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An Experimental Evaluation of Axial Load Bearing Capacity of Belled and Straight Piles Embedded in Sand

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ABSTRACT

This paper presents the laboratory axial load test results of two different geometries of model aluminum pile groups, such as equal section piles, and enlarged base (Belled) piles embedded in locally available river sand. For belled piles, the enlarged diameter is achieved by providing a 3-degree outer extension angle at the middle of equal section piles to all three L/D ratios. The load versus settlement tests are carried out on 1X1 and 1X2 of both pile groups having a length to diameter ratios (L/D) of 12, 17, and 22. The spacing to diameter (S/D) of 3, 4, and 5 times of D and 3, 4, and 5 times of D_b. (Where D is 31mm equal section outer diameter of model pile and D_b is 46.7mm enlarged base diameter of belled pile respectively). To avoid overlapping stress zone at bottom of piles during application of load. All the tests are conducted in a brick masonry testing tank of 1X1X1m. The vertical load is applied on a single pile and group of both piles by using a 30kN capacity of hydraulic inverted jack, run by a 1HP single phase motor. The load-bearing capacity is evaluated and a comparison is made between straight piles and belled piles. It is observed that the load-carrying capacity is higher in a belled model pile at a lesser L/D ratio. However, the load-carrying capacity increased 40% higher than straight piles, because of the extension angle. In addition, (S/D) and (S/D_b) make significant variations in bearing capacity.

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1. INTRODUCTION

1. 1. General The most common foundations in coastal areas offshore, and waterlogged areas are pile foundations. These foundations are quite commonly subjected to lateral loads and vertical loads, the failure of these foundations is usually due to earthquakes, wind force, and some of the unexpected major impacts from the nature. Often deep foundations are constructed in groups to withstand the structure and the behavior of these groups of piles differs considerably comparing to single piles. However, in the case long piles (Flexible piles) are required to construct deeper in the ground, which requires more usages of concrete as compared to short piles (Rigid piles). Sandy soil, saturated soil deposit and marine clay supporting deep foundations under lateral and vertical loading shows deterioration in rigidity and decreases in shear strength. The problems under such loadings on piles in these soils are formation of gap at pile soil interface, and it develop the pore pressure and retreat of soft soils, causes the measurable deformations and greater bending moments than uniform loading. However, most of the researchers have investigated pile foundations in groups of piles as well as single piles under vertical and lateral loading conditions but a few kinds of literature are reported on the effect of increasing the L/D ratio and most common failures. In this present study, attempts are made to analyze the effect of the L/D (12, 17, and 22) ratio in equal section piles and partially tapered belled piles under vertical load with evaluating critical S/D ratio in both geometry of piles.When the flexible piles are under vertical load the pile resists load through pile-soil interaction and base the resistance. However, when the

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load is acting with some inclination, it is the reason for the decrease in resistance offered by the pile foundations, because of deficiency in the base resistance and the shaft friction.

2. LITERATURE REVIEW

Previous investigations stated that increasing the embedment ratio can increase the load-carrying capacity by creating friction on the surrounding soil and pile surface [1]. Harris and Madabhushi [2] investigated the effect of changing the angle of the under-reamed bulbs on pullout and load-displacement curve in three-dimensional models by varying density of dry sand. They concluded that there is a measurable impact on uplift capacity by varying angles of the under-reamed bulb and it also depends on the state of sand deposit around the pile surface. Arabpanahan et al. [3] have studied and examined the behavioral aspects of five strip foundations keeping width constant and varying the embedment depth in loose sandy soil under vertical loading. They have concluded that increasing the depth to width ratio from 0 to 1.2 causes an increase in load-carrying capacity and axial stiffness for 33 and 23% respectively. The investigations on displacement behavior of belled piles are relatively very less. These piles are having more vertical bearing capacity, due to providing a large bottom surface. Rahman et al. [4]. studied on single and group piles with various L/d ratios and maintaining pile material as same, that is aluminum pile having a hollow tube of 19 mm outside diameter and 0.81 mm wall thickness which was used and the outer diameter was 20 mm with L/d ratio of 20, 30, and 35. The lateral load resistance of a single L/d ratio is 32, and different S/D ratios as 6D and 3D. Khari et al. [5], the model pile group configurations such as 1X2, 1X3, 2X2, 3X3, and 3X2 were selected in two different relative densities of sand. In addition, the pile cap made up of steel plate having a thickness of 0.64 cm was used. For all configurations such as the 1X2 and 2X2 pile groups, in the experimental setup, the model tank of dimension 1x1x1m was used**.** They have concluded that the difference in lateral displacement increased when the relative density increased from 30 to 75% under the same loading condition. Pile to pile interaction is very minimum in 6d ratio in dense sand but sometimes it may be more in a loose state. Soil medium as sand was poured at a height of 0.5 meters into the tank and maintained uniform density, thereafter the lateral load was applied by pulley arrangement with flexible wire attached to the pile cap. Displacements were measured by sensitive dial gauges having a 0.01 mm least count. In the test, one a single pile was tested with L/D ratios of 20, 30, and 35 and obtained the test results as 107N, 196N, and 225N, respectively. As the L/D ratio increases the lateral load, carrying capacity increases in a single pile. In test two having a 2X2 pile group and L/D ratio was kept as constant as 20, but varying S/D ratios as 3d, 4.5d and 6d. The obtained values were 166N, 196N and 225N, respectively. In the third test having a 2X1 pile group again, L/D was kept constant at 20 and S/D as 3d, 4.5d, and 6d the obtained values were 117.2N, 147N, and 166N, respectively. All these test results are compared with theoretical values suggested by and got almost same values. In the 2X2-pile group, the S/D ratio of 3 is 41.63% greater than the 1X2 pile group of S/D of 3. In the 2X2-pile group, the S/D ratio of 4.5 is 33.33% greater than the 1X2-pile group of S/D of 6. In the 2X2-pile group, the S/D ratio of 6 is 35.3% greater than the 1X2 pile group of S/D of 6. Finally, it is observed that the length to diameter ratio takes a major role in increasing the lateral capacity of the single pile and pile group. This investigation helps to study about L/D ratio and S/D ratio. The gap in the research work is the relative density of sand when the cohesive less soil is considered as a soil medium, the relative density takes a major role in the results. On the other hand, the pore water pressure also makes a significant difference in the loading mechanism. Issac and Thomas [6] In this paper the behavior of single model steel and concrete piles subjected to changing inclination loads to failure in cohesion-less soil was investigated. Under various inclination loads, experimental results of the ultimate vertical load-bearing capacity and lateral load-carrying capacity of piles immersed in the sand were plotted. They concluded that the axial load and the lateral capacity of the pile increase with the increase in L/D ratios [7-11]. The circular deep foundations are evaluvated in series of 3D numerical analyses on pile raft pile length, spacing, and pile configurations inorder to evaluate the numerical modeling results of previous investigators. They conclued that soft soil, dense soil, pile spacing, and length of pile are the main parameters used to reduce the settlement and increas in pile contribution ratio. This could be due to an increase in passive resistance with the increase in pile length. Constructing more numbers of piles to increse the performance of foundation sutaible only limited to optimum level further incresing leads to no additinoal benefits in beasring capacities. During the installation of mini pile the excess pore water pressure increase in satureated soil mass around the surface of clay. The excess pore water pressure decreases by increasing over consolidation ratio during installation of mini piles. The axial load capacities of concrete piles are found to be more than that of steel piles. Whereas lateral load capacities of steel piles were found to be more than that of concrete piles furthermore, thousands of researches are completed on the experimental side and theoretical side to examine the loading mechanism and the reason for the failure of deep foundations.

However, very least research was conducted, by considering combined loading with saturated conditions of soil medium to understand the failure mechanism of single and group of piles. These ample literatures are mainly focused on experimental and theoretical investigations of vertically and laterally loaded flexible piles. A few studies were found on belled piles in order to increase the bearing capacity in weak soil. In this present study, trials were made to increase the load-carrying capacity by providing a minimum extension angle at the bottom of the pile. This can be the main reason to reduce the consumption of concrete and avoid the failure of long (flexible piles).

3. MATERIALS AND EXPERIMENTAL SETUP

3. 1. Model Piles

The model pile materials and dimensions selected to adhere to similitude laws. Wood et al. [12] and Chandrasekaran et al. [13] proposed the scaling law, based on their scaling laws, and the reference, the dimensions are selected for experimental investigation in the present study. The following flexural rigidity equation used to calculate the field pile parameters.

$$\frac{\text{Em Im}}{Ep\ Ip} = \frac{1}{n^5}$$

where, E_m = modulus of elasticity of model pile, E_p = modulus of elasticity of prototype pile, I_m = moment of inertia of model pile, I_p= moment of inertia of prototype pile and 1/n = scale factor for length.1/10 is fixed as scaling factor for length and $1/10^5$ is adopted as pile flexural rigidity. Aluminum 3mm gauge hollow tube of outer diameter 31mm and inner diameter is 25mm selected as model piles to ensure the prototype pile of 550mm diameter of solid section made-up of reinforced cement concrete having the compressive strength of 25N/mm^2 (M25 grade). Figure 1 shows the prototype piles used for tests.

The length to diameter ratio selected as 12, 17, and 22 to avoid boundary effects and stressed zone in the testing tank. In the present investigation, the model piles are design in order to reduce material consumption during the construction of pile foundations. Generally, the equal section piles (uniform diameter piles) have diameters of 1m, 1.5m, 2m, and 2.5m also with varying lengths of piles in large-scale construction activities. This uniform diameter of piles can consume large-scale concrete material and more space and it can lead to increase in project cost. In order to reduce the material consumption, space, and cost to achieve a higher ultimate bearing capacity a small 3 outer extension angle is adopt at the middle of the equal section piles, it enlarges the pile base diameter. During large-scale constructions, in the low bearing capacity of soils, the enlarged base diameter piles are most suited. In such conditions simply increasing, the length leads to a decrease in the performance of equal section piles. The load versus settlement behavior is observe in three different lengths to diameter ratios and three spacing to diameter ratios are investigated in both straight and belled piles. To ensure the rigidity in the pile cap the mild steel plates having a thickness of 20mm used as pile caps. The threads are provided at all piles top and the same pitch screws are made in pile cap up to 10mm deep, by screwing piles into the pile cap fixity condition is achieved.

Figure 1. Prototype aluminum pile

3. 2. Sand

The locally available river sand is used for experiments. Initially, the sand was in wet condition so it completely air-dried and kept in an open atmosphere to ensure complete dry condition. It is

TABLE 1. Model pile parameters

D_s	Alpha (α^0)	(L/D)	D_b (mm)	S/D	Remark
31	3^0	12	46.7	3 4 5	Belled Pile
		17	53.3	3 4 5	
		22	59.8	3 4 5	
31	0^0	12	31	3 4 5	Straight piles
		17	31	3 4 5	
		22	31	3 4 5	

For belled pile, D_b is used, and for straight pile, D is used. α is extension angle, D_b is base diameter and D is outer diameter of equal section pile.

sieved from 600 microns IS sieve to maintain homogeneity, the basic properties of sand were carried out according to IS 2720 (Part 4)-1985 [14] represented in Table 2. Based on the sieve analysis test, the sand is classified as poorly graded sand (SP). Figure 2 shows the particle size distribution curve. The sand bed is prepared by rainfall technique, several trials are made at the laboratory to attain medium dense state, and it is achieved at height of fall of 70cm from the base. In addition, the relative density measured 39.5% at medium dense sand.

3. 3. Test Setup and Procedure The line diagram experimental setup used for axial compression load tests on pile groups is shown in Figure 3. The tests are conducted on prototype piles embedded in sand bed prepared in testing tank build up with brick masonry having dimensions of 1x1x1meters (LxBxH) to ensure there is no boundary effect. The load applied on the pile cap, made up of mild steel having a thickness of 20mm, the piles placed in the testing tank with respect to the center of gravity (CG) of the testing tank and pile cap. A 70% of the tank is filled with sand at the calculated

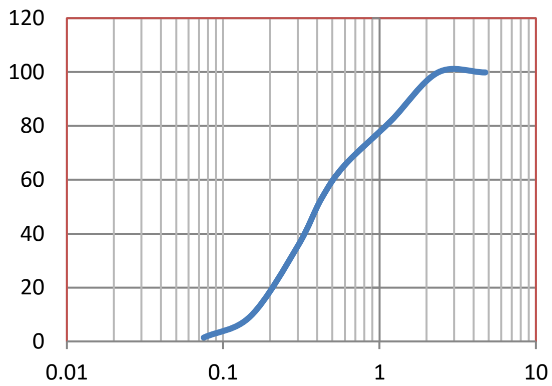

Figure 2. Shows particle size distribution curve

TABLE 2. Physical Properties of Sand

Parameter	Symbol and Unit	Values
Specific gravity	-	2.64
Coefficient curvature	C_c	1.02
Uniformity coefficient	C_u	3.25
Maximum dry density	gr/cm^3	1.81
Minimum dry density	gr/cm^3	1.466
Maximum void ratio (e_{max})	-	0.96
Minimum void ratio (e_{min})	-	0.46
Relative density	%	39.5
Classification	-	SP

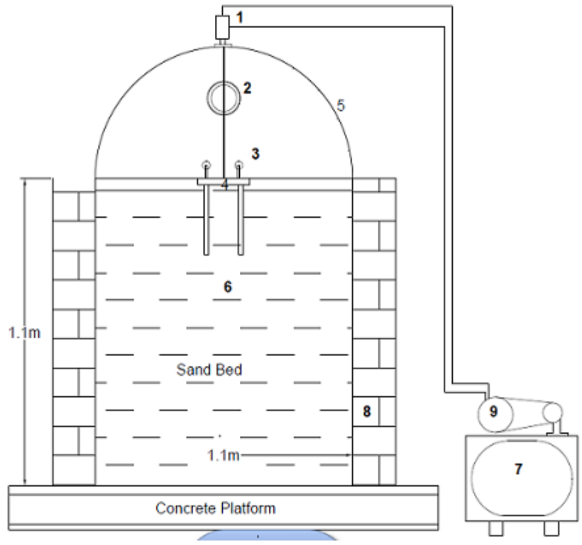

Figure 3. The systematic loading setup line diagram

height of fall then piles are carefully placed in a tank and continued sand bed preparation until the top surface of the tank. However, the loading frame designed and constructed in a laboratory, the 10mm thick solid mild steel having a width of 3cm is fixed an arch-shape, which is connected to two parallel "L" shaped angles fixed in the testing tank. Additional care is taken to minimize any deflections during the application of loads to the pile groups. The model piles are fixed to the pile cap by providing the thread system at the top of the pile and respective threads are made in the pile cap at depth of 10mm to ensure rigidity. The load application procedure is as follows, the 30kN capacity of the inverted hydraulic jack is fixed at the center of the arch-type of loading frame and the 1HP single-phase motor is used to operate the jack. The rate of the load is maintained at 1.25mm/min and for every 30-second interval, the dial gauge readings and 30kN capacity of proving ring readings are measured.

3. 4. Pile Spacing The group effect is compared between single piles and groups of both belled piles and straight piles. The three different spacing to diameter (S/d) is adopted as 3D, 4D, and 5D. Where D is the outer diameter of 31mm for equal

TABLE 3. Description of loading setup

SL No.	Description	
1	Inverted Hydraulic jack	6. Sand Bed
2	Proving ring	7. 1 Hp Single Phase Mortar
3	Dail Gauge	8. Brick Masonry
4	Pile Cap	9. Oil Tank
5	M.S.Steel Section	

section piles. For belled piles, the S/D ratio is maintained as the same parameters but where D_b is enlarged base diameters 46.7mm to avoid the stress zone in between the pile group. Figure 4. Shows configuration of pile groups Khari et al. [5] they have investigated on twelve model pile groups under monotonic lateral loading. The pile groups configurations as 1 X 2, 1 X 3, 2 X 2, 3 X 3, and 3 X 2 and L/D ratio of 32. All groups of piles placed in loose and dense dry sand. They concluded that 53% higher ultimate lateral load was achieved in increasing s/d ratio from 3 to 6, and increasing number of piles in groups reduced the efficiency of group due to overlapped stress zone. Rollins et al. [15] focused on effect of pile spacing in stiff clay, s/d ratio 3.3, 4.4, and 5.65 times the pile diameter. They found effect of decrease in load carrying capacity by increasing the spacing. The pictorial view of configuration of pile groups is shown in Figure 5. In addition, the pictorial view of configuration of pile groups is depicted in Figure 6.

4. RESULTS AND DISCUSSION

The load-displacement curve is plotted from the test results; the ultimate load is obtained by the tangent intersection method [13, 16-21]. In which initial and final tangent lines are drawn to the load-displacement curves and the point of intersection of this tangent line

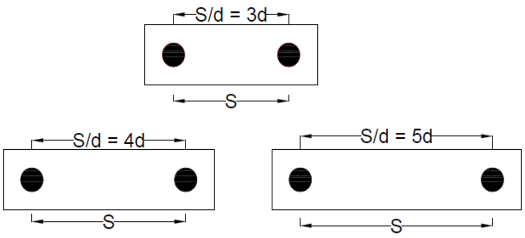

Figure 4. Configuration of pile groups

Figure 5. Pictorial view of configuration of pile groups

Figure 6. Pictorial representation of loading setup

is the ultimate load-carrying capacity (Q_u) also the corresponding settlement of pile for applied load is discussed. In Figure 7 the load versus settlement test conducted to a single belled pile L/D ratio of 12, initially, the curve is straight which means the model pile carries the vertical load. After reaching, the optimum level there is a defalcation in a curve, which indicates settlement of belled pile.

In Figure 7, the length to diameter ratio of 12 is tested and the ultimate load-carrying capacity Q_u is observed as 6.83kg. Comparison of load deflection behavior of single belled piles is shown in Figure 8. In Figure 9, the ultimate load-carrying capacity of a single straight pile is noted as 3.25kg. It is clearly observed that the maximum load observed in the straight piles 1X2 group of piles 3D, 4D, and 5D pile spacing carries load of 5.70Kg, 4.40Kg, and 4.18Kg, respectively, in L/D ratio 12. Whereas, in belled piles, $3D_b$, $4D_b$, and $5D_b$ pile spacing carries the load in the 1X2 group of belled piles as 9.38Kg, 8.06Kg, and 7.03Kg, respectively. As the spacing of piles increases, there is a decrease in the load-carrying capacity of the pile group.

As compared to the belled pile group, the load-carrying capacity is 40% more than that of straight pile groups in 3D and further, increasing the pile spacing there is decrement in load-carrying capacity. It is proved that the load settlement of belled piles were higher than that of straight piles. However, this does not mean that the bearing capacity of belled piles were always higher than those of straight piles, since the method for obtaining bearing capacities of both piles is measured based on extension angle and equal section piles.

The comparison of load deflection behavior of belled pile groups is shown in Figure 10. Comparison of load deflection behavior of belled pile groups for different Qu combination of L/D are illustrated in Figures 11-15.

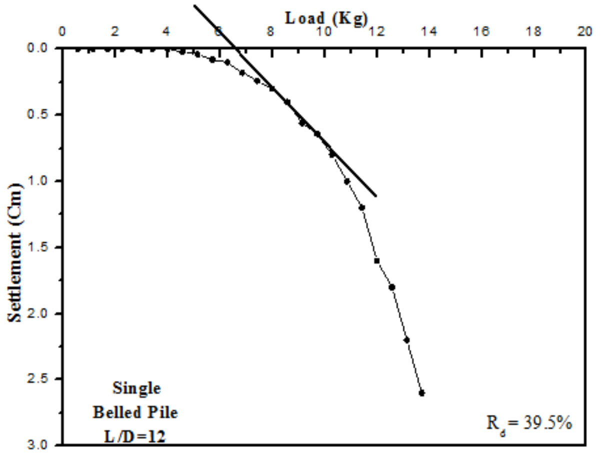

Figure 7. Load deflection behavior of single belled pile (Q_u= 6.83Kg)

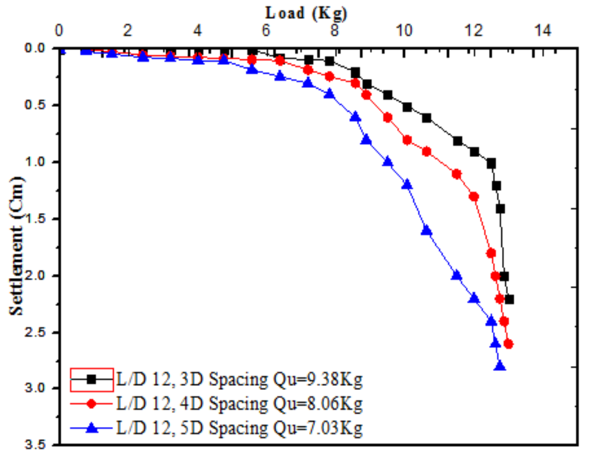

Figure 10. Comparison of load deflection behavior of belled pile groups

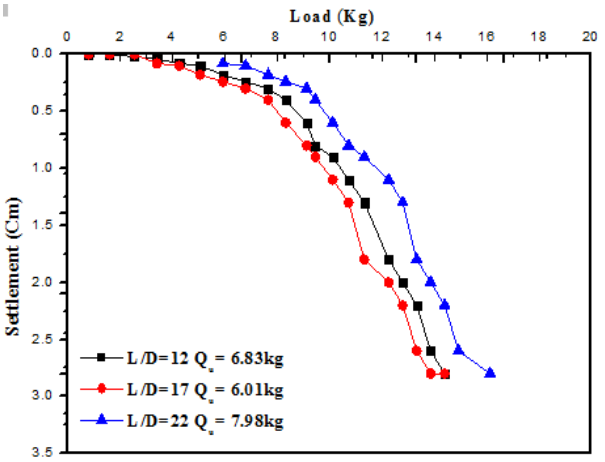

Figure 8. Comparison of load deflection behavior of single belled piles

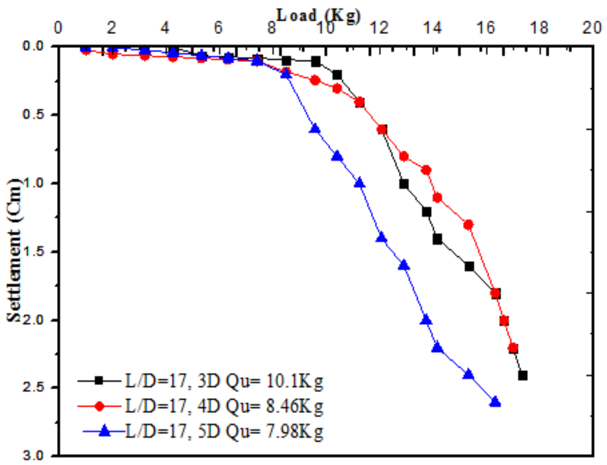

Figure 11. Comparison of load deflection behavior of belled pile groups

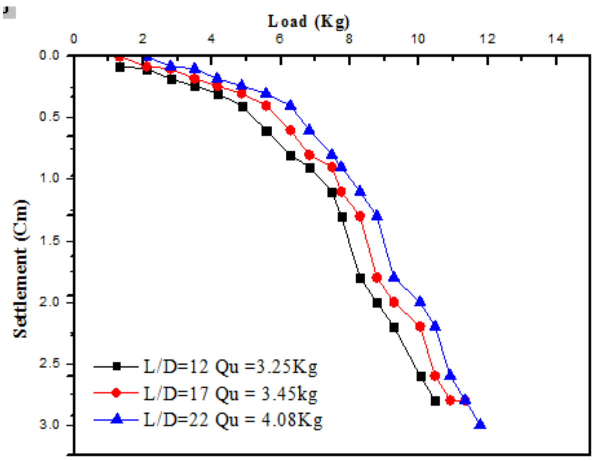

Figure 9. Comparison of load deflection behavior of single straight piles

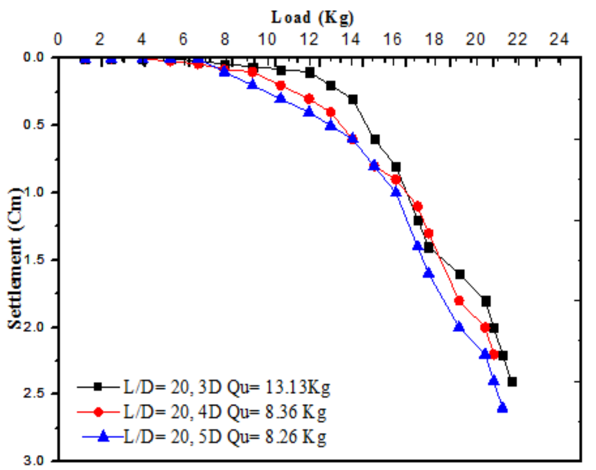

Figure 12. Comparison of load deflection behavior of belled pile groups

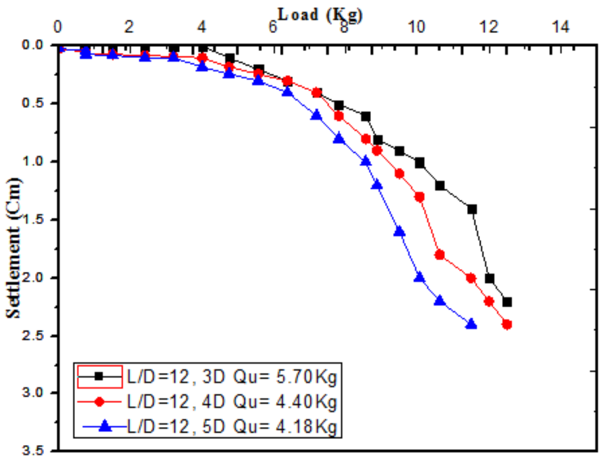

Figure 13. Comparison of load deflection behavior of straight pile groups

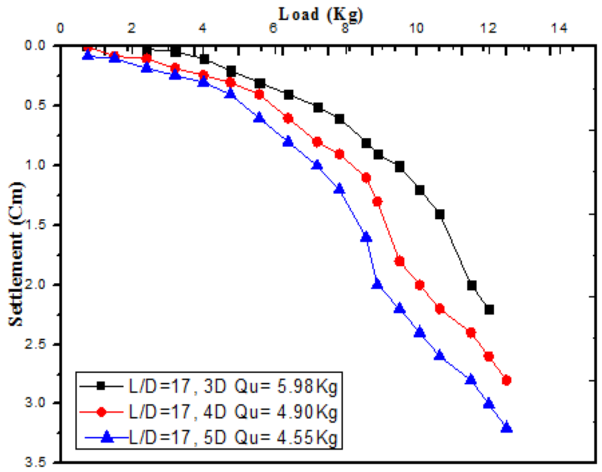

Figure 14. Comparison of load deflection behavior of straight pile groups

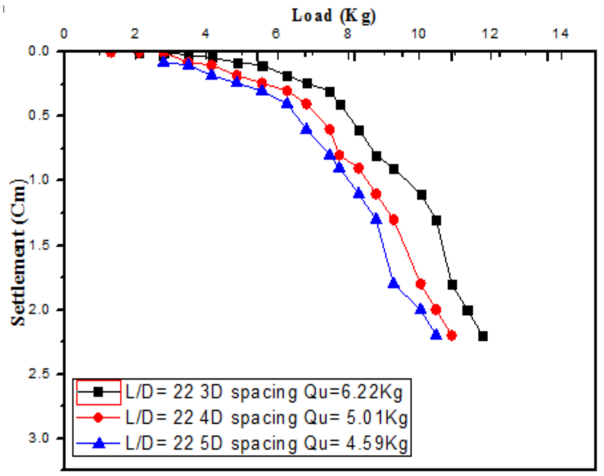

Figure 15. Comparison of load deflection behavior of straight pile groups

TABLE 4. Vertical load carrying capacity of Single and group of both Piles

Sand bed	R_d (%)	L/D	S/D	Q_u (Kg)	Pile Group	Remark
Medium dense sand	39.5	12	-	6.83	1X1	Belled piles
			$3D_b$	9.38		
			$4D_b$	8.06	1X2	
			$5D_b$	7.03		
		17	-	6.01	1X1	
			$3D_b$	10.1		
			$4D_b$	8.46	1X2	
			$5D_b$	7.98		
		22	-	7.28	1X1	
			$3D_b$	13.13		
			$4D_b$	8.36	1X2	
			$5D_b$	8.26		
Medium dense sand	39.5	12	-	3.25	1X1	Straight piles
			3D	5.70		
			4D	4.40	1X2	
			5D	4.18		
		17	-	3.45	1X1	
			3D	5.98		
			4D	4.90	1X2	
			5D	4.55		
		22	-	4.08	1X1	
			3D	6.22		
			4D	5.01	1X2	
			5D	4.59		

R_d is Relative density. Q_u is Ultimate load bearing capacity, L/D Length to diameter ratio and S/D Spacing to Diameter.

5. CONCLUSION

The purpose of this investigation is to attain the higher bearing capacity by reducing the length of pile and finding the optimum pile spacing. Increasing the base diameter of pile by providing small degree of extension angle can increase the benefits. Such piles are suitable for medium dense sand and soft soils with less consumption of concrete. Based on the present experimental work on model belled piles and straight piles in medium dense sand, the following conclusion is stated.

1) It is concluded that, the embedment ratio, pile spacing, and extension angle are the main parameters that affect the vertical load-carrying capacity of belled piles and straight bored piles. In a single belled pile of L/D ratio 12 is achieved bearing

capacity of 25% higher than that of L/D 12 of single straight pile.

2) Compared with equal section pile, the ultimate bearing capacity of single belled pile L/D 12 attains 40% higher than L/D 22 of the equal section pile. Providing a small extension angle of 30 at middle straight pile increases the base diameter lead to an increase load-carrying capacity. So that in equal section pile of L/D 22 the length of pile is more, that means concrete consumption is more in the field.
3) The efficiency of pile group is mainly depending on pile spacing and pile configuration. In the present investigation, the load-carrying capacity of 1X2 belled pile of L/D 12 is 20% greater than 1X2 straight pile of L/D 22 of 5D and $5D_b$ spacing respectively. The spacing between the piles and extended base diameter is directly proportional to the load-bearing capacity of piles.
4) It is clearly proves that the optimum pile spacing in all three L/D ratios is $3D_b$ of 1X2 configurations of belled pile group. The ultimate load carrying capacity Q_u is in increasing order as embedment ratio increases with same $3D_b$ spacing. Further, in $4D_b$ and $5D_b$ the Q_u is similar of $3D_b$. that means increasing the pile spacing the Q_u is linearly horizontal. Based on the laboratory test results the $3D_b$, 3D of belled pile and equal section pile attains the higher values, and there is no further increment in Q_u even increasing the pile spacing.
5) The 3^0 outer extension angle increases the base diameter, as compared to equal section piles, the load-carrying capacity is relatively high in belled piles. In addition, the material consumption is increasing as increasing the L/D ratio but it is more economical and cost-saving method to design belled piles.

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Persian Abstract

چکیده

این مقاله نتایج آزمایش بار محوری آزمایشگاهی دو هندسه مختلف از گروه‌های شمع آلومینیوم مدل، مانند شمع‌های مقطع مساوی و شمع‌های پایه بزرگ شده (Belled) تعبیه‌شده در شن و ماسه رودخانه‌ای موجود را ارائه می‌کند. برای شمع های زنگ دار، قطر بزرگ شده با ارائه یک زاویه ۳ درجه ای گسترش بیرونی در وسط شمع های بخش مساوی به هر سه نسبت L/D به دست می آید. آزمایش های بار در مقابل نشست بر روی X1۱ و X2۱ هر دو گروه شمع با نسبت طول به قطر 12 (L/D)، ۱۷ و ۲۲ انجام می شود. فاصله تا قطر 3 (S/D)، ٤، و ٥ برابر D و ۳، ٤ و ٥ برابر) .Dbکه در آن D 31 میلی متر قطر خارجی بخش مساوی شمع مدل و Db به ترتیب ٤٦.٧ میلی متر قطر پایه شمع زنگ دار بزرگ شده است). برای جلوگیری از همپوشانی ناحیه تنش در پایین شمع ها در هنگام اعمال بار. تمام آزمایشات در یک مخزن آزمایش سنگ تراشی آجری به ابعاد X1X1۱ متر انجام می شود. بار عمودی بر روی یک شمع و گروهی از هر دو شمع با استفاده از ظرفیت ۳۰ کیلونیوتن جک معکوس هیدرولیک که توسط یک موتور تک فاز HP۱ اجرا می شود اعمال می شود. ظرفیت باربری ارزیابی شده و مقایسه ای بین شمع های مستقیم و شمع های زنگ دار انجام می شود. مشاهده شده است که ظرفیت حمل بار در یک شمع مدل زنگ دار با نسبت L/D کمتر بیشتر است. با این حال، ظرفیت حمل بار ٤٠٪ بیشتر از شمع های مستقیم افزایش یافته است، زیرا زاویه امتداد دارند. علاوه بر این، (S/D)و (S/Db)تغییرات قابل توجهی در ظرفیت باربری ایجاد می کنند.