is observed when compared to three normal piled cap in very soft clay, soft clay, medium clay and hard clay soil.

From the Fig. 16, for a point load of 1504 kN applied on a four piled cap, a 23% decrease in settlement value in four under-reamed piled cap is observed when compared to four normal piled cap in very soft clay, soft clay, medium clay and hard clay soil.

From the Fig. 17, for a point load of 1504 KN applied on a four piled cap, a 28% decrease in stress value in four under-reamed piled cap is observed when compared to four normal piled cap in very soft clay, soft clay, medium clay and hard clay soil.

Table 8 presents the analysis results of the pile cap with five normal and under-reamed piles in four different types of clayey soils.

From the Fig. 18, for a point load of 1880 kN applied on a five piled cap, a 39% decrease in settlement value in five under-reamed piled cap is observed when compared to five normal piled cap in very soft clay, soft clay, medium clay and hard clay soil.

From the Fig. 19, for a point load of 1880 kN applied on a five piled cap, a 13% decrease in stress value in five under-reamed piled cap is observed when compared to five normal piled cap in very soft clay, soft clay and hard clay soil. In medium clay soil there was 17% decrease in stress value.

Table 9 presents the analysis results of the pile cap with six normal and under-reamed piles in four different types of clayey soils.

From the Fig. 20, for a point load of 2256 kN applied on a six piled cap, a 26% decrease in settlement value in six under-reamed piled cap is observed when compared to six normal piled cap in very soft clay, soft clay and medium clay soil. In hard clay soil there was 23% decrease in settlement value.

From the Fig. 21, for a point load of 2256 kN applied on a six piled cap, a 23% decrease in stress value in six under-reamed piled cap is observed when compared to six normal piled cap in very soft clay, soft clay, medium and hard clay soil.

Table 10 presents the analysis results of the pile cap with eight normal and under-reamed piles in four different types of clayey soils.

From the Fig. 22, for a point load of 3008kN applied on an eight piled cap, a 29% decrease in settlement value in eight under-reamed piled cap is observed when compared to eight normal piled cap in very soft clay, soft clay and medium clay soil. In hard clay soil there was 26% decrease in settlement value.

From the Fig. 23, for a point load of 3008 kN applied on an eight piled cap, a 13% decrease in stress value in eight under-reamed piled cap is observed when compared to eight normal piled cap in very soft clay, soft clay and medium clay soil. In hard clay soil there was 5% decrease in stress value.

6. Conclusions

This paper presents an analytical study on the variation of the settlement and stress values of various piled group combinations considering different types of clayey soils by using finite element method. Four types of clay soils are considered and the loading was done according to the load bearing capacities of different pile combinations. Loads are applied over the centre of the pile cap of the normal piles and under-reamed piles and the values obtained from the analysis are compared. From the study the following conclusions were obtained.

1. Settlement of under-reamed piles is reduced by 20%, 21%, 12%, 23%, 39%, 25% and 28% when compared to normal piles with single, two, three, four, five, six and eight piled cap combinations respectively.
2. Stresses of under-reamed piles is reduced by 21%, 16%, 27%, 29%, 15%, 23% and 12% when compared to normal piles with single, two, three, four, five, six and eight piled cap combinations respectively.

From the study it can be concluded that Settlement and stresses reduces significantly in pile cap with under-reamed piles when compared to pile cap with normal piles. It means that the ultimate load bearing capacity of pile cap with under-reamed piles are greater than the pile cap with normal piles. This will help buildings, bridges and power plant industry in getting adequate solutions for many problems related to foundation

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