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Undrained Uplift Capacity of Under-Reamed Pile in Layered Clays

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Abstract. Under-reamed piles are generally a choice of foundation for structures subjected to the uplift load; especially for the transmission line towers, patrolling towers, chimneys, tall and slender structures, etc. In the study, the undrained up- lift capacity of single under-reamed pile embedded in layered clay is evaluated using finite element (FE) method-based software Plaxis 2D. The geometry of the under-reamed pile is chosen as per the standard codal provision. In the analysis, the soil is assigned with Mohr-Coulomb model and pile is assigned with Linear Elastic model. The thickness of layered clays i.e., soft clay overlain hard clay and hard clay overlain soft clay is varied with cohesion ratio = 2. The FE results are compared with the solutions available in the literature. The uplift capacity ratio defined as ultimate uplift capacity of under-reamed pile in single clay to that in layered clay having different clay layer thickness ratio (h/H = 0 to 1) are evalu- ated. The present study results are represented as design charts so as to be used in the design practice.

Keywords: Under-reamed pile, Finite element method, Mohr-Coulomb model, Layered clay, Uplift load, Undrained loading.

1 Introduction

Conventional cylindrical piles will not be able to provide the sufficient uplift resistance required for the tall structures like transmission line towers, patrolling towers, chim- neys, tall and slender structures, etc., therefore, in such cases, the under-reamed piles are used to withstand the uplift forces. In case of piles in clay, the cohesion strength may vary linearly throughout its depth, or the soil deposit may have layered clay as soft over hard clay and vice-a-versa. Therefore, it is necessary to assess the undrained uplift capacity of the under-reamed pile in layered clayey soil.

The research that has already contributed to the understanding on behaviour of under-reamed pile is reasonably addressed [1-7]. According to Martin and Stephen [1], a twin bulb under-reamed pile can be used as an alternate foundation for over consolidated hard clay. In terms of dimensional stability and homogeneity for the piles, Peter et al. [2] reported that self-compacting concrete perform better. Contrarily, piles formed of vibrated concrete exhibit comparable compression and uplift outcomes. George and Hari [5] used finite element analysis to assess the compressive and uplift capacity of the under-reamed pile in homogeneous clay. The uplift capacities of conventional pile, single under-reamed pile, and double under-reamed pile in clay with linearly increasing cohesion of soil with depth were determined using finite element limit analysis by Khatri et al. [7]. With reference to other areas of research on under-reamed pile, the undrained uplift capacity of the under-reamed pile in layered clay is still not completely understood. In this regard, the undrained uplift capacity for the layered clay as soft over hard clay and vice-a-versa with a cohesion ratio of 2 is evaluated in the study for vary- ing clay thickness ratio as h/H = 0 to 1, and different L/D ratio of pile.

2 Problem Statement

In the study, the under-reamed pile with single bulb in soft clay overlain hard clay and hard clay overlain soft clay is simulated to determine the failure load for various h/H ratios of layered clay and varying L/D ratios of pile. For this, the finite element software Plaxis 2D is used. The codal provision (IS 2911 Part III [8]) is used to determine the geometry (**Fig. 1**, D = diameter of shaft, D_u = 2.5 times diameter of bulb) of the under- reamed pile. The pile length is kept constant as L = 4.5 m, and the L/D ratio is varied as 5, 15, and 20. The diameter of the shaft is varied to vary the L/D ratio. The pile is modelled using Linear Elastic model while the soil is modelled using Mohr-Coulomb model, the properties of the soil and pile are provided in **Table 1**.

The cohesion ratio of soil is taken as 2 in the study, where soft soil is having un-drained cohesion value of 15 kPa and hard clay is having the undrained cohesion value of 30 kPa. The layered clay is modelled by considering soft clay overlain hard clay and hard clay overlain soft clay, and the value of undrained uplift capacity is determined. Based on several trials, a fine mesh (**Fig. 2)** is selected in the study, and it appears to be the most appropriate for this analysis and the water table level is considered at ground level i.e., the top boundary of FE model. The soil has the following values: friction angle = 0°, unit weight = 16 kN/m^3, Young's modulus = 15 MPa, and Poisson's ratio = 0.35. The pile is modelled using linear elastic with the following values: unit weight = 27 kN/m^3, Young's modulus = 31000 MPa, and Poisson's ratio = 0.15.

Table 1: Material properties of soil and pile used in study [after George and Hari [3]]

Parameter	Soil	Pile
Frictional angle (φ)	0°	-
Unit weight (γ)	16 kN/m^3	27 kN/m^3
Young's modulus (E)	15 MPa	31000 MPa
Poisson's ratio (ν)	0.35	0.15

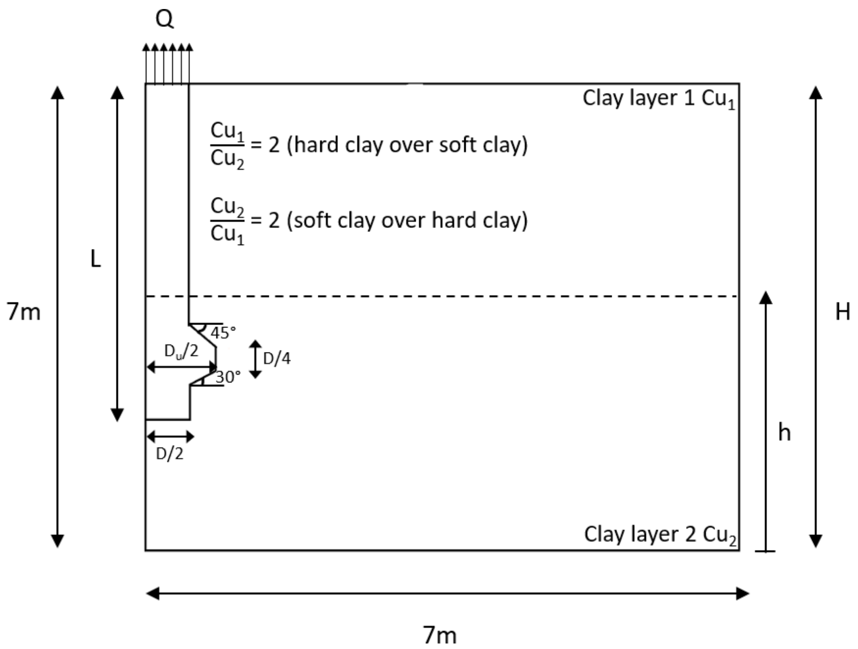

Fig. 1 Schematic representation of single under-reamed pile in layered clay

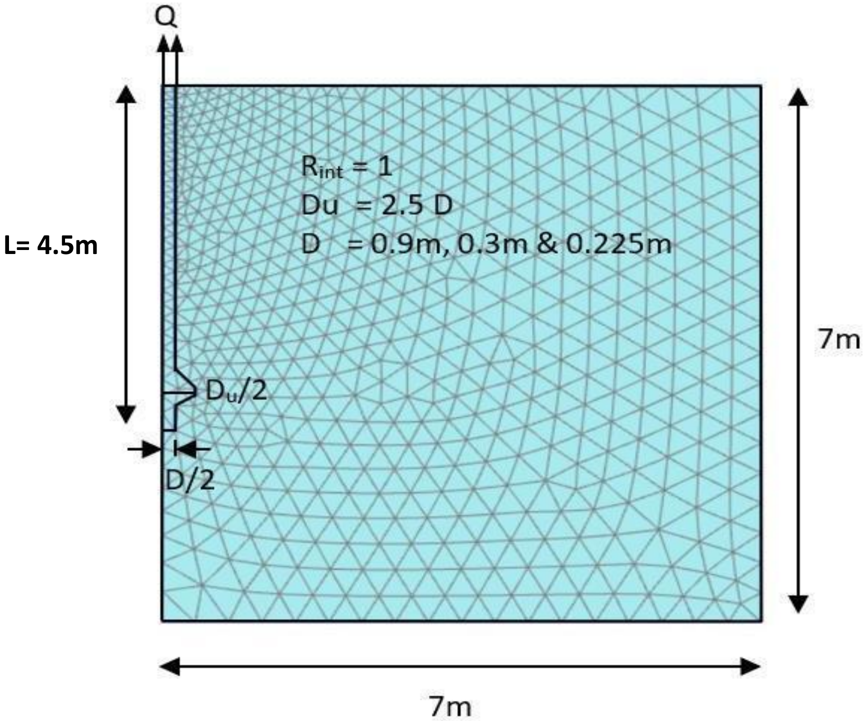

Fig. 2 FE model of single under-reamed pile in layered clay

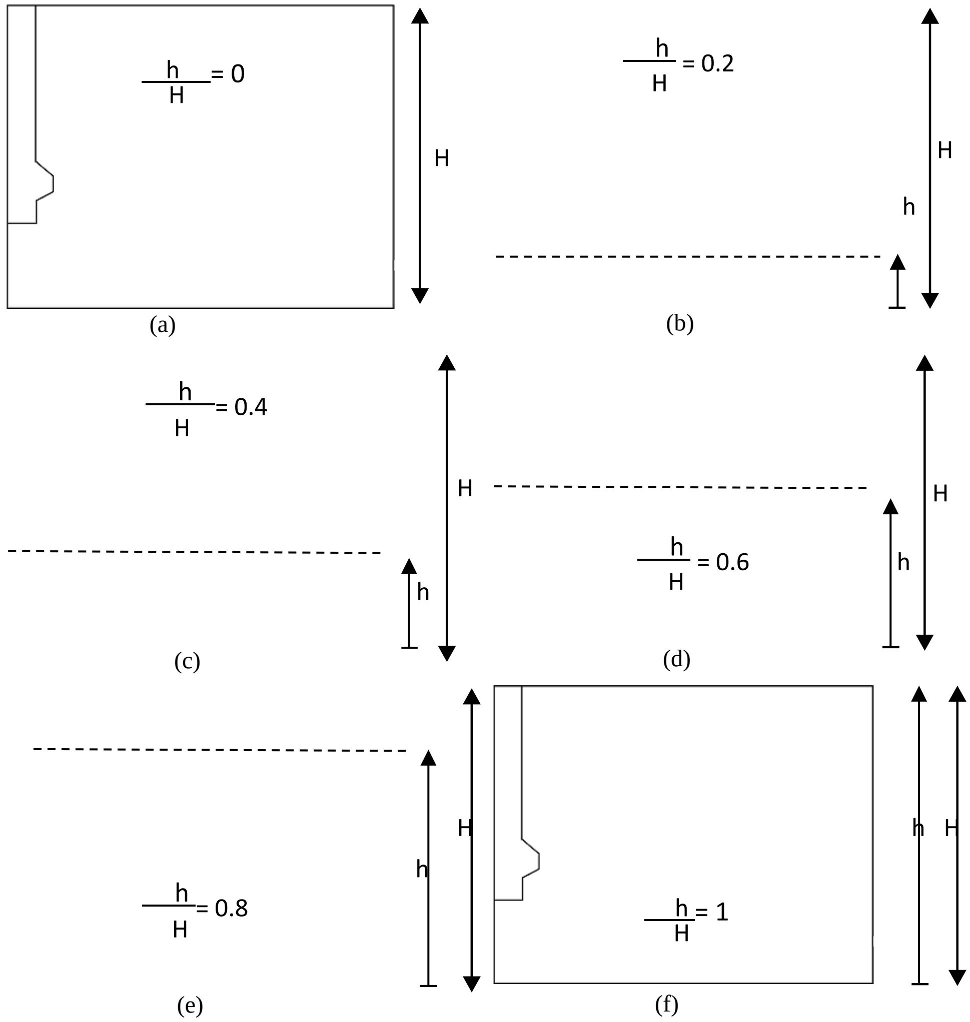

Fig. 3 A representation showing the variation in h/H ratio from 0 to 1

In this study, the *h*/*H* ratio is varied by considering the variation in *h* from the bottom of FE domain (see **Fig. 3**), where the overall height of model H = 7 m which is fixed and the thickness of top clay layer is varied from 0 to 7 m to have the variation in *h*/*H* ratio. For each fixed value of the *L*/*D* ratio, i.e., 5, 15, 20 the undrained uplift capacity of the under-reamed pile in both the cases of soft clay overlain hard clay and hard clay overlain soft clay is evaluated. Then, considering both cases i.e., soft overlain hard and vice-a-versa, a design chart is prepared.

3 Validation

In the study, the undrained capacity of single under-reamed pile is evaluated using FE analysis considering the data from George and Hari [5], Khatri et al. [7] and Codal guidelines (IS 2911 Part III [8]). George and Hari [5] used Plaxis 3D and Khatri et al.

[7] used Optum G2 in their studies. The geometry and model characteristics are same as used by George and Hari [5], which are listed in Table 2. Based on present FE analysis, the load-deformation plot are obtained, and then the FE results are compared with the solution of George and Hari [5], Khatri et al. [7] and IS 2911 Part III [8] (see Fig 4). The present study results match well with the value obtained from IS 2911 Part III, and reasonably well with George and Hari [5], Khatri et al. [7]. Then using the same validated model, the layered clay is introduced with varying h/H ratio for different L/D ratio of under-reamed pile subjected to uplift load in undrained clay.

Table 2: The properties of soil and pile as per George and Hari [5]

Parameter	Soil	Pile
Frictional angle (φ)	1°	-
Unit weight (*γ*)	16 kN/m^3	27 kN/m^3
Cohesion (*c*)	15 kPa	-
Young's modulus (*E*)	15 MPa	31000 MPa
Poisson's ratio (*v*)	0.35	0.15
Length (*L*)	-	4.5 m

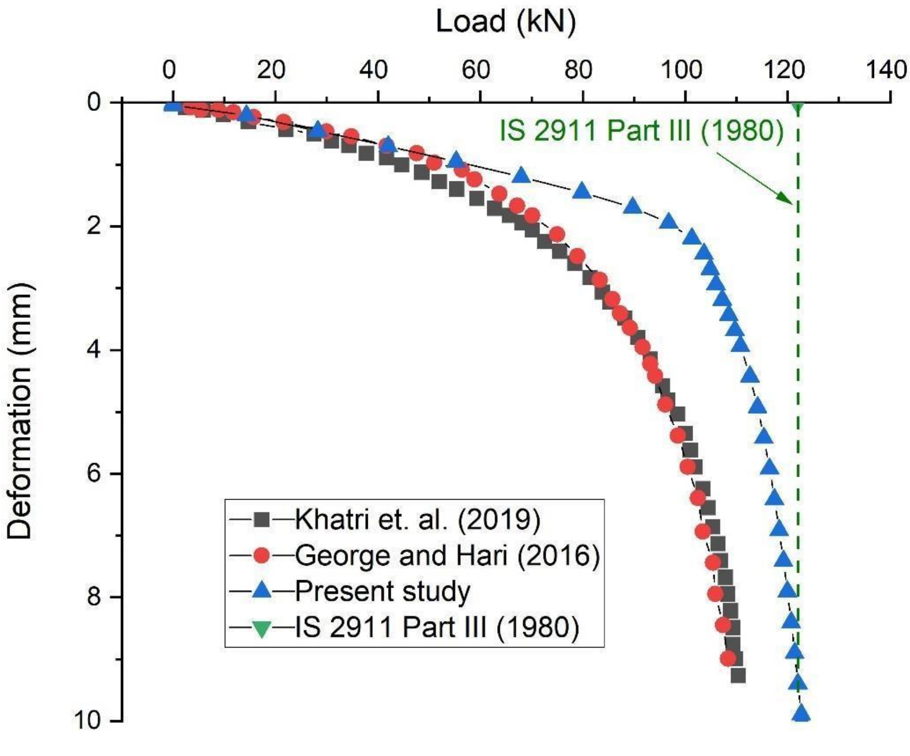

Fig. 4 The comparison of present study results with literature

4 Results and Discussion

In the study, the undrained capacity of under-reamed pile in layered clay is evaluated and is normalized by dividing the ultimate failure load of pile in layered clay with the ultimate failure load of pile in single clay layer. This normalized factor is reported as F_c. The F_c for under-reamed pile in layered clay with soft clay overlain hard clay and hard clay overlain soft clay is evaluated and depicted in **Fig. 5**. For each *L*/*D* ratio, considering the soft undrained clay (c_u =15 kPa) overlain by hard undrained clay (c_u = 30 kPa), the undrained uplift capacity of under-reamed pile increases with increase in the *h*/*H* ratio, indicating that the presence of a thicker hard clay layer below the soft clay layer result in higher undrained capacity. Similarly, the F_c reduces for a thicker soft clay layer below the hard clay layer which result in lower undrained capacity. The results from the study are also provided in **Table 3**.

$$F_c = \frac{Failure\ load\ of\ pile\ in\ layered\ clay}{Failure\ load\ of\ pile\ in\ single\ clay}$$

With increase in the *L*/*D* ratio from 5 to 20 (i.e., D = varying, L = 4.5 m = constant), there is a decrease in the uplift load carrying capacity since the diameter of the under- reamed pile decreases while the length of pile is constant. The undrained uplift load carrying capacity of under-reamed pile is affected by the shaft and bulb diameter, *h*/*H* ratio of layered clay, *L*/*D* of pile and this parameter shall be taken care in design of under-reamed pile in layered clay. In the study the cohesion ratio was kept constant = 2 and the R_{int} = 1, therefore for more practical scenarios this study should be extended for different cohesion ratio and interface strength.

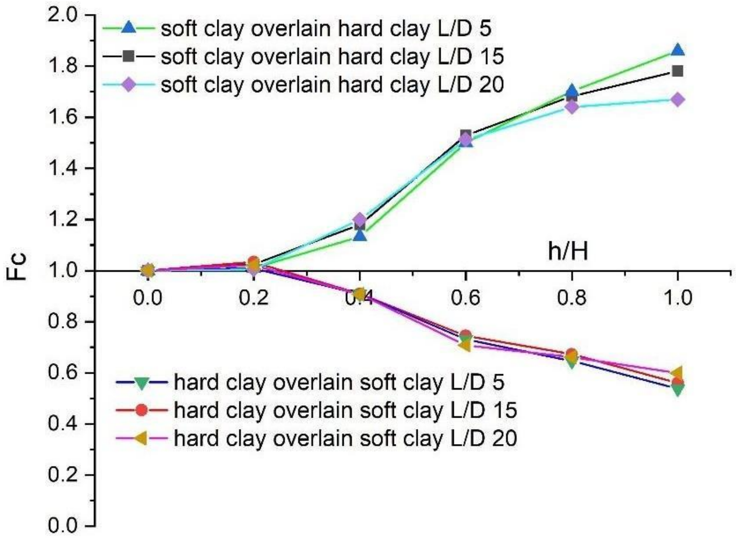

Fig. 5 The variation in Fc for different *L*/*D* ratio of single under-reamed pile and *h*/*H* ratio of layered clay

Table 3 Ultimate uplift failure load of under-reamed pile obtain from FE analysis for varying *L*/*D* and *h*/*H* ratios

L/*D*	*h*/*H*	Soft clay over hard clay		Hard clay over soft clay	
		Uplift Load (kN)	F_c	Uplift Load (kN)	F_c
L/*D* = 5	0	716.37	1.00	1064.90	1.00
	0.2	686.35	0.96	1037.80	0.97
	0.4	789.46	1.10	986.33	0.92
	0.6	937.49	1.31	861.03	0.80
	0.8	991.99	1.38	773.88	0.72
	1	1064.90	1.49	716.37	0.67
L/*D* = 15	0	147.78	1.00	263.11	1.00
	0.2	151.5	1.02	272.03	1.03
	0.4	174.35	1.17	239.19	0.91
	0.6	225.92	1.52	195.96	0.74
	0.8	248.64	1.68	177.09	0.67
	1	263.11	1.78	147.49	0.56
L/*D* = 20	0	95.31	1.00	177.23	1.00
	0.2	96.23	1.01	178.74	1.01
	0.4	107.97	1.13	160.98	0.91
	0.6	143.01	1.50	129.56	0.73
	0.8	162.18	1.70	114.56	0.65
	1	177.23	1.86	95.31	0.54

5 Conclusions

Based on the evaluation of undrained uplift capacity of single under-reamed pile using finite element approach, it is concluded that the uplift capacity of a single bulb under-reamed pile increases with increase in the diameter of the bulb and shaft. The undrained the uplift capacity of a single bulb under-reamed pile is significantly affected by pres- ence of layered clay as soft clay overlain hard clay and hard clay overlain soft clay. In the case of soft clay overlain hard clay, the undrained uplift capacity of under-reamed pile increases with increase in the *h*/*H* ratio i.e., the thickness of hard clay is increasing. Whereas in the case of hard clay overlain soft clay, the undrained uplift capacity of under-reamed pile reduces with increase in the *h*/*H* ratio i.e., the thickness of soft clay is increasing. Further, it is noted that the undrained uplift load carrying capacity of under-reamed pile is affected by the shaft and bulb diameter, *h*/*H* ratio of layered clay, *L*/*D* of pile and this parameter shall be taken care in design of under-reamed pile in layered clay. In the study the cohesion ratio was kept constant = 2 and the R_{int} = 1, therefore for more practical scenarios this study should be extended for different cohe- sion ratio and interface strength.

6 References

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