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Experimental Work on the Effect of Under-reamed Pile Geometry on the Pullout Capacity of Sand

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ABSTRACT

This work presents an experimental study that investigates the behavoir of both conventional and under-reamed piles embedded in a single layer of sand with varying relative densities and examines piles in different soil layers, subjected to pullout static monotonic loading. The study focuses on the influence of the spacing ratio between under-reams and the number of bulbs on the pile's ultimate pullout load. A uniform pile stem, a pile with a single bulb, and a pile with twin bulbs were the three varieties of small-scale models of aluminum piles that were utilized. The pile's measurements were 25 mm in shaft diameter by 550 mm in height, with a 62.5 mm bulb diameter. To establish their impact on the uplift capability of an under-reamed pile in sand, the current work examines the location, spacing between bulbs, and the number of bulbs. At 35% relative density, the influence of various bulb spacing ratios S/Du is investigated (S/Du =1.0, S/Du = 1.25, S/Du = 1.5, S/Du = 1.75, and S/Du = 2). The test results revealed that the maximum ultimate pullout capacity is achieved when the bulb spacing ratio is S/Du =1.5. The pullout capacity increases 3.5 times for a single bulb and 7 times for a double bulb compared with a straight pile under the same condition, as well as an under-reamed pile in a dense or medium sand layer overlain by loose sand rises to a peak before capacity declines. Load-displacement curves and initial stiffness improve compared to homogeneous, loose, sandy soil.

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1. INTRODUCTION

The under-reamed piles are enlarged piles constructed insitu with single or more bulbs around a pile shaft to resist compressive loading, uplift loading, and ground movement. They are a type of deep foundation for different structures, such as offshore platforms, multi-story buildings, and transmission towers. Das and Shin [1], Khatri et al. [2] explained that belled pile are very promising in terms of tensile load resistance and suited for soil that experiences ground movements as a result of seasonal moisture variation.These piles had been introduced first in India for use in expansive soil, which is classified as problematic soil. Soil layers and pile dimensions greatly affect the load capacity of an under-reamed pile. Hassan [3] reported that under-reamed piles are considered a good foundation technique due to being the safest and most economical foundation. Patra et al. [4] evaluated experimentally and discovered that the maximum uplift load capacity for medium-dense (DR = 52%) over dense conditions (DR = 80%) was greater than for dense conditions overlaid on medium-dense conditions. Liu et al. [5] concluded that the uplifted movement of the belled pile decreases when the uplift loading is increased to its maximum. Bose and Krishnan [6] demonstrated that for a given displacement, the pile resistance to pullout load increases with surface finishes ranging from smooth to rough. In addition, when the slenderness ratio increases, the pile resistance at any axial displacement increases exponentially. Nazir et al. [7] demonstrated that the embedment ratio (L/D) has a main consequence on the support of any increasing pullout load, and increases in the angle of the base and stem diameter result in a slightly reduced failure displacement and net uplift capacity. Harris et al. [8] studied experimentally the effects of varying the under-reamed

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angle, θ (20°, 30°, 40°, 60°, and 75°), on uplift capacity and load-deformation curves. The results showed that the capacity drops off when the bulb angle of the under-ream pile is increased, which is especially apparent at an angle of 75°. Christopher and Gopinath [9] showed that when the space between two bulbs was increased up to 150 mm, an increase in pile capacity occurred. The improvement in load-carrying capacity becomes smaller as the spacing increases. Moayedi and Mosallanezhad [10] indicated that the pullout resistance increases by more than 60% when the under-reams is positioned at the base of the pile and reduces by around 4% when it is installed at a depth corresponding to 33% of the pile's length. Schafer and Madabhushi [11] made a study to clarify the impact of different layers of soil, and they concluded that the uplift capacity gradually rises, and the installation of a lower layer of dense sand under a higher layer of loose sand improves an under-reamed pile foundation's peak uplift capability but has no influence on the displacement necessary to achieve this peak. Substituting clay for the overlying loose sand layer can raise the uplift even more. Nasr et al. [12] showed that the uplift capability of a belled base piles installed in sandy soil with various unit wieghts increases when the ratio of embedment length to base diameter (L/D_b) rises. Sakr et al. [13] and Sakr et al. [14] performed an experimental study to clarify the influence of under-reamed pile factors such as position, spacing between bulbs, and bulb numbers on the pullout loading. They noticed that the pile pullout load increased with increasing under-ream diameter, number of bulbs, and relative density. Alhassani [15] conducted numerical research using the ABAQUS program to explore the behaviour of the under-reamed pile undr the pullout, lateral, and compression loads. The results of the testing models revealed that the uplift pile capacity of SURP and DURP is much greater than that of a straight pile for all L/D pile ratios. Al-Tememy et al. [16] used PLAXIS-3D software to examine a model of the steel pipe pile installed in dry sand. Based on the outcomes, the relative density of the sand has an influence on the peak resistance pullout load of vertical piles. When the relative density of sand improves from 40% to 60%, the ultimate pullout load of a vertical pile increases by around 35%–56%. Goudar and Kamatagi [17] tested the influence of two distinct geometries of aluminum model pile groups, L/D ratios, and S/D spacing ratios. The investigation employed uniform pile section and enlarged base (Belled) piles embedded in locally accessible sandy soil. It was discovered that the load-carrying capability of a belled model pile increases at a greater L/D ratio. However, the extension angle enhanced the load-carrying capacity by 40% over straight piles. Furthermore, (S/D) exhibits large variability in bearing capability.

Under-reamed piles are used to enhance the performance and stability of foundations in weak soil conditions, control settlement, improve lateral, uplift stability, and provide a cost-effective solution for constructing buildings and structures on challenging soil types. Experimental findings can contribute to the development of improved construction techniques for under-reamed piles. By understanding the behavior of these piles under uplift loads, researchers can suggest optimized installation procedures, reducing construction costs and potential issues during installation. Finally, the conventional pile used to estimate the improvement of adding one or double bulbs to the uniform pile shaft.

There are a lack of comprehensive experimental studies specifically focused on the behavior of under-reamed piles subjected to pullout loads. This could result in a scarcity of data regarding factors such as load-displacement behavior, failure mechanisms, and load transfer characteristics and The interaction between the under-reamed pile and different types of soil, including cohesionless and different soil strata, may not be fully understood. The influence of various soil properties, such as shear strength, soil density on the pullout behavior of under-reamed piles may require further investigation

So, this research shed light on the behavior of load-displacement curve of under-reamed piles, both single and double bulb configurations, improves compared to straight piles when embedded in loose, medium, and dense sandy soil. On other hand, the investigation studies the performance of piles in different soil layers and its effect on the load- displacement curves when subjected to pullout load. Furthermore, an experimental work was conducted in the current study to evalute the effect of under-reamed pile’s geometry (the distance between bulbs and the number of bulbs) on the uplift resistance load with varying relative densities of dry sand.

2. METHODOLOGY

2. 1. Soil Properties Sand soil used is classified as (SP) poorly graded according to the USCS. Various tests are made on this sand per ASTM specifications to obtain its properties (physical and mechanical), as shown in Table 1. Three states of relative density were used to achieve the goal of the study (the loose, medium, and dense states).

2. 2. Pile Model Three small-scale models of aluminum piles used of length 550 mm in length were used, with a bulb diameter of 62.5 mm for a 25 mm pile diameter. Three pile shapes were adopted in this study: the stright pile and multi under-reamed piles (single bulb and two bulbs) with different vertical spacings between bulbs. The design of the under-reamed pile and under-reams was carefully chosen per the Indian Code (IS 2911) specification [18]. Table 2 depicts the pile model properties used in the study, and Figure 1 depicts its shape.

TABLE 1. Soil used properties

Property	Value	Specification
Maximum unit weight kN/m^3	17.1	ASTM D 4253
Minimum unit weight kN/m^3	14.88	ASTM D 4254
Effective Size,		
D_{30}	0.12	ASTM D 422 and ASTM D 2487
D_{10}	0.195	
D_{60}	0.28	
Friction angle at 35% R_D (γ_{used}=15.6) kN/m^3	30°	
Friction angle at 55% R_D (γ_{used}=16.0) kN/m^3	35°	ASTM D 3080
Friction angle at 75% R_D (γ_{used}=16.5) kN/m^3	39°	

TABLE 2. Model piles used

Description	Notation	Dimension
Pile length, mm	L	550
Pile diameter, mm	D	25
Under-reames diameter, mm	D_u/Dp=2.5	62.5
Bulb spacing ratio C-C (S/D_u)	$1D_U$	62.5
	$1.25D_U$	78
	$1.5D_U$	93
	$1.75D_U$	109
	$2D_U$	125
Upper angle of under-reams pile, degree	Ø1	45
Lower angle of under-reames pile, degree	Ø2	45

(a) (b) (c)

Figure 1. Pile geometries considered, a. conventional pile, single and double under-reamed piles, b. bulb spacing c-c, c. under-reamed geometries

2. 3. Pile Model Preparation and Testing To prepare the soil bed, a steel container measuring (650 mm× 650 mm× 750 mm) was used, and to avoid the effect of lateral fraction, a rubber layer was applied to the inner faces of the container. The soil was poured into the container and tamped to the desired density; after that, the pile model was put precisely in its location during the soil preparation (see Figure 2).

A strain-controlled pullout system was used with a 0.25 mm/min sustained rate until the displacement reached 30 mm. In addition, all the pile model tests were carried out at a static monotonic load; as it has been reported by Qian et al. [19].

3. RESULTS AND DISCUSSION

Outcomes of effectiveness of relative density, number of bulbs, and bulb spacing ratio on the ultimate pullout capacities and their discussions are described below. Schafer and Madabhushi [11], the ultimate capacity was determined according to the clear breakpoint (maximum uplift load before failure).Vali et al. [20] and Kumar et al. [21] used the double tangent technique to evaluated the ultimate pullout carying capacity. It was discovered that the outcomes were 99 percent similar between the two methods.

3. 1. Influence of Relative Density Figures 3, 4, and 5 depict the pullout load-displacement relation for the conventional pile, and the one and two under-reamed piles, respectively. All figures show that the pull-out load increases as the relative density increases to some limiting values, after which the value becomes nearly constant and insensitive to the change in displacement that continues to increase. This behavior is attributed to the roughness between the soil and the pile skin. The ultimate pullout carrying capacity of the different types of model piles is shown in Table 3.

Table 4 shows the improvement in the pullout load of one and two under-reamed piles in three relative densities compared to a conventional pile. A good enhancement is observed compared to the staright pile was detected.

By evaluating the results for a single pile (P) and after adding one bulb PSUR and two bulbs PDUR, it was

Figure 2. Under-reamed pile test

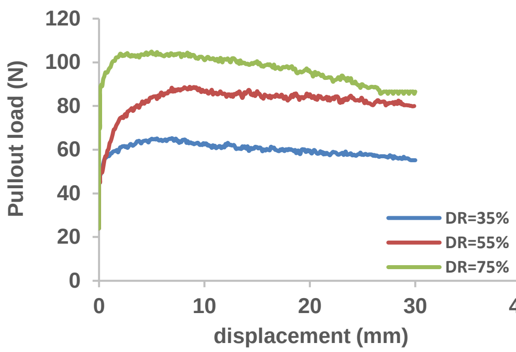

Figure 3. The load-displacement curves for the conventional pile

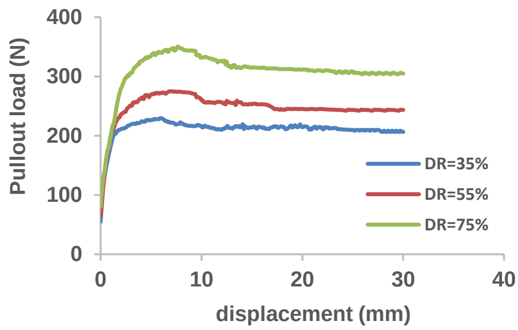

Figure 4. The load-displacement curves for single under-reamed pile

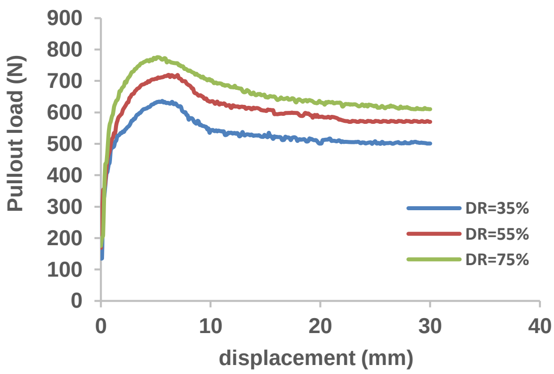

Figure 5. The load-displacement curve for double under-reamed pile

TABLE 3. Pullout load value of the different types of model pile

Relative density (DR%)	Pullout carrying capacity (N)		
	Conventional pile	One under-reamed pile	two under-reamed pile
35%	65	229.7	637
55%	90	275	719
75%	107	350	775

TABLE 4. Uplift loading improvements of one and two under-reamed piles

Soil types	% Degree of Improvement	
	One under-reamed pile	two under-reamed pile
Loose	250 %	800%
Medium	205 %	700%
Dense	227 %	600%

obvious that raising the relative density increased the pullout load and caused a corresponding decrease in the displacement for all types of piles. In all cases, a double under-reamed pile had the higher pullout force than a single under-reamed pile. It indicates that increasing the number of under-reams will improve its pullout capacity. However, this comes at the expense of more concrete being used to make bulbs. Therefore, under-reamed piles perform better when buried in loose, medium-density sand.

3. 2. Influence The Bulb Spacing In order, to study the under-reams spacing ratio S/Du effect, the relative density was kept constant throughout this set of tests. The bulbs were spaced at S/Du = 1.0, S/Du = 1.25, S/Du = 1.5, S/Du = 1.75, and S/Du = 2, where Du is the bulb diameter. Figure 6 shows the load-deformation curves for various spacings between bulbs. The results of the pullout load indicate that the best value was obtained when S/DU = 1.5; below and above this ratio, the pullout load decreases. This behavior is mainly attributed to the load gated from the above bulb and between the two bulbs and its effect on the failure zone. Figure 7 shows the highest value of the ultimate uplift capacity for each experiment conducted by changing the distance between the two bulbs.

3. 3. Influence of the Number of Bulbs Figure 8 shows the results of increasing the number of under-reams to D_u/D_p = 2.5 with various relative densities. It

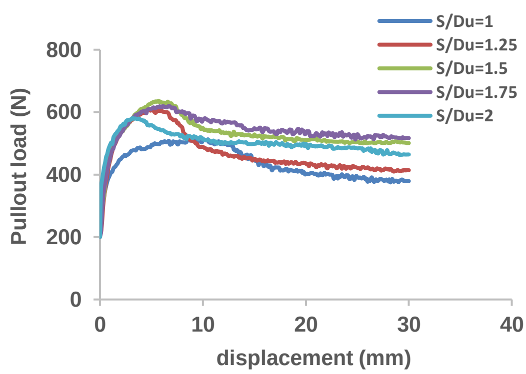

Figure 6. The load-displacement curve of different vertical spacing between the bulbs

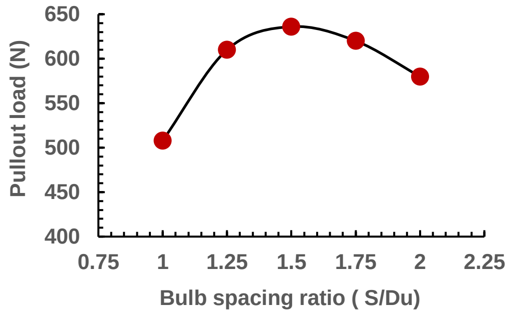

Figure 7. The ultimate pullout capacity with different vertical spacing between the bulbs

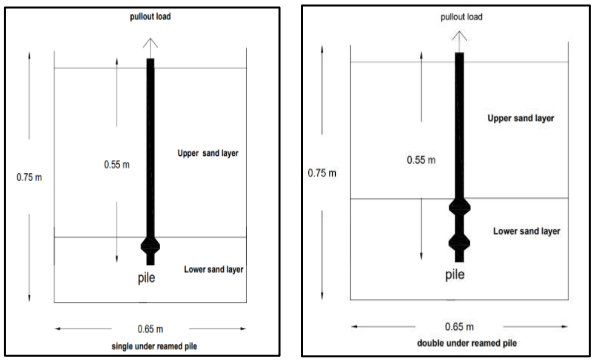

Figure 9. embedded test model

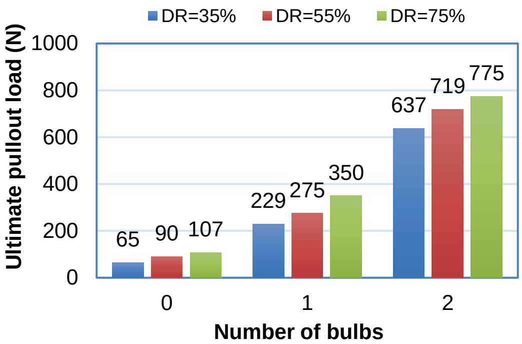

Figure 8. Variation of ultimate pullout load with bulb number

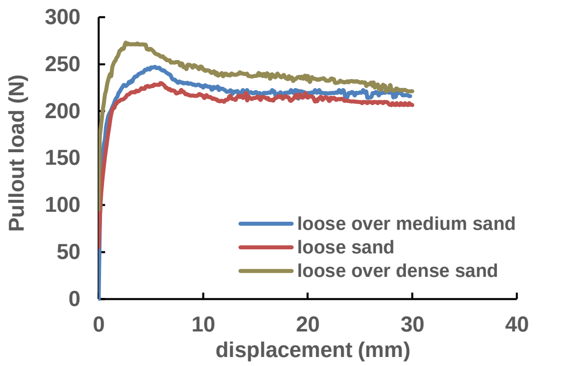

Figure 10. Load -displacement curve of single under-reamed pile

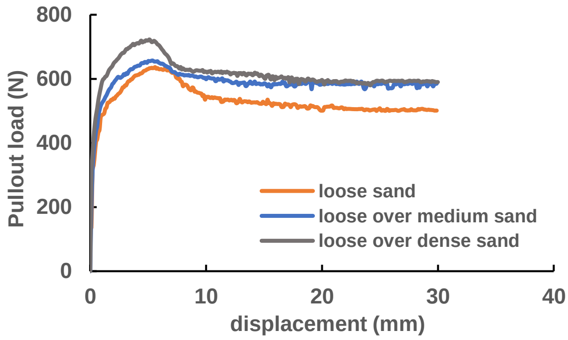

Figure 11. Load -displacement curve of double under-reamed pile

can be noted that the ultimate pullout capacity increases as the number of bulbs increases, which means that increasing the number of bulbs has an important effect on the ultimate pullout load. Also, it can be observed that the increasing number of bulbs is greater when the sand is in a loose state. This behavior is caused by the surrounding soil adhering to the under-ream, which has the advantages of increasing soil strength and reducing deformation.

3. 4. The Behavior of Under-Reamed Piles Under Pullout Loads in Layered Stratum As a result, this study tries to provide a clear image of the under-reamed pile anchored to a two-layers system. Figure 9 shows the problem statement model of (single and double bulbs) in the soil's layers.

Hence, the study could shed light on the load-displacement response of a single and double under-reamed pile embedded in a dense and medium sand layer overlain by loose sand is shown in Figures 10 and 11.

The load-displacement response of an under-reamed pile placed in a dense or medium sand layer overlain by loose sand shows a rise to a peak before a decline in capacity caused by soil arching at large displacements. The overall form of the curve is quite similar to that observed in a homogenous loose sand bed, but the ultimate capacity is substantially higher. This indicates that the bottom dense layer of sand has a significant influence on the peak capacity of the under-reamed pile. The initial stiffness measured at a small strain is slightly higher than that measured in homogenous loose sand. Table 5 illustrated the ultimate pullout loading for the belled pile in layered soil.

A double under-reamed pile will initially show more powerful resistance to pullout load than a single under-reamed pile due to the extra bearing surface and load

TABLE 5. ultimate pullout load for under-reamed pile embedded in soil layered system

Type of soil	Ultimate pullout load (N)	
	Single under-reamed pile	Double under-reamed pile
Medium sand overlined by loose sand	247	657
Dense sand overlined by loose sand	271	720

distribution given by the two under-reams, the load-displacement curve for a double under-reamed pile may demonstrate higher initial stiffness and load-carrying capability. The inclusion of two under-reams can improve load distribution and contribute to a more progressive displacement progression before the peak or ultimate load.

4. CONCLUSIONS

The influence of the number of bulbs and spacing between under-reams in the under-reamed pile was investigated with various relative densities to examine the pullout load of an under-reamed pile subjected to the axial pullout force. Following conclusions result from the study's outcomes:

1. In terms of increasing pullout capacity, under-reamed pile is more advantageous in different relative densities composed of loose and dense.
2. Spacing between bulbs affected on pullout capacity. When spacing is less than 1.25 Du, the pile doesn't work effectively. When spacing between bulbs is 1.25–1.5 Du, the pile and soil work together as one block, which enhances the maximum uplift load. After this value, decrease in the maximum load is very clear.
3. Rate of pullout load for a single under-reamed pile rises from no bulb to one bulb by up to 200%. For double under-reamed piles, where it surpasses 700%, the influence of an increase in the number of bulbs on pullout loads is particularly significant.
4. For a two-under reamed pile, the influence of increasing the number of bulbs on a pullout capacity is more advantageous, but this necessitates using more concrete for bulb formation.
5. In the term of layered soil, load-displacement response of an under-reamed pile placed in a dense or medium sand layer overlain by loose sand shows a rise to a peak before a decline in capacity. In general, there is an improvement in the load-displacement curves and show higher initial stiffness compared with homogeneous loose sandy soil.

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Persian Abstract

چکیده

این کار یک مطالعه تجربی را ارائه می‌کند که به بررسی رفتار شمع‌های معمولی و کم‌پرده‌شده در یک لایه ماسه با تراکم‌های نسبی متفاوت می‌پردازد و شمع‌ها را در لایه‌های مختلف خاک بررسی می‌کند._در معرض بارگذاری یکنواخت ایستا خروجی. این مطالعه بر روی تأثیر نسبت فاصله بین زیرپوش ها و تعداد لامپ ها بر بار خروجی نهایی شمع متمرکز است. یک ساقه شمعی یکنواخت، یک شمع با یک حباب تکی و یک شمع با حباب های دوقلو سه نوع از مدل های کوچک مقیاس شمع های آلومینیومی بودند که مورد استفاده قرار گرفتند. اندازه های شمع ۲۵ میلی متر در قطر شفت در ۵۵۰ میلی متر در ارتفاع، با قطر لامپ ٦٢.۵ میلی متر است. برای تعیین تأثیر آنها بر روی قابلیت بالا بردن یک شمع زیردریایی شده در ماسه، کار فعلی مکان، فاصله بین لامپ ها و تعداد لامپ ها را بررسی می کند. در تراکم نسبی ۳۵ درصد، تأثیر نسبت‌های مختلف فاصله لامپ S/Du بررسی می‌شود (S/Du = 1.0، S/Du = 1.25، S/Du = 1.5، S/Du = 1.75، و S/Du = 2). نتایج آزمایش نشان داد که حداکثر ظرفیت خروجی نهایی زمانی حاصل می شود که نسبت فاصله لامپ S/Du = 1.5 باشد. ظرفیت خروجی ۳.۵ برابر برای یک لامپ تک لامپ و ۷ برابر برای یک لامپ دوبل در مقایسه با یک شمع مستقیم در شرایط مشابه افزایش می‌یابد. و همچنین یک شمع کم‌آرام‌شده در یک لایه ماسه متراکم یا متوسط که با ماسه شل پوشیده شده است، قبل از کاهش ظرفیت به اوج می‌رسد. منحنی های بار–جابجایی و سفتی اولیه در مقایسه با خاک همگن، سست و شنی بهبود می یابند