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Analysis of Under-reamed Piles Subjected to Different Types of Load in Clayey Soil

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ABSTRACT

Under-reamed piles with one or more bulbs have been widely used in almost all types of soil to support a range of structures. In some cases, in addition to vertical compressive or uplift loads, piles must withstand a considerable lateral load. A 3-D finite element study using ABAQUS software was conducted to examine the behavior of under-reamed piles in clay soil under pure lateral, pure uplift, and combined uplift and lateral loads. In this study, pile (L/D) ratios of 11.66, 15, 20, and 25 were considered by adjusting the pile length to simulate the behavior of rigid and flexible piles. The piles were modeled as a linear elastic material, and the soil behavior was simulated using the Drucker-Prager constitutive model. The findings show that the lateral resistance of piles with (L/D) ratios of 11.66 and 15 increased slightly when under-reamed piles were used. However, no change in lateral resistance was observed for under-reamed piles with (L/D) ratios of 20 and 25 compared with straight piles. The uplift capacity of under-reamed piles was significantly greater than that of a straight pile. The lateral capacity was marginally influenced by the prior uplift loading, such that it decreased for a rigid under-reamed pile, and increased for a flexible under-reamed pile.

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1. INTRODUCTION

Under-reamed piles are bored concrete cast-in situ piles with one or more bulbs created by widening the stem of the pile. These piles were first introduced in India for use in expansive soils. Under-reamed piles are commonly used to support a wide range of structures in almost all types of soil. When used for towers, shed structures, bridge abutments, and other high-rise structures, the piles are subjected to a significant lateral load. However, the guidelines available for their design under lateral loads are highly empirical [1, 2]. With bulbs, it has been suggested that short under-reamed piles act more like rigid piles, and analysis may be conducted accordingly. For simplification purposes, as conservative assumption, the effect of the bulb can be ignored.

Most previous studies have focused primarily on estimating the compression and tension capacities of under-reamed piles. However, few studies in the literature, have examined the behavior of under-reamed piles exposed to a lateral load. Shrivastava et al. [3] used Hrennikoff's approach [4] to examine the behavior of a single and a group of under-reamed piles with a single bulb. A pile was considered as a rigid pole and rotated about the underream (bulb) center, and the soil was idealized as a nonlinear deformation spring. The soil above the bulb was thought to be lifted up on one side and pushed down on the other side, forming a couple. Soneja and Garg [5] reported that, the first bulb significantly increased the resistance of the lateral load, based on several field tests on RC piles in sandy soils. However, addition of a second bulb, did not result in any substantial increase in capacity over single under-reamed piles.

Parakash and Ramakrishna [6] proposed an analytical method to predict the ultimate lateral load capacity of under-reamed piles in both Ø-soils and c-soils, including the effect of bulb size, bulb position, the number of bulbs, and pile (L/D) ratio. That study concluded that for c-soils, the bulb located closer to the ground surface provides greater resistance for single under-reamed piles. For Ø-soils, a bulb located at a depth of 0.4–0.6 times the length

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of the pile provides the highest resistance. The study also showed that the lateral capacity of under-reamed piles increases significantly with an increase in the number of bulbs. However, as the number of bulbs increases, the improvement in lateral capacity decreases, remaining almost constant beyond three bulbs. This was observed in both soils. It was also found that, with an increase in (L/D) to a certain value, the lateral resistance of under-reamed piles also increased, but decreased beyond that. Prakash and Chandra [7] conducted field tests on single bulb piles in a sandy soil deposit and reported that a single bulb pile acts as a short, rigid pile. They also reported that the point of rotation was near the center of the bulb; the predicted ultimate capacities and deflection using different techniques were found to be in good agreement with the observed values.

Several studies have been conducted to assess the efficiency of under-reamed piles, particularly with uplift loads [8-12]. Martin and De Stephen [8] reported that for overconsolidated stiff clay, a foundation of under-reamed piles with two bulbs is an acceptable option. It was further reported that the distance between the bulbs should be (1.5–2) times greater than the diameter of the bulb.

Watanabe et al. [13] conducted studies on under-reamed piles in clay subjected to compression and tensile loads, demonstrating that, under-reamed piles have sufficient resistance to tensile and compressive loads. Niroumand et al. [14] showed that the uplift resistance of under-reamed piles in sandy soil depends on the relative undrained/drained shear strength of the soil and the number of bulbs. George and Hari [15] performed an FE analysis to estimate the compression and uplift capacity of under-reamed piles in homogeneous clay, reporting an improvement in uplift capacity of approximately 119% for a single under-reamed pile and 204% for a double under-reamed pile with a bulb diameter 2.6 times greater than the pile stem.

Although bulbs in under-reamed piles provide a good benefit, the analysis is more complex. The problem becomes more complicated because these piles may be subjected to a combination of axial and lateral loads, as well as moments. For such a problem, a complete solution can be obtained through a 3-D continuum analysis.

The idea of this study was deduced due to the lack of literature in studying the behavior of the under-reamed pile subjected to lateral loads. In this study, the behavior of under-reamed piles in clay was numerically examined under separate and combined uplift and lateral loads. Pile (L/D) ratios of 11.66, 15, 20, and 25 by adjusting the pile length were investigated. ABAQUS-3D software was used to model the interaction between the uplift and lateral loads on the piles.

2. PROBLEM STATEMENT

This study examined straight and under-reamed piles with single or double bulbs embedded in a clay layer. The piles were subjected to lateral loads, uplift loads, and combined lateral and uplift loads. The loads were applied at a pile head 1 m above the ground surface. The diameter of the pile stem (D) was chosen as 0.3 m; the bulb diameter (D_u) was taken as 2.5D ($D_u = 0.75$ m), according to Indian standards [1]. The location of the lower bulb relative to the pile tip, and the distance between the bulbs also followed the standard requirements [1]. The diameter of the pile stem for straight and under-reamed piles with single or double bulbs was 0.3 m, and the pile length ranged from 3.5–7.5 m to achieve an embedment pile ratio of 11.66, 15, 20, and 25.

In this study, P, SURP, and DURP refer to the straight pile, the single under-reamed pile, and the double under-reamed pile, respectively. The soil properties used for the FE analysis were taken from Helwany's book [16] and considered as a thick homogeneous saturated clay layer under drained conditions, with the groundwater table level coinciding with the top surface of the soil. The properties of the soil and the piles are presented in Table 1. The constitutive model used to simulate the behavior of the soil mass was the Drucker–Prager/cap failure criterion, and the pile was considered as an elastic material.

3. NUMERICAL MODEL

A full 3-D finite element model using ABAQUS software was used to assess the behavior of P, SURP, and DURP under pure lateral, pure uplift, and combined lateral and uplift loads. To prevent any significant boundary effects, the locations of the bottom and lateral sides of the domain were chosen sufficiently far from the pile. Karthikeyan et al. [17] suggested that the lateral sides should be located 20D from the pile axis (the lateral domain for this study was calculated with respect to the diameter of the bulb

TABLE 1. Properties of soil and piles

Part	Soil	Pile
Model	Drucker-Prager	Linear elastic
E (kPa)	68900	30E6
Density (kN/m^3)	19	24
Cohesion (kPa)	0	-
Poisson's ratio	0.3	0.2
Angle of friction (°)	30	-
Length (m)	-	3.5, 4.5, 6, 7.5

D_u), and the total thickness of the soil stratum was ($L_{pile} + 20D$).). The boundary condition was set such that the bottom of the domain was restrained in three directions; at the lateral sides of the domain, movement was prevented horizontally but allowed vertically. Contact between the soil and pile surfaces was simulated using the basic Coulomb friction model, with penalty tangential contact and normal hard contact.

Figure 1(a-d) shows the schematic 3-D finite element mesh discretization of the pile–soil continuum.

4. MODEL VALIDATION

To ensure reliable results from the numerical analysis, the model and software must be validated. Validation can be performed by comparing the numerical data with the experimental data or the prescribed computed data. In this analysis, the model was validated for two cases of loading, lateral and uplift loads. To verify the pile model subjected to lateral load, the piles foundation for a high-speed railway in Taiwan were employed. In this project, two pile groups and several single piles were subjected to full-scale load testing [18]. The tested piles were either driven or bored. The findings of a lateral loading test performed on a single pile symbolized as B7 are considered in this study. The details of loading test and the computations by LPILE program using constant EI were stated in details by Huang et al. [18]. Pile B7 was a 34.9 m long bored reinforced concrete pile with a diameter of 1.5 m.The structural properties of the pile used in this analysis are shown in Table 2. According to the site exploration, the soil within the first 80 m depth may be described as a silty sand with layers of sandy silt. As illustrated in Figure 2, the soil strata is subdivided into six layers. It is found that the groundwater was at a depth 1m with buoyant unit weight of the soil $\gamma' = 9\, kN/m^3$ [18]. Table 3 lists the other soil properties utilized in the study.

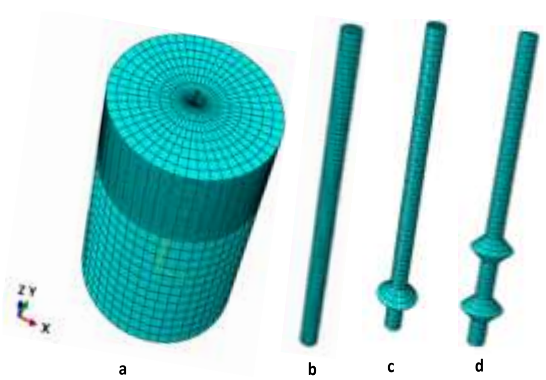


Figure 1. FE mesh for; a. soil domain, b. straight pile, c. single bulb under-reamed pile, double- bulb under-reamed pile adopted for current analysis

TABLE 2. Structural properties of the pile considered for simulating the pile model subjected to lateral load

γ (kN/m^3)	E (kPa)	Poisson's ratio	Dia. (m)	Length (m)
25	30E6	0.2	1.5	34.9

"To evaluate the initial field stress in the subsoil before the loading test, the coefficient of earth pressure at rest is estimated on the basis of the values of the stress index K_D provided by the DMTs which were performed after pile installation, using an empirical relationship published in the literature [19], was found that a value of k_o= 0.72 can be assumed for any soil layer" [20]. Due to the fact that the soil in front of the pile is freely to move, the dilation effect may be not important in the situation under consideration. Taking this into account, the angle of dilatancy is assumed zero [20] (nominally taken 0.1). Figure 3 displays the obtained findings compared with the measured results in terms of the (lateral deflection-lateral load) curve and also involving the computed results by LPILE. As can be seen, the simulation and observation findings are in good agreement.

The pile model subjected to uplift load was validated using the model presented by George and Hari [15]. The soil and pile properties used in this validation are shown in Table 4. The uplift load–pile head deflection curve of the numerical model obtained by using ABAQUS compared with that presented by George and Hari indicates a good agreement, as shown in Figure 4.

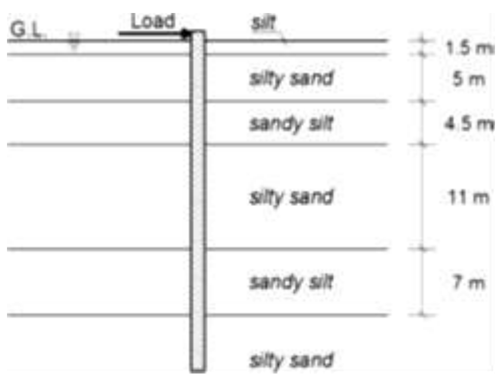


Figure 2. Subsoil layers as documented by Huang et al. [18]

TABLE 3. Soil properties as reported by Conte et al. [20]

Layer No.	G (kPa)	v'	c'	$\emptyset'$ (°)	φ'(°)
1	30800	0.3	0	33	0
2	57700	0.3	0	34	0
3	57800	0.3	0	28	0
4	87700	0.3	0	33	0
5	87700	0.3	0	28	0
6	87700	0.3	0	30	0

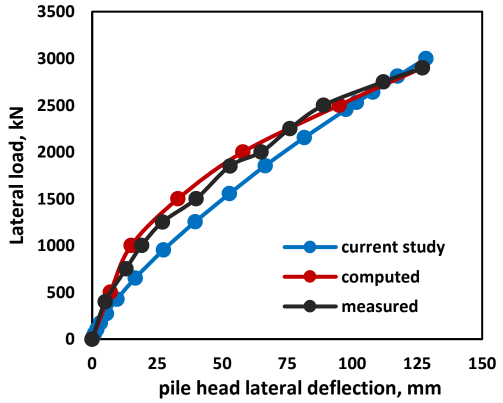


Figure 3. Comparison of measured and predicted findings involving the computations by LPILE program using constant EI

TABLE 4. Properties of soil and piles used for validation model pile subjected to uplift load [15]

Part	Soil	Pile
Model	Mohr–Coulomb	Linear elastic
E (kPa)	15000	31E6
Density (kN/m^3)	16	27
Cohesion, (kPa)	15	-
Poisson's ratio	0.35	0.15
Angle of friction (°)	1	-
Length (m)	-	4.5

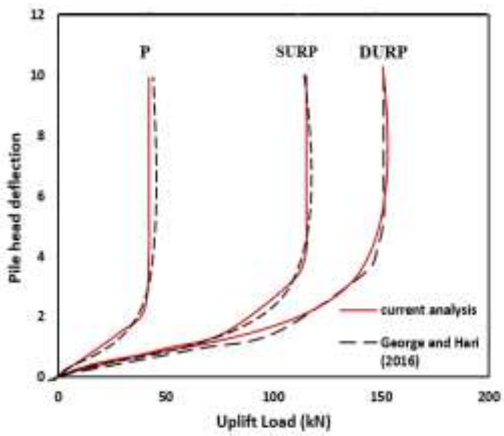


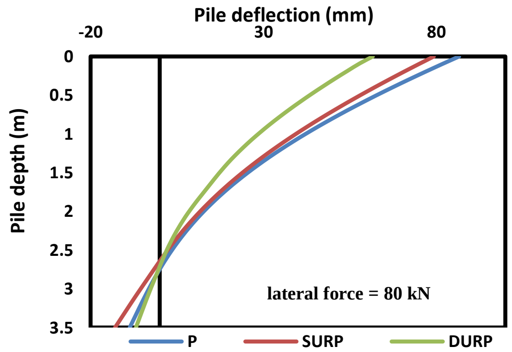
Figure 4. Validation of proposed model with results documented by George and Hari [15]

5. RESULTS AND DISCUSSIONS

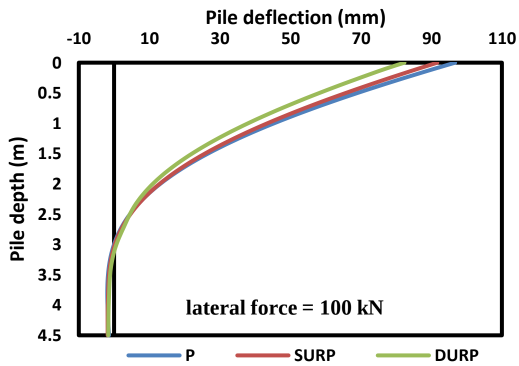
A series of 3-D FE models were used to study the behavior of under-reamed piles with single and double bulbs. Three cases of loading were considered in this analysis, pure lateral loads, pure uplift loads, and combined uplift and lateral loads. In this study, pile (L/D) ratios of 11.66, 15, 20, and 25 were investigated. The findings for different loading cases are summarized as follows:

5. 1. Behavior of Piles Subjected to Lateral Load

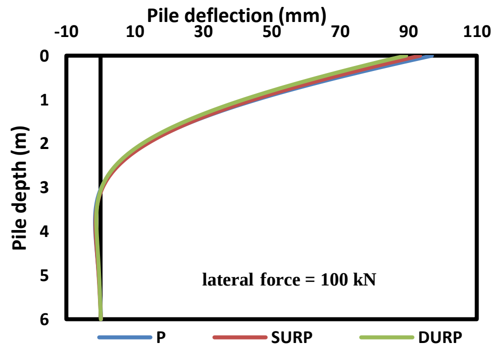
Figure 5(a-d) shows the computed lateral deflection along the pile depth for SURP and DURP compared with straight piles (P) for pile ratios of 11.66, 15, 20, and 25. From Figure 5, it can be concluded that piles 4.5 m, 6 m, and 7.5 m in length behave as flexible piles according to the shape of pile deflection. At the initial depth, the pile deflection is large; at a depth of approximately 3 m, the



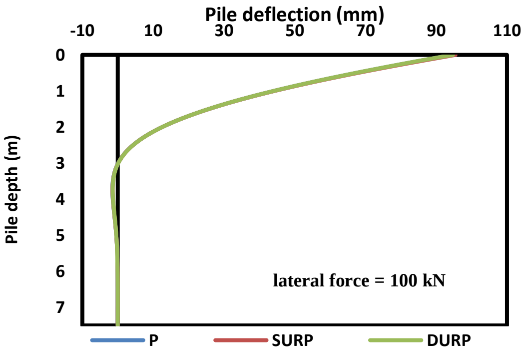
a. L/D = 11.66



b. L/D = 15



c. L/D = 20



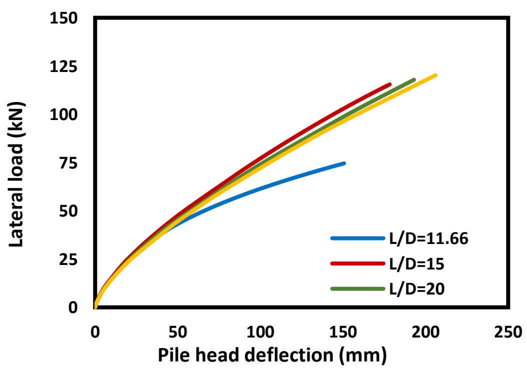
d. L/D = 25

Figure 5. Lateral deflection along the piles

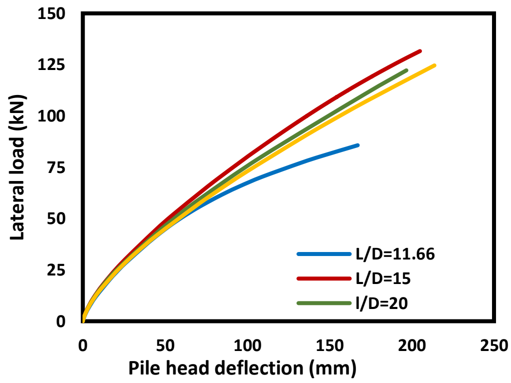
deflection is nearly zero. In addition, the piles do not rotate around a point.

For 3.5 m piles, there is rotation around a point at a depth of approximately 2.7 m, indicating rigid behavior. For shorter piles (L/D =11.66, 15) under a certain lateral force, under-reamed piles noticeably reduced the pile deflection. For longer piles (L/D = 20, 25), no change in lateral pile resistance was observed using under-reamed piles with single or double bulbs.

Figures 6(a) and 6(b) show the lateral load-deflection curves for single and double under-reamed piles with different (L/D) pile ratios subjected to pure lateral loads. It is observed that the lateral resistance of under-reamed piles with single and double bulbs increases considerably as the (L/D) pile ratio increases to 15. Further increasing of (L/D) ratio decreases the lateral resistance. This may be because initially, as the pile length increases, the passive pressure also increases. Howevere, decreasing the lateral resistance with increasing pile length (L/D > 15) may be because “the soil resistance mobilized along the effective pile length and the ultimate moment of pile material governed the capacity of the long flexible piles” [21]. Figures 7(a) and 7(b) show viewport clarify the lateral displacement for short and long DURP.



a. SURP

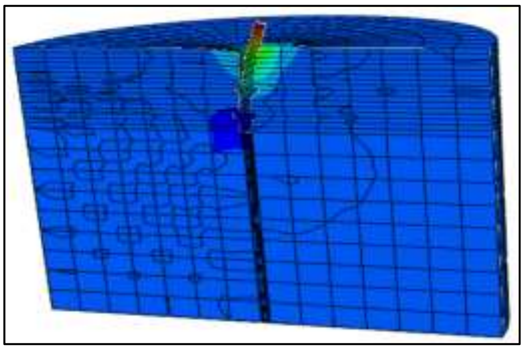


b. DURP

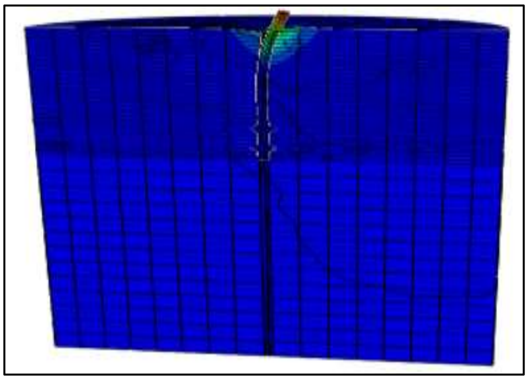
Figure 6. Distribution of lateral load vs. pile head deflection for different L/D ratios

5. 2. Behavior of Piles Subjected to Uplift Load

The behavior of P, SURP, and DURP subjected to pure uplift loads was examined. The variation of uplift load vs. pile head deflection for P, SURP, and DURP with different (L/D) pile ratios is shown in Figure 8 (a-d). As expected, the uplift pile capacity is greatly improved for SURP and DURP compared with a straight pile for all (L/D) pile ratios.

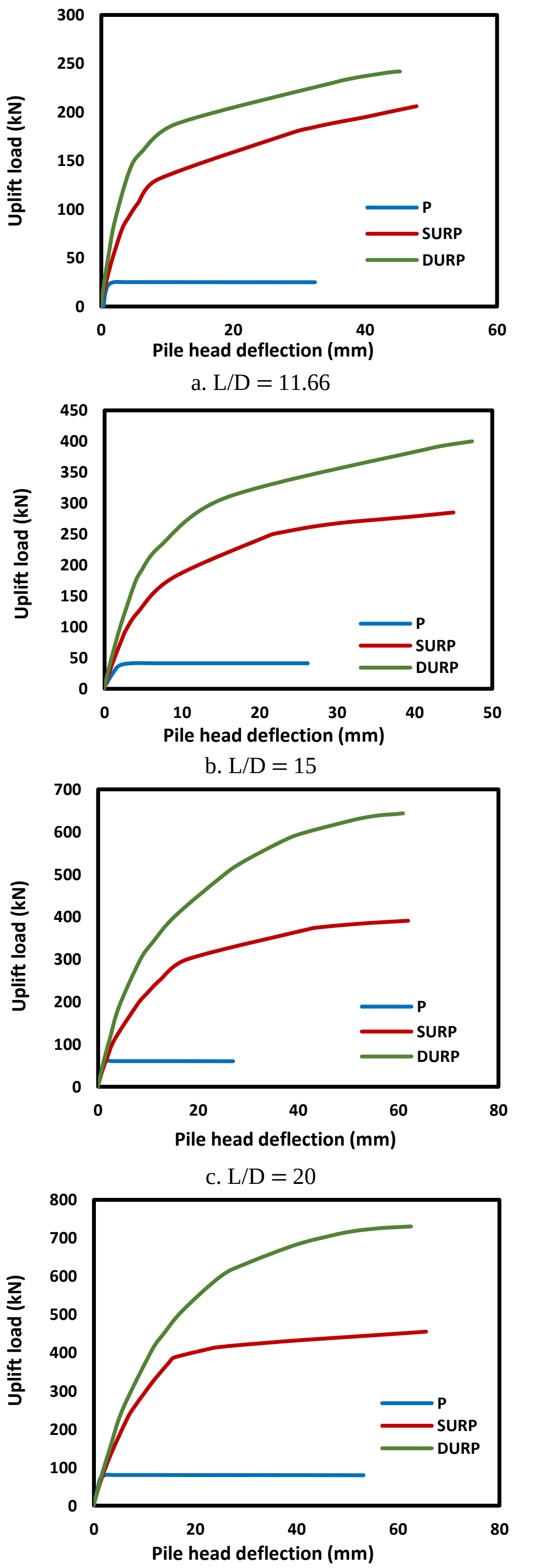


a. L/D=11.66



b. L/D=25

Figure 7. lateral displacement for DURP. (This viewport was magnified five times)



a. L/D = 11.66

b. L/D = 15

c. L/D = 20

d. L/D = 25

Figure 8. Distribution of uplift load vs. pile head deflection for P, SURP, and DURP

Table 5 presents the ultimate uplift capacity for P, SURP, and DURP for (L/D) pile ratios of 11.66, 15, 20, and 25. The double tangent method suggested by Shanker et al. [22] was used for interpreting the ultimate uplift pile capacity.The ultimate uplift capacity for SURP increased by a factor of (3.8, 4.24, 4.33, and 4.38) from the ultimate uplift capacity of the corresponding P pile, for (L/D) pile ratios of (11.66, 15, 20, and 25), respectively. The ultimate uplift capacity for DURP increased by a factor of (5.8, 6.07, 6.25, and 6.43) for (L/D) pile ratios of (11.66, 15, 20, and 25), respectively.

It is also observed from Table 5 that the ultimate uplift capacity increases significantly with increasing the (L/D) ratio. In addition, for a specific (L/D) pile ratio, there is an improvement in the ultimate uplift capacity of the DURP from that of the SURP.

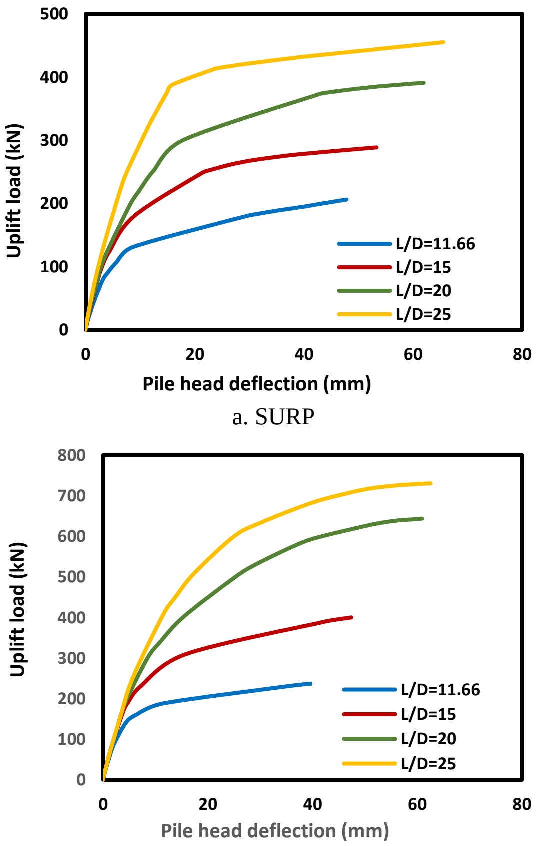
Figures 9(a) and 9(b) show the influence of the (L/D) pile ratio on the uplift pile capacity; the uplift pile capacity increases considerably with increasing (L/D) ratio for SURP and DURP.

5. 3. Behavior of Piles Subjected to Combined Uplift and Lateral Loads

To investigate the effect of an uplift load on the lateral response of the SURP and DURP, the loading was applied in two steps. First, the pre-quantified uplift load was subjected to the pile head, which is represented in this study as the uplift load prior to lateral load (UPL). Second , the uplift load from the first step was maintained, and the lateral load was added. The lateral load was applied using displacement control; the displacement was specified as 0.5D. Uplift loads (here, UPLs) were chosen as a percentage of the previously evaluated ultimate uplift capacity (V_{ult}). The

TABLE 5. Ultimate uplift pile capacity of P, SURP, and DURP for different (L/D) ratios

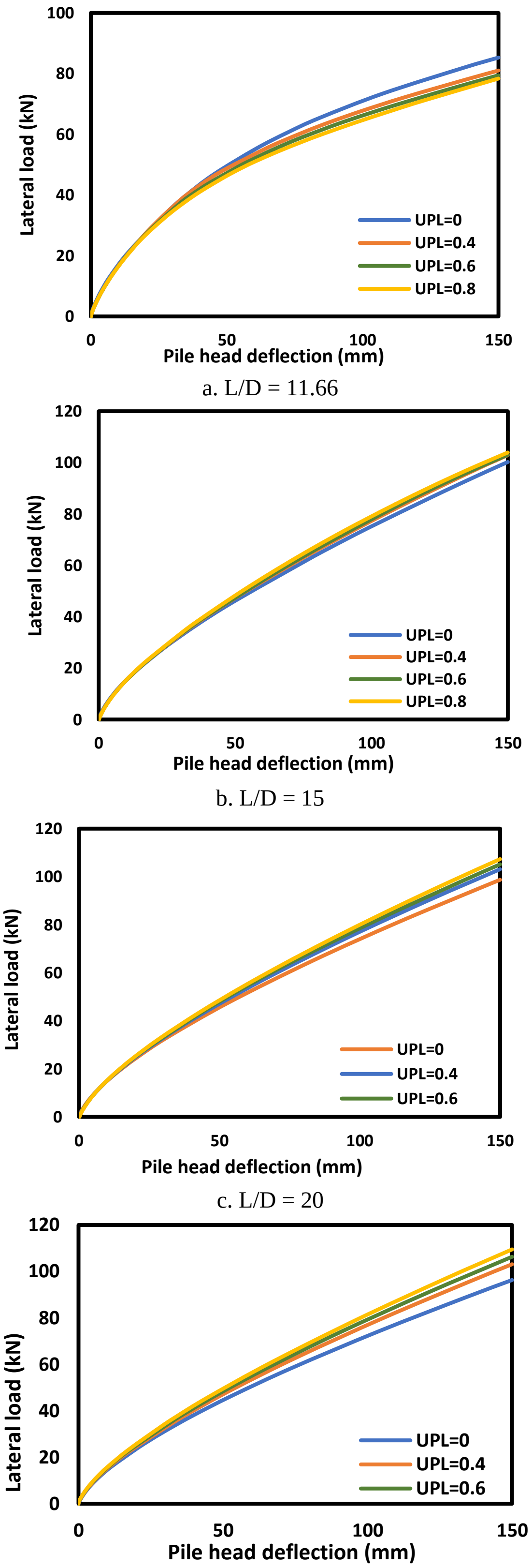
L/D	Pile type	Ultimate uplift pile capacity	Increase factor
	P	25	
11.66	SURP	120	3.8
	DURP	170	5.8
	P	41	
15	SURP	215	4.24
	DURP	290	6.07
	P	60	
20	SURP	320	4.33
	DURP	435	6.25
	P	78	
25	SURP	420	4.38
	DURP	580	6.43



a. SURP

b. DURP.

Figure 9. Influence of L/D ratio on the uplift pile capacity



a. L/D = 11.66

b. L/D = 15

c. L/D = 20

d. L/D = 25

Figure 10. Distribution of lateral load vs. pile head deflection under pre-uplift load for SURP

uplift load was chosen as (UPL = 0, 0.4 V_{ult}, 0.6 V_{ult}, and 0.8 V_{ult}).

The lateral load vs. pile head deflection for SURP and DURP subjected to combined uplift and lateral loads is shown in Figure 10 (a–d). Due to the similarity in the response of SURP and DURP, only SURP is shown. When the lateral load is extremely low, the lateral load–pile head deflection response is not significantly influenced by the pre-uplift load. It is clear from the figures that the load–deflection response is still nonlinear, even with UPL.

It is also observed that the influence of (UPL = 0.4, 0.6, and 0.8_{ult}) on the lateral pile capacity depends on the embedment pile ratio. For an under-reamed pile with a (L/D) pile ratio of 11.66, the lateral pile capacity decreases with the UPL. For under-reamed piles with a (L/D) pile ratio of 15, uplift loading has no significant effect on the lateral pile capacity. However, for under-reamed piles with embedment pile ratios of 20 and 25, the lateral capacity increases marginally with increasing UPL. It can be concluded that the UPL reduces the lateral capacity of rigid Under-reamed piles and increases the lateral capacity of flexible under-reamed piles.

6. CONCLUSIONS

In this study, a numerical analysis for a straight pile (P) and under-reamed piles with a single bulb (SURP) or a double bulb (DURP) was conducted to investigate their response under lateral, uplift, and combined lateral and uplift loads. Based on the results, the following conclusions can be drawn.

1. The lateral resistance was affected slightly by using under-reamed piles with single or double bulbs. P, SURP, and DURP with pile (L/D) ratios greater than 20 had nearly the same lateral resistance.
2. The ultimate uplift capacity for the under-reamed piles (SURP, DURP) was (3.8, 5.8), (4.24, 6.07), (4.33, 6.25), and (4.38, 6.43) times greater than the ultimate uplift capacity for the corresponding P pile, for pile (L/D) ratios of (11.66, 15, 20, and 25), respectively.
3. The lateral load–deflection behavior was nonlinear under both pure and combined loading.
4. For a specific (L/D) pile ratio, there was an improvement in the ultimate uplift capacity of the DURP compared with that of the SURP.
5. The lateral resistance of under-reamed piles with single and double bulbs increased considerably as the (L/D) pile ratio increased up to a certain value, beyond which the lateral resistance decreased.
6. The lateral capacity was marginally influenced by the uplift loading; it decreased for rigid under-reamed piles and increased for flexible under-reamed piles.

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Persian Abstract

چکیده

شمعهای زیر ریم شده با یک یا چند حباب تقریباً در همه انواع خاک برای پشتیبانی از طیف وسیعی از ساختارها به طور گسترده ای استفاده شده است. در بعضی موارد ، شمع ها علاوه بر بارهای فشاری عمودی یا صعودی ، باید در برابر بار جانبی قابل توجهی مقاومت کنند. یک مطالعه ۳-D عنصر محدود با استفاده از نرم افزار ABAQUS برای بررسی رفتار شمعهای تحت اصلاح در خاک رس تحت بارهای جانبی خالص ، صعودی خالص ، و صعودی جانبی و جانبی خالص انجام گردید. در این مطالعه با تنظیم طول شمع برای شبیه سازی رفتار شمع های سفت و سخت و انعطاف پذیر ، نسبت های شمع (L / D) 11/66، ۱۵ ، ۲۰ و ۲۵ در نظر گرفته شد. شمع ها به عنوان ماده الاستیک خطی مدل سازی شدند و رفتار خاک با استفاده از مدل سازنده دراکر-پراگر شبیه سازی شد. یافته ها نشان می دهد که مقاومت جانبی شمع هایی با نسبت (L / D) 11.66 و ۱۵ هنگامی که از شمع های تحت ریم استفاده می شود کمی افزایش می یابد. با این حال ، هیچ تغییری در مقاومت جانبی برای شمعهای تحت ریام با نسبت (L / D) 20 و ۲۵ در مقایسه با شمع های مستقیم مشاهده نشد. ظرفیت صعودی شمعهای زیر ریمینگ به طور قابل توجهی بیشتر از یک شمع مستقیم بود. ظرفیت جانبی تحت تأثیر بارگذاری قبل از بالا بردن تحت تأثیر قرار گرفت ، به طوری که برای یک شمع سفت و سخت تحت ریشه کاهش یافته و برای یک شمع قابل انعطاف تحت ریش افزایش می یابد.