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An Experimental Study on Vertical and Oblique Pullout Capacity of Belled-Wedge Piles in Cohesionless Soil

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Abstract

The study deals with the uplift and oblique pullout (inclined loading) capacity of tapered piles and tapered piles connected with an enlarged base at the bottom (belled-wedge piles). Two aluminum piles with taper angle of 1 degree and 2 degrees, each having a length of 300 mm, were used. The 1 degree tapered pile having a top diameter of 48 mm and bottom diameter of 37.5 mm, while the 2 degree tapered pile has a top diameter of 48 mm and bottom diameter of 27 mm. Bells (enlarged bases) at the bottom are made of aluminum and have different bell angles of 30, 45, and 60 degrees. The piles were placed into model tank of size 1200 × 720 × 750 mm filled with cohesionless soil medium. The model tank is made of mild steel. The pile combinations such as tapered pile, tapered pile connected with different bells at bottom are tested under three different loading angles namely 0, 30, and 45 degrees and uplift capacity of each combination was determined. The results indicated that uplift capacities of tapered piles are influenced by taper angles and D_b/D_s (diameter of bell to average diameter of shaft) ratio. The oblique loading angles also play an important role in uplift and oblique pullout capacity of piles. The belled-wedge pile performs better under uplift loads. Conventional tapered piles are highly effective in resisting compressive loads due to the change in cross-sectional area and better material distribution along the length of the pile. Additionally, tapered piles play a significant role in reducing negative skin friction in loose and filled soils.

Categories: Geotechnical Engineering
Keywords: tapered pile, belled wedge pile, load inclination, axial and oblique pullout, bell angle, taper angle, diameter (db/davg) ratio, oblique loading

Introduction

Pile foundations are a type of deep foundations, which are used in foundations of transmission towers, solar panels, jetties, moorings, tall chimneys, and wind turbines. In such foundations, eccentric loading, overturning moments, wind loads, and uplift loading are predominant. Therefore, the uplift load-carrying capacity of piles is an important design consideration in deep foundations. In recent years, new types of foundations have been introduced with an enlarged base at the bottom. The enlarged bases like plates, cones, bells, and wedges are connected at the bottom of pile to increase the uplift and bearing resistance of the pile.

Many studies deal about the uplift capacity of normal circular and tapered piles. Therefore, in this study, an attempt is made to develop a belled-wedge pile by fixing three different bells with bell angles of 30, 45, and 60 degrees at the bottom of a conventional tapered pile. The main objective of this research is to study the behavior of tapered piles, tapered piles with an enlarged base (bells) at the bottom, called belled-wedge piles, under 0, 30, and 45 degree oblique pullout loading. Tapering of the pile will lead to better material distribution and ease of driving into the ground. The bell at the bottom helps to distribute the load uniformly to the surrounding soil. The present paper also investigates the oblique pullout capacity of the belled-wedge pile in a sand bed. The oblique pullout resembles the wind loads, water forces, and seismic forces that act in an inclined direction.

Literature review

Many studies on pile foundation give a brief knowledge on pullout capacity of piles. The present study involves the uplift and oblique pullout capacity of piles in medium dense sand.

Agarwal et al. [1] carried out a comparative study on uplift capacity of solar array frames subjected to high wind forces and found that the foundation should be carefully designed with optimum pullout loads using numerically force coefficients.

Al-Suhaily et al. [2] conducted a study on the uplift capacity of piles with enlarged bases. This study concluded that provision of end gates and an enlarged base increases the uplift capacity of piles.

Dickin and Leung [3], EI-Naggar and Wei [4,5] conducted a study on the axial response of piles with varying top and bottom diameters and concluded that as taper angle increases, shaft resistance increases. They also found that shaft resistance is higher in tapered piles than in round piles.

Ilamparuthi and Dickin [6] developed a concept of effective diameter and effective embedment ratio to determine the relation between pullout load and displacement.

Ismael [7] reported the difference between tapered and uniform cross-section piles in their investigation. The test results showed that the bearing capacity of tapered pile is 30-50% more than that of normal round uniform cross-section piles.

Patra and Pise found that with an increase in oblique angle, the uplift capacity increased by 20-50%. Krishna and Patra [8] also observed a similar prediction.

Sawaguchi [9] studied the effect of surcharge weights on uplift capacity. The taper angle and surcharge load influence the uplift capacity of pile, and he also studied effective ways reducing the negative skin friction due to surcharge loads.

Sakr et al. [10] studied double under-reamed piles which are placed in a layered sand bed and subjected to uplift loads. They have maintained a spacing ratio of 4 and concluded that the efficiency was less than 100% in the case of 2 pile, 3 pile, and 4 pile configurations in a dense sand bed.

Dhatrak et al. [11] carried out a study on circular, tapered, belled, and belled-wedge piles embedded in sand; they considered pile spacing and number of piles. It is observed that single and groups of belled-wedge piles provide much higher pullout capacities than circular piles.

EI-Nagar and Wei [12] carried out a study on the axial response of tapered piles. They found that the shaft resistance is more in tapered piles than in round piles and the load distribution is the same in both piles. The load transfer was significantly affected by confining pressure. It is concluded that the tapered pile offers more resistance than the round pile.

EI-Naggar and Wei [13,14] conducted studies by using model tests and centrifuge model tests. The results showed that the side resistance of tapered piles is larger than that of regular round uniform cross-section piles, and the tip resistance of round uniform cross-section piles was found to be more than that of the tapered piles.

Fattah and Al-Soudani [15] studied about the uplift capacity of piles with enlarged bases. The study concluded that provision of end gates, and an enlarged base increases the uplift capacity of piles.

Ilamparuthi and Dickin [16] developed a concept of effective diameter and effective embedment ratio to determine the relation between pullout load and displacement.

Singh et al. [17] studied the load displacement behavior under oblique pullout loads. They found that, as ultimate pullout capacity decreases as the angle of load inclination increases with the pile axis.

Kong et al. [18] developed a new pile called the belled-wedge pile by combining belled pile and tapered pile. The construction methods and quality assurance (QA)/quality control (QC) of a belled-wedge pile are briefly discussed.

Patra and Pise [19] found that with an increase in oblique angle, the uplift capacity was found to increase by 20% to 50% and also observed a similar prediction.

Raju et al. [20] conducted a series of model tests on belled piles subjected to vertical and oblique pullout loads. They concluded that uplift capacity is influenced by oblique angle, bell angle, L/D ratio, and D_b/D_s ratio.

Nazir [21] observed from the study that as bell angle and shaft diameter increases, the uplift capacity decreases with short displacement. They concluded that this behavior is because of the less volume of sand column developed at the top of the sand bed.

Rybnikov [22] reported the difference between tapered and uniform cross-section piles in their investigation. The test results showed that the bearing capacity of tapered pile is 30-50% more than that normal round uniform cross-section piles.

Wang et al. [23] conducted a field load tests for large diameter belled piles embedded in collapsible loess. The test data was used to provide insight into the development of negative skin friction, uplift capacity of belled piles, and compressive load-bearing capacity.

Hussain et al. [24] performed a study on micro pile groups under oblique pull-out loads in sand. They concluded that the length to diameter ratio and angle of inclination are functions of pile load capacity and group efficiency.

It is observed from the literature review that the investigations carried out on axial and oblique pullout capacity of belled-wedge piles are very limited, and most of the studies are confined to analytical or numerical modeling aspects of belled-wedge piles. Hence, this present research focuses on the experimental study of axial and oblique pullout behavior of the belled-wedge pile in comparison with the conventional tapered pile. In addition, an investigation is made to study the influence of taper angles, diameter (D_b/D_s) ratio, and bell angles on axial and oblique pullout capacity of the belled-wedged pile.

Materials And Methods

Materials and methodology

Sand

The locally available river sand has been used as a foundation material for the present work. The index and engineering properties of the sand are presented in Table *1*.

Soil Parameters	Value	Standard
Specific gravity (G)	2.61	IS:2720 (part-3/Sec-2)-1980 (reaffirmed 1987)
D_{10}	0.29 mm	IS:2720 (part-4)-1985
D_{30}	0.58 mm	
D_{60}	0.78 mm	
Cu = (D_{60}/D_{10})	2.68	
Cc =$(D_{30})^2/(D_{60}*D_{10})$	1.52	
Soil classification	Poorly graded sand	
Maximum unit weight (γ_{max})	16.75 kN/m^3	IS:2720 (part-14)-1983
Minimum unit weight (γ_{min})	15.20 kN/m^3	
Maximum void ratio (e_{max})	0.68	
Minimum void ratio (e_{min})	0.53	
Relative density (R_d)	60%	
State of density	Medium dense state	
Angle of internal friction (φ)	38^o	IS:2720 (part-13)-1986

TABLE 1: Properties of sand

The sand is classified as poorly graded sand based on the results of sieve analysis. The experiments were conducted on medium dense state sand with unit weight (γ) of 16.09 kN/m^3, corresponding to the relative density of 60%. Using the direct shear test, the shear parameters are determined, corresponding to a vertical stress of 150 kPa, the angle of internal friction (ϕ) was found to be 38 degrees with respect to the medium dense state of sand.

Model Pile

The model study has been made using tapered piles with bells that are fabricated using aluminum metal. Since aluminum material is a lightweight metal, it helps easy working during the model study. The aluminum piles are used by referring to scaling laws. Two types of tapered piles are used in this study: the pile having a 1 degree tapered angle was made with a top and bottom diameter of 48 mm and 37.5 mm, respectively, and the pile having a 2 degree tapered angle was made with a top and bottom diameter of 48 mm and 27 mm, respectively. The diameter of bell to average diameter of bottom shaft (D_b/D_{avg}) ratio is maintained as 1.5 and 2. The bottom bell diameters were 72 mm and 96 mm, respectively; the top diameter of bell was so adjusted to match with the bottom diameter of pile shaft. Solid aluminum was used to make the bell and the thickness of model pile is 5 mm. The bell angles of were 30, 45, and 60 degrees were used. The schematic diagrams of tapered and belled-wedge piles are shown in Figure *1* and the properties of piles are as shown in Table *2*. Figures *1* and 2 show the model piles and bells used in the present study. The length to average diameter of the pile shaft was found to be 7 and 8 for 1 degree and 2 degree tapered piles respectively. David et al. proposed the scaling laws, which are used in this study to select the pile dimensions. The model piles were fabricated using aluminum metal with a scale factor of 1/40, which simulates the steel prototype pile with elastic modulus E = 210 GPa, length of 12 m, and diameter of 600 mm.

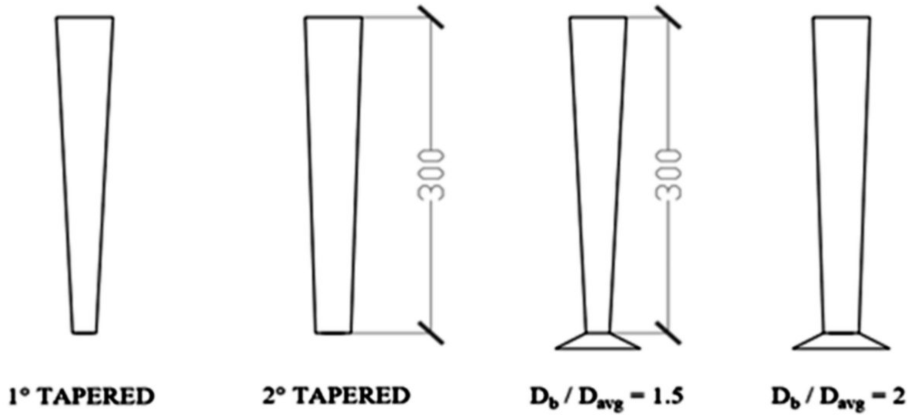

FIGURE 1: Schematic diagram of model piles

FIGURE 2: Model piles

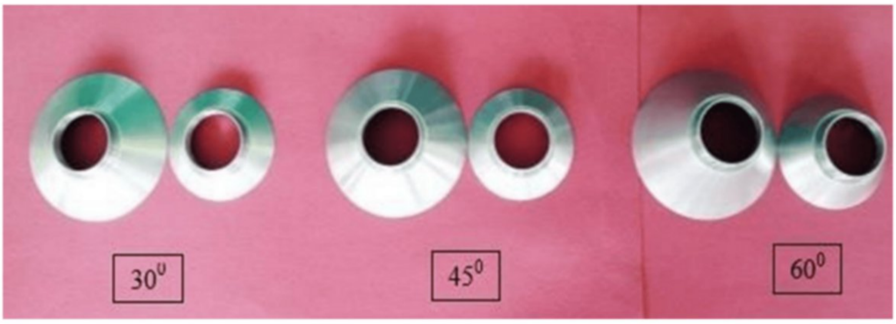

FIGURE 3: Model bells with different bell angles

Particulars	Values
Parameter	Model pile
Material	Aluminium
Modulus of elasticity, E (GPa)	70
Tapered angle (degrees)	1 and 2
Pile thickness (mm)	5
Bell angles (degrees)	30, 45, and 60
Bell diameter (mm)	72 and 96
D_b/D_s	1.5 and 2
Length of the pile (mm)	300
Diameter of pile shaft at top (mm)	48
Diameter of pile shaft at bottom (mm)	37.5 and 27
Length to diameter ratio (L/D_{avg})	7 and 8

TABLE 2: Properties of model pile

Model Tank

The model tank was made of 10 mm thick mild steel plate, the model tests were conducted in a model tank of size 1200 mm × 720 mm × 750 mm. The size of the model tank was chosen based on the criteria of failure zones developed during uplift, in order to overcome boundary effects. For sandy soil, the tank dimensions should not be less than three times the diameter of the pile. In the present study, the tank dimension is 7.8 times greater than the diameter of the bell in the least dimension of the tank. To maintain the different oblique angles in the model tank, a movable pulley arrangement was made. The experimental procedure adopted in this study is as given below.

Initially, the piles were positioned in the tank as per the requirement to coincide with the point of axial pullout. A metal rope was used to connect the pile top, proving ring, and the loading unit (lever hoist). One end of the rope was connected to a hook at the pile top and the other end of the rope was connected to the proving ring. The oblique angle positions were marked corresponding to 0, 30 and 45 degree respectively at the top of the model tank, and then the pulley was fixed to the marked positions while applying the oblique loads. The lever hoist was provided with a hand winch that helps to apply the load manually. The load was applied using the hand winch and the displacement was measured using a dial gauge after each increment of loading. Two dial gauges with a least count of 0.01 mm and a displacement measuring capacity of 50 mm were used to measure the displacement horizontally and vertically. Anyhow, the study is limited to determine the behavior of tapered and belled-wedge piles under different loading; hence, a standard dial gauge is used. The vertical dial gauge was connected to the rod attached to the reaction frame, which helps to connect the dial gauge above the pile top, and the horizontal dial gauge was connected using a magnet mount stand. Figure *4* shows the schematic sketch of the model tank with vertical and oblique pullout arrangement, respectively.

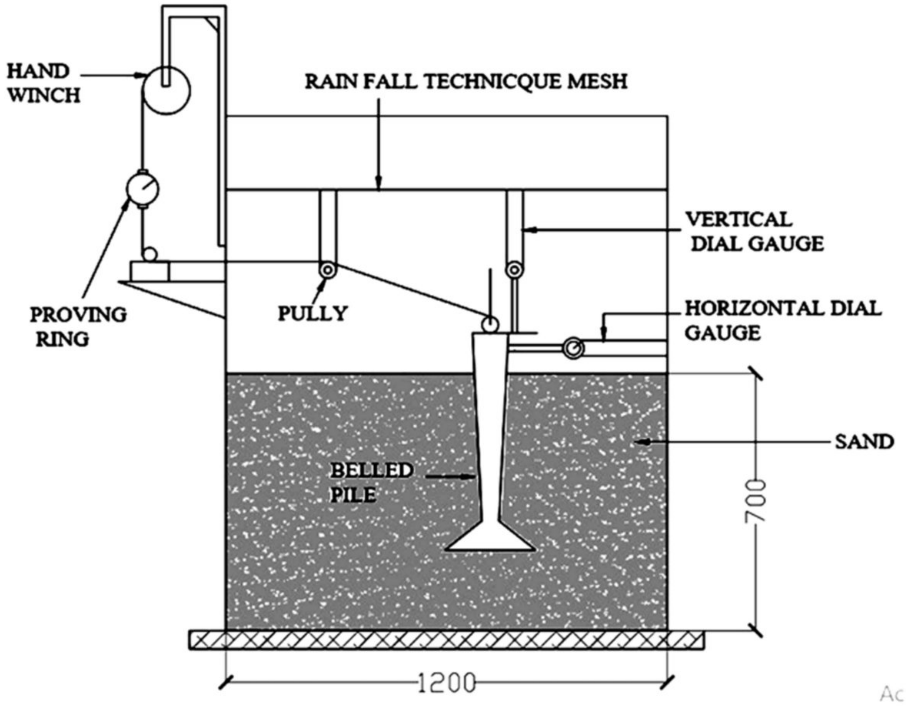

FIGURE 4: Schematic representation of experimental setup

Rainfall Technique

The model tank was filled by using the rainfall technique; a raining mesh was used to pour the sand from a desired height to achieve the required density. The rainfall technique is a method in which the sand is poured from different heights into the container of known volume and its weight is measured after the complete filling of the container. Then the density of the sand is determined. Similar trials were repeated for different heights of fall of sand, and the corresponding density values were determined, and a plot was developed between relative density and corresponding height of fall. In addition, Figure *5* shows the rainfall technique arrangement made in our model tank; Figure *6* shows the real image of pouring sand by the Dry pluviation technique. This technique is also called as pluviation technique. The height of fall and corresponding unit weight, the desired relative density were achieved by using rainfall technique, and the height of fall is calibrated by using maximum and minimum unit weight for the sand used in the study. In the present study, the sand was poured at a height of 30 cm corresponding to a medium dense state to achieve a relative density of 60%. The maintained density is also assured by keeping a known volume container in model tank while filling the sand, and its density was measured after the completion of the model test.

Figure *5* shows the calibration of the height of fall.

FIGURE 5: Rainfall technique arrangement

FIGURE 6: Dry pluviation technique

Experimental Procedure

The model tank was used to prepare the foundation bed for model piles. The model piles were placed at zero oblique angle position, which is marked on the reaction frame. Initially, the piles were placed vertically at the zero angle position, and the raining mesh was placed on the marked position of the tank with respect to the fixed height of fall. At the beginning of the test, the raining mesh was positioned directly above the model tank and sand was poured in the tank continuously through the raining sieve, keeping the height of fall of about 300 mm, corresponding to medium dense state with unit weight 16.09 kN/m^3 (Rd = 60%). The pile installation method used in this study was to simulate non-displacement piles. In this method, there would be movement of sand particles occurs during the pluviation technique and no displacement of the pile was made during installation, which helps to maintain a constant relative density of 60% throughout the experimental work. Then, piles were placed at pre-located positions to avoid boundary effects from surrounding tank and then using rainfall technique sand was poured into the tank up to the top of pile. The raining mesh was raised for every 10 cm rise of sand bed to maintain relative density throughout the length of pile. Oblique pullout load was applied with the help of hand-winch arrangement, which was provided with the special pulley arrangement whose length may be altered so that wire rope passes over it achieves a desired loading angle (0, 30, 45 degrees) with respect to vertical axis of pile. The dial gauge with a magnetic stand was rigidly mounted on the model tank to measure the displacement of the piles.

An arrangement was made to fix the dial gauge needle on top of the pile head to measure the horizontal and vertical displacement of pile head. Dial gauge readings were measured until maximum deformation of 50 mm. The above procedure is carried out for different bell angles and different diametric ratio (D_b/D_{avg}) with varying inclinations of load. The above procedure was carried out for mono pile without bell at bottom and belled-wedge piles under different load inclination angles.

The parameters considered in this study include two different tapered piles with taper angles of 10 and 20 degrees, which were used as model piles; ratio of diameter of bell to average diameter of shaft (D_b/D_{avg}) was varied as 1.5 and 2. The bell angles considered in this study are 30, 45, and 60 degrees and oblique angles are 0, 30, and 45 degrees with respect to the pile axis, respectively. The density in the sand bed was maintained uniform throughout the tank and the relative density was maintained constant throughout the experimental work. Locally available river sand has been used as a foundation material to fill the tank.

Results

Results and discussions

In the present study, number of model tests were conducted repeatedly to determine the axial and oblique pullout capacity of tapered piles and belled-wedge piles by applying the pullout load vertically and in the oblique direction. The comparison of results has been made with respect to uplift capacity of conventional tapered piles. No cylindrical mono piles are considered in this study, and the study is limited to assess the behavior of tapered piles.

Piles having tapered angle of 1 and 2 degrees were tested in the model tank. The piles were inserted in sand of density 16.09 kN/m_3 having a relative density of 60%. Different parameters of the piles and loading orientation considered for the experimental work are as follows:

1. Tapered angle

2. Diameter of the bell to diameter of bottom shaft ratio (D_b/D_{avg})

3. Bell angle

4. Loading inclination angle

The detailed results of piles subjected to the pullout loads were discussed and various quantities such as load, displacement for different load orientation, and pile configurations are shown as below.

Load Displacement Curve for Tapered Pile

Figure 7 shows the plot between uplift loads and vertical displacement of 1 degree tapered pile under axial and oblique loading. The displacement was considered up to ultimate failure point. As load increases, the displacement also increases up to peak point, after reaching the ultimate peak point, the piles lose the resistance and fail vertically by tension loading. The ultimate load is the maximum load resisted by the pile during the test before failure. In general, the total uplift force is equal to the sum of the weight of the pile and the soil in an inverted cone above the belled base surrounding the pile, plus the shearing resistance along the perimeter of the failure surface.

The ultimate load measured was found to be 42 N, 46 N, and 50 N, and the displacement was found to be 56 mm, 32.4 mm, and 43.7 mm.

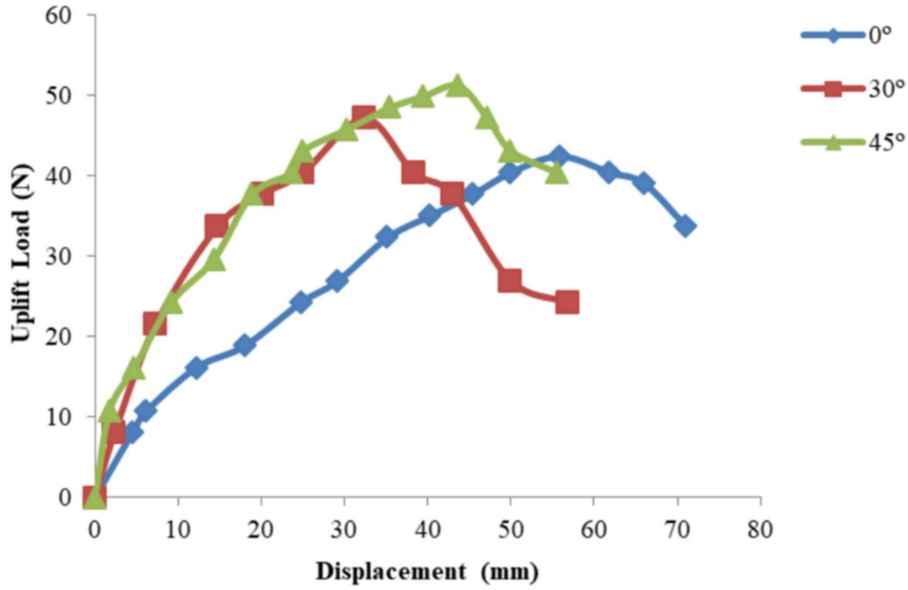

FIGURE 7: Uplift load vs. displacement for 1 degree tapered piles

Figure 8 shows the plot between uplift loads versus vertical displacement of the pile. The three different curves represent the load displacement curves at different oblique loading angles such as 0, 30, and 45 degrees. The ultimate uplift loads are given by 29 N, 33 N, and 40 N and displacements are given by 35.9 mm, 25 mm and 24.5 mm, respectively.

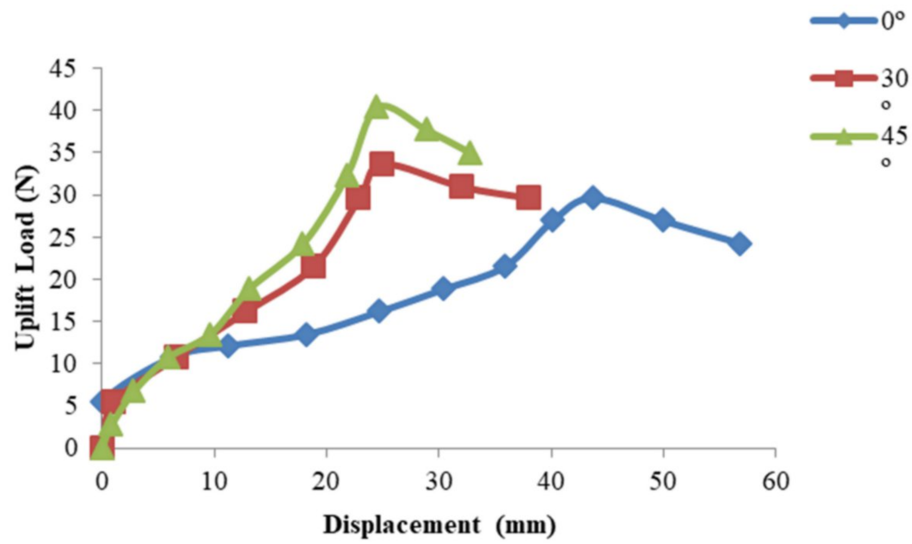

FIGURE 8: Uplift load vs. displacement for 2 degree tapered piles

Load Displacement Curve for Belled-Wedge Pile

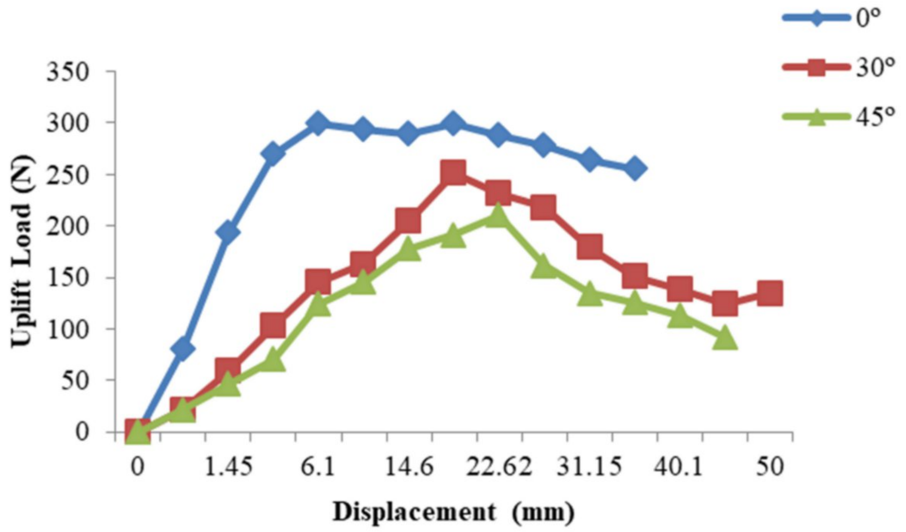

FIGURE 9: Uplift load vs. displacement curve for 1 degree belled-wedge pile with a bell angle of 30 degree and Db/Davg ratio of 1.5

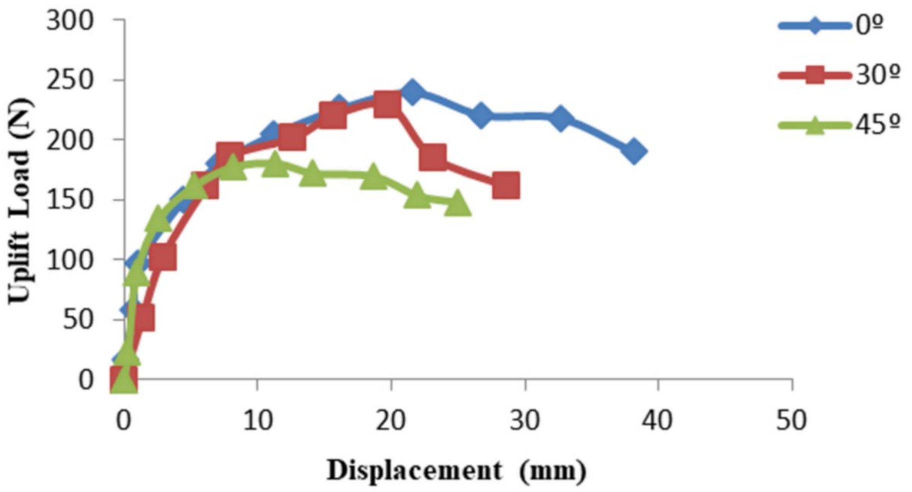

FIGURE 10: Uplift load vs. displacement for 2 degree belled-wedge pile with a bell angle of 30 degree and Db/Davg ratio of 1.5

Figures 9 and 10 describe the load displacement behavior of 1 and 2 degrees belled-wedge pile with a 30 degree bell at bottom having diametric ratio (D_b/D_{avg}) of 1.5 under different loading angles like 0, 30, and 45 degrees.

Effect of Tapered Angle on Ultimate Uplift Capacity

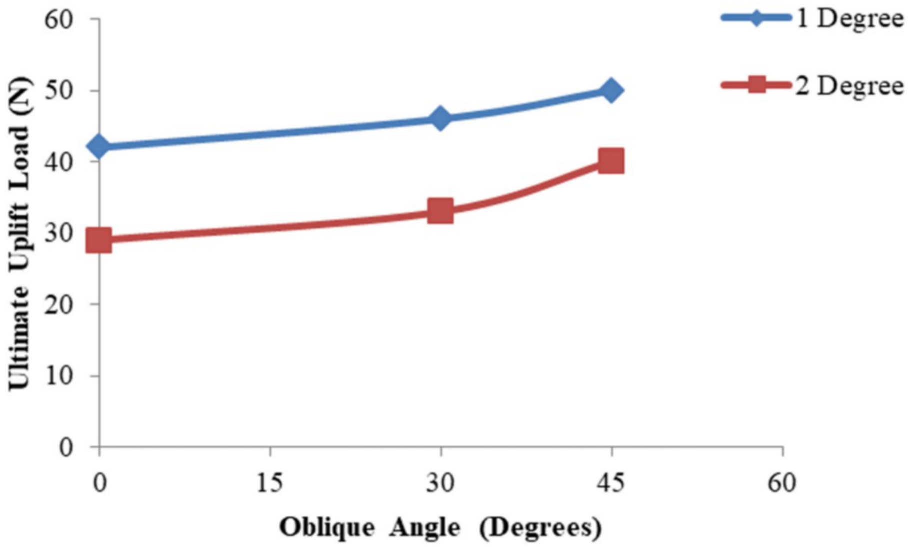

FIGURE 11: Ultimate uplift capacity vs. oblique angle for tapered piles

Figure 11 shows the plot between ultimate uplift loads versus oblique angle. The graph shows that as oblique angle increases, the uplift capacity also increases in case of both 1 and 2 degree tapered piles. The base diameter of 1 degree tapered pile is higher than the 2 degree tapered pile hence the pullout capacity of 1 degree tapered pile is higher.

The load carried by 1 degree tapered pile under 0, 30, and 45 degrees are 42, 46, and 50 N, respectively, and the loads carried by 2 degree tapered pile are 29, 33, and 40 N, respectively.

Effect of Oblique Angle on Pullout Capacity of One Degree Belled-Wedge Pile

In this section, a comparison was made between the pullout capacities of the 1 degree tapered pile with different bell angles subjected to various oblique angles. Piles with different diametric ratios are tested and the peak pullout capacities have been discussed in this case.

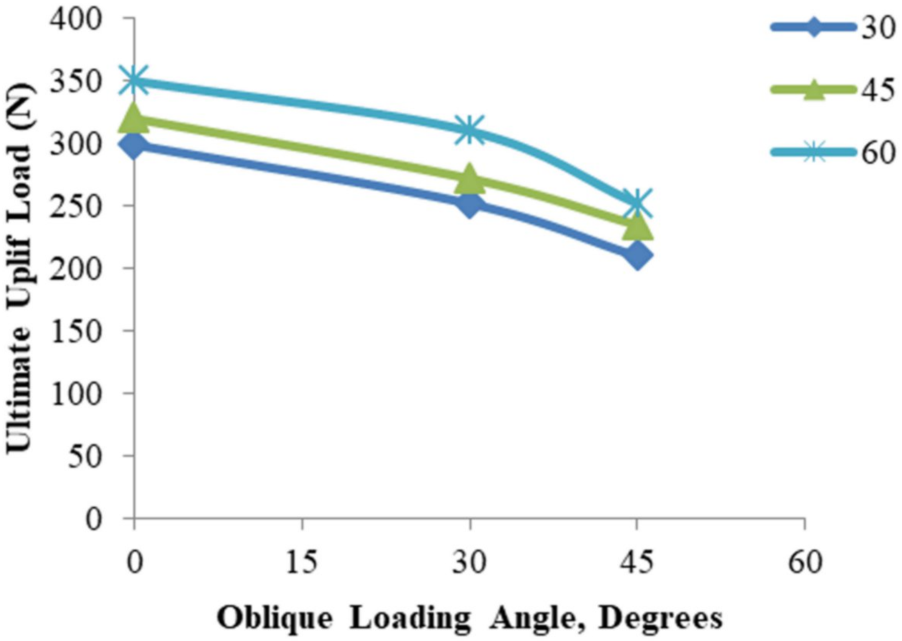

FIGURE 12: Ultimate uplift load vs. oblique angles for belled-wedge piles with a Db/Davg of 1.5 and a taper angle of 1 degree

Figure 12 shows the plot between ultimate uplift load versus oblique angles for a belled-wedge pile with taper angle of 1 degree and D_b/D_s ratio was 1.5. From the above graph, it is clear that as oblique angle increases, the uplift capacity of the pile decreases.

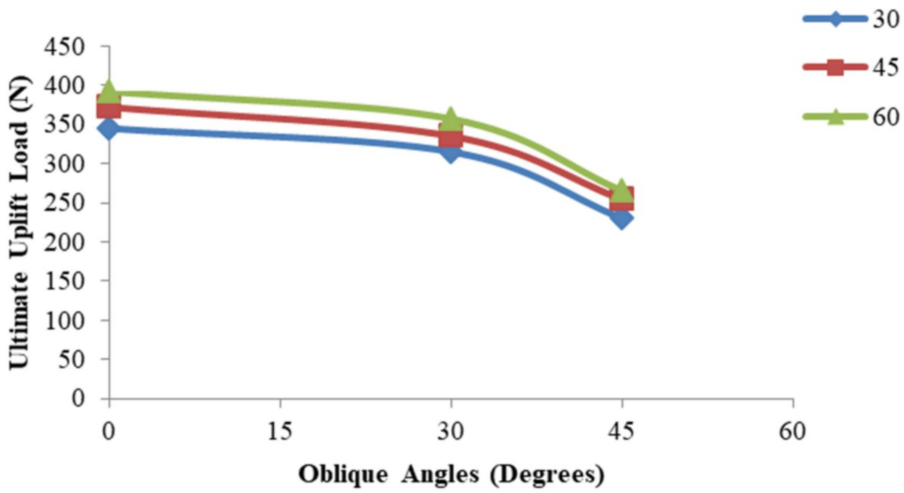

FIGURE 13: Ultimate uplift load vs. oblique angles for belled-wedge piles with a Db/Davg of 2 and a taper angle 1 degree

Figure 13 shows the plot between ultimate uplift load versus oblique angles for a belled-wedge pile with taper angle of 1 degree and D_b/D_{avg} ratio is 2. In this case, the ultimate uplift load decreases with increase in oblique load angles.

Effect of Oblique Angle On Pullout Capacity of Two Degree Belled-Wedge Pile

In Figures 14 and 15, it is observed that the graphs are drawn between pullout capacities of piles versus oblique angles.

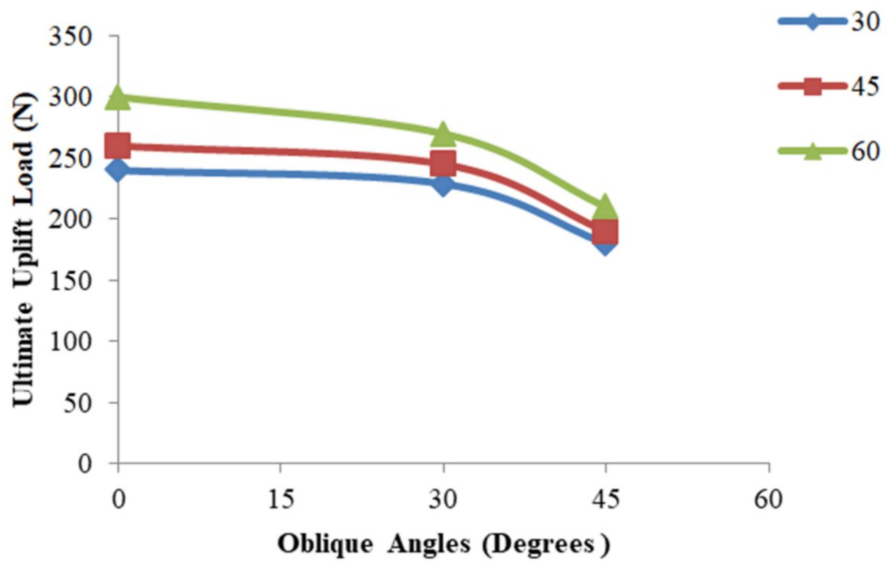

FIGURE 14: Ultimate uplift load vs. oblique angles for belled-wedge piles with a Db/Davg of 1.5 and taper angle of 2 degrees

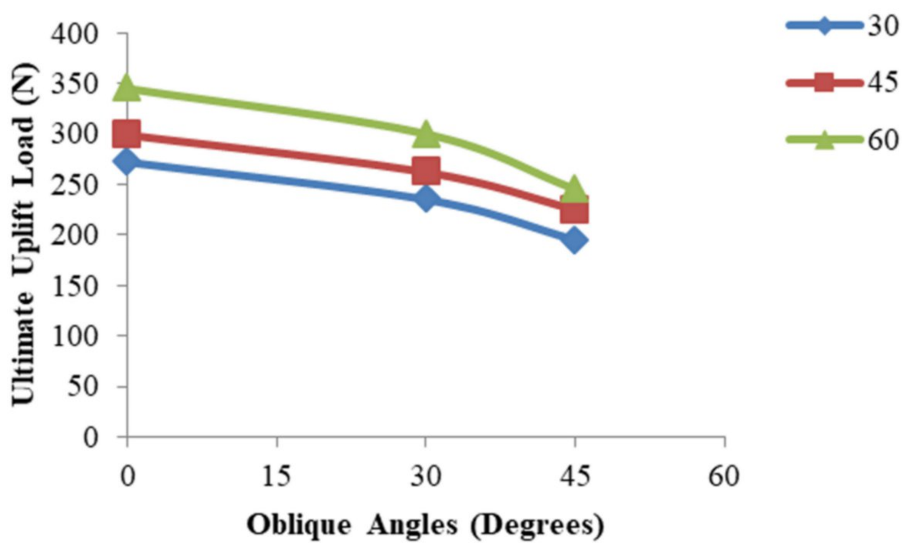

FIGURE 15: Ultimate uplift load vs. oblique angles for belled-wedge piles with a Db/Davg of 2 and taper angle of 2 degrees

Effect of Tapered Angle On Ultimate Uplift Capacity of Belled-Wedge Piles

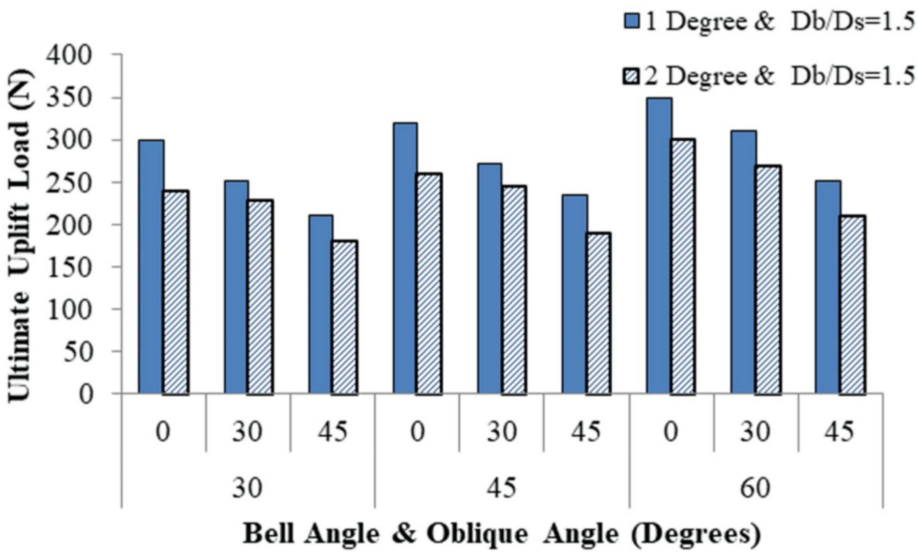

FIGURE 16: Ultimate uplift load vs. oblique angles and bell angles for belled-wedge piles with a Db/Davg of 1.5

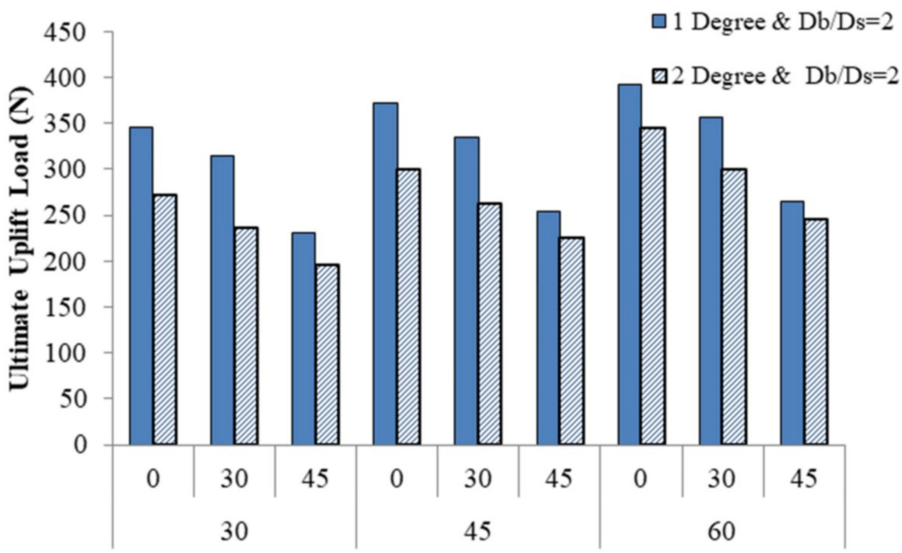

FIGURE 17: Ultimate uplift load vs. oblique angles and bell angles for belled-wedge piles with a Db/Ds of 2

Figures 16 and 17 show the plot between ultimate uplift load versus oblique angles and bell angles for belled-wedge piles with Db/Davg ratio of 1.5 and 2, respectively.

Effect of D_b/D_{avg} Ratio on Pullout Capacity of Tapered Piles

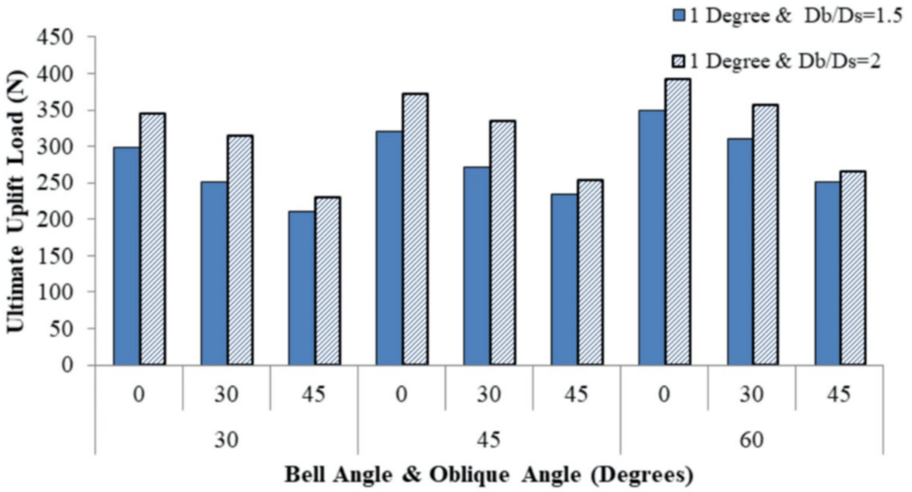

FIGURE 18: Ultimate uplift load vs. bell angles and oblique angles for belled-wedge piles with tapered angle of 1 degree

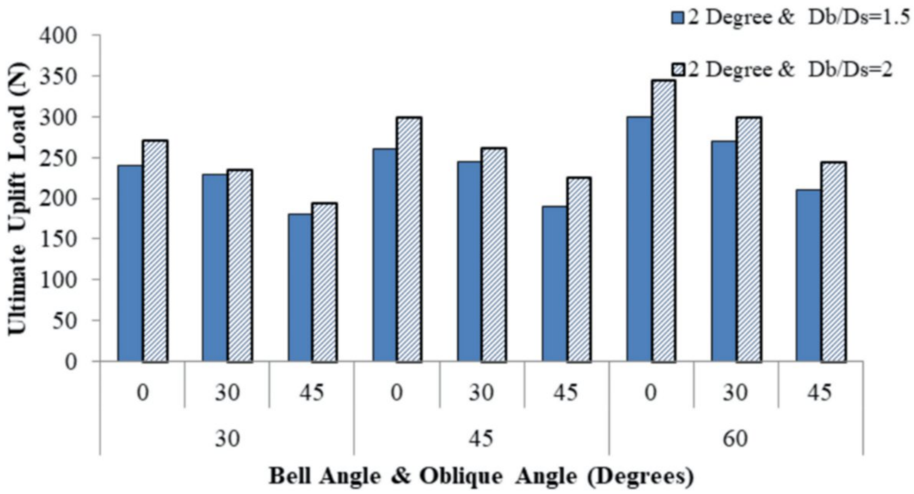

FIGURE 19: Ultimate uplift load vs. bell angles and oblique angles for belled-wedge piles with tapered angle of 2 degrees

Figures 18 and 19 show the effect of D_b/D_{avg} ratio and bell angle on uplift capacity of belled-wedge piles in sand bed.

Comparison of Overall Results

In this study, piles with two different tapered angles were considered; the taper angles are 1 degree and 2 degrees with respect to pile axis and tested under axial and oblique pullout loading. The other parameters considered in the study are belled-wedge piles (tapered pile with enlarged base) with varying bell angles of 30, 45, and 60 degrees and ratio of diameter (D_b/D_{avg}) of 1.5 and 2 were used. The piles were tested under axial and oblique pullout loading with oblique angles of 0, 30, and 45 degrees, respectively.

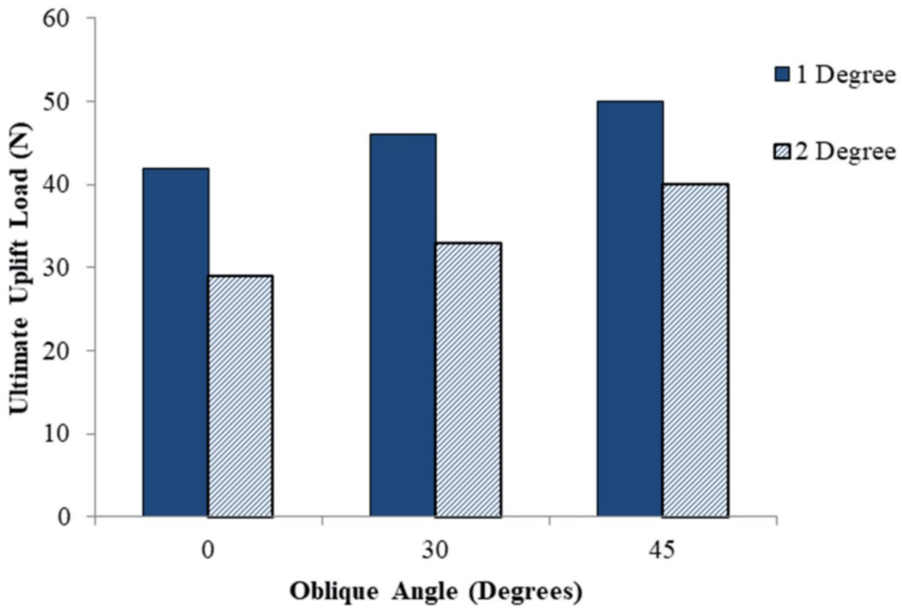

FIGURE 20: Ultimate uplift load vs. oblique angles for tapered piles

Figure *20* represents the tapered pile results.

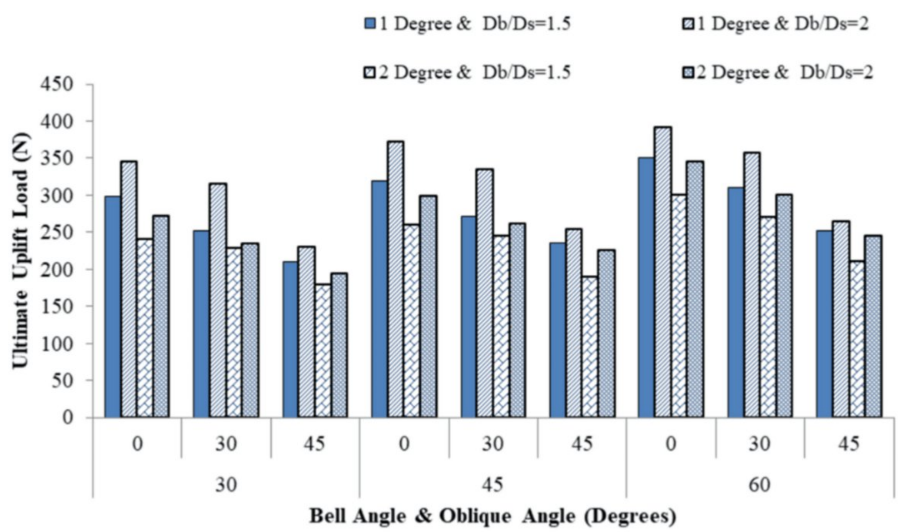

FIGURE 21: Ultimate uplift load versus oblique angles for belled-wedge piles

Figure *21* represents the plot between bell angle and oblique angle on x-axis and ultimate uplift load on y-axis.

Pile Type	Tapered Angle	D_b/D_{avg}	Bell Angle	Oblique Angle	Ultimate Uplift Load N	Vertical Displacement in mm	Horizontal Displacement in mm
				0	42	50	0

Monopile	1 Degree	NA	NA	30	46	7.2	2.45
				45	50	42	20.9
	2 Degree	NA	NA	0	29	35.9	0
				30	33	6.6	4.5
				45	40	9.63	6.45
Tapered Pile	1 Degree	1 Degree & D_b/D_{avg} = 1.5	30	0	299	9.3	0
				30	252	16.4	15.5
				45	210	20.1	29.4
			45	0	320	15.3	0
				30	272	25	23.7
				45	235	20.6	26.3
			60	0	350	48.5	0
				30	310	25	30.6
				45	252	12.5	22.55
		1 Degree & D_b/D_{avg} = 2	30	0	345	22.8	0
				30	315	11.7	11.2
				45	230	10.2	19.15
			45	0	372	15.5	0
				30	335	31.3	47.4
				45	254	18.3	29.4
			60	0	392	24.5	0
				30	357	28.82	46.05
				45	265	19.73	29.5
Tapered Pile	2 Degree	2 Degree & D_b/D_{avg} = 1.5	30	0	240	11.25	0
				30	229	19.8	24.6
				45	180	11.4	14.9
			45	0	260	45.1	0
				30	245	14.6	18.65
				45	190	18.8	27.5
			60	0	300	52.2	0
				30	270	39.65	46
				45	210	13.75	17.05
		2 Degree & D_b/D_{avg} = 2	30	0	272	10.9	0
				30	235	19.8	24.6
				45	195	11.4	14.9
			45	0	299	8.9	0
				30	262	11.65	14.53
				45	225	14.1	30.3
			60	0	345	35.6	0
				30	300	31.6	48.8

		45	245	14.2	26.97

TABLE 3: Ultimate uplift loads and displacements of tapered and belled-wedge piles

Displacement of Pile To Achieve Ultimate Uplift Load

Figures 22, 23, 24, and 25 represent the plots between settlement of pile, oblique angle, and bell angle for different pile combinations.

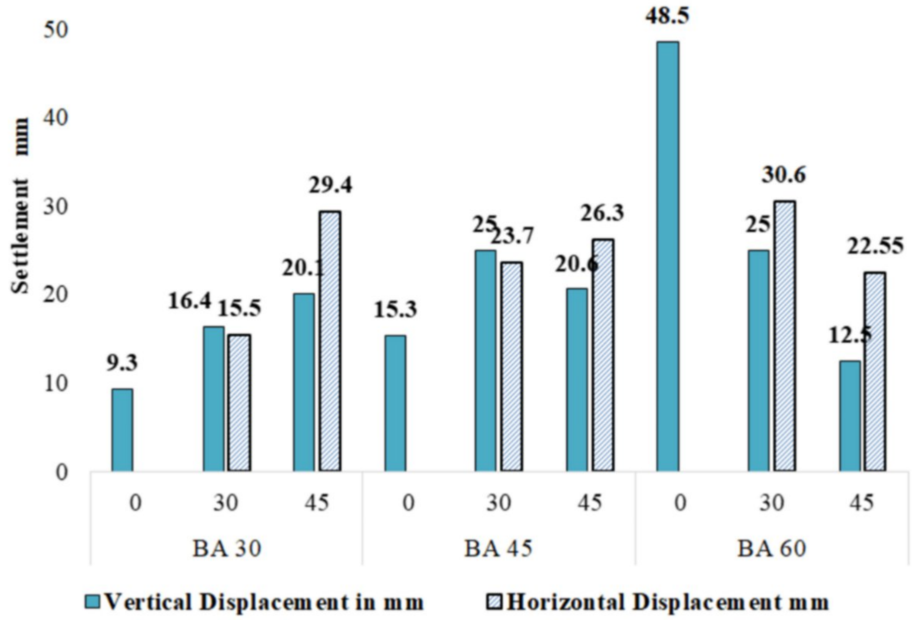

FIGURE 22: Vertical and horizontal displacement of piles, with a diametric ratio of 1.5 and a tapered angle of 1 degree

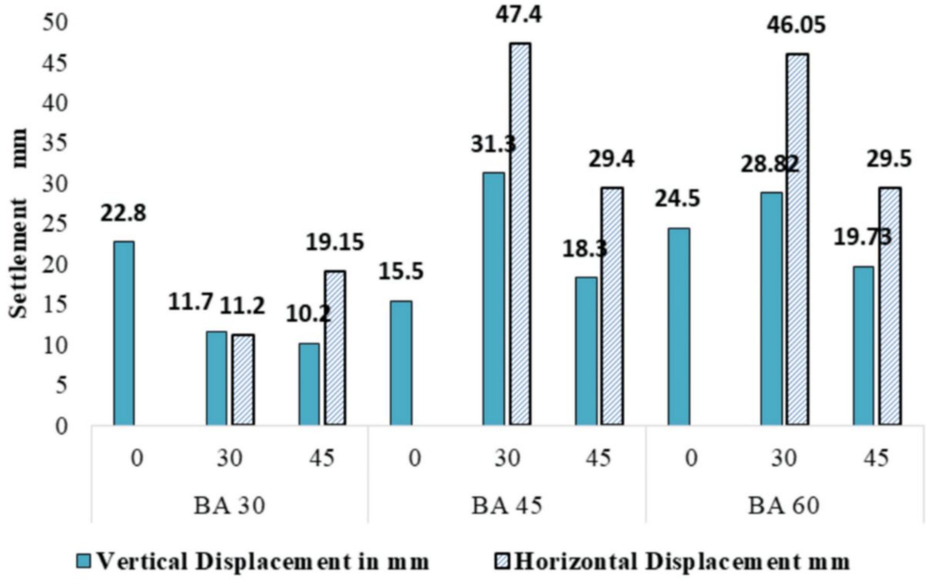

FIGURE 23: Vertical and horizontal displacement of piles, with a diametric ratio of 2 and a tapered angle of 1 degree

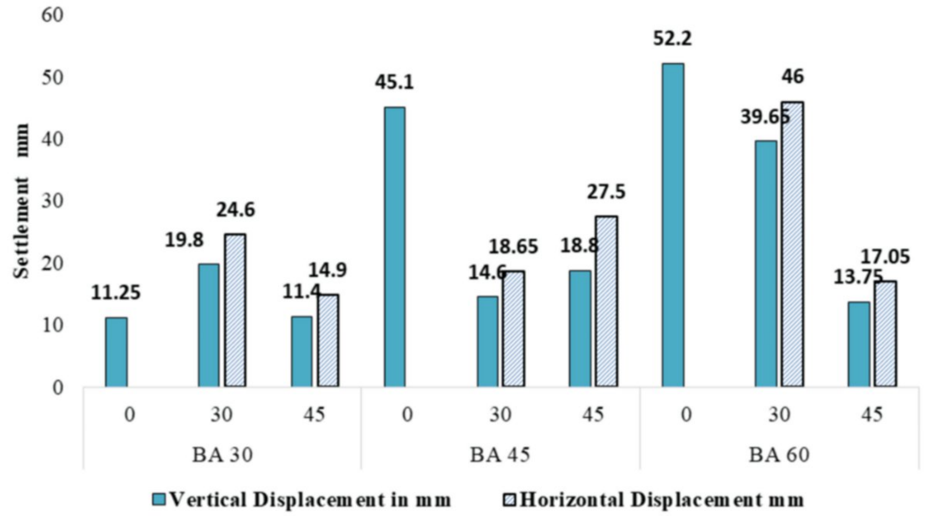

FIGURE 24: Vertical and horizontal displacement of piles, with a diametric ratio of 1.5, and a tapered angle of 2 degrees

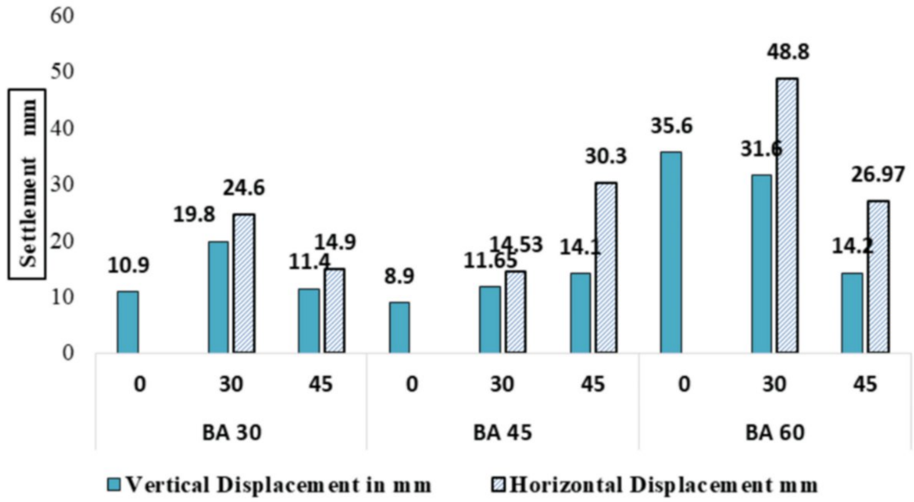

FIGURE 25: Vertical and horizontal displacement of piles, with a diametric ratio of 2, and a tapered angle of 2 degrees

The failure mechanism of the model pile

The tapered piles and belled-wedge piles fail similarly. The bulging of sand occurs at the top of the sand surface; these slip surfaces usually develop from the bottom of the pile and reach the top at the stage of applying uplift load. This means the failure surfaces develop from the bottom edge of the pile and extend up to the top of the sand bed.

Axial Slip Failure

The vertical loading of piles was applied with a zero-degree loading angle. The pile fails axially under ultimate uplift loading. It is observed that bulging of soil occurs on top of the sand bed around the pile. The extension of sand is due to the extension of slip surface above the actual sand bed.

Oblique Slip Failure

The pile fails by pullout failure under oblique load angles of 30 and 45 degrees. Here, the pile fails by combined loading action; the oblique pullout consists of axial and inclined loads.

Discussion

The model piles are positioned with larger diameter at the top and small diameter at the bottom; the larger pile diameter at the top resists the oblique pulling of the pile in the sand bed. Hence, the horizontal component is more than the vertical component, and oblique load carrying capacity is more than the vertical uplift capacity of the pile.

From graphs 7 and 8, it is observed that as the oblique angle increases, the uplift capacity of the tapered pile also increases. Hence, the oblique angle significantly affects the uplift capacity of tapered piles. It means tapered piles perform better in oblique loads than in vertical uplift loads.

From Figures *9* and 10, it is clear that as the oblique angle increases, the uplift capacity of belled-wedge piles reduces. This behavior is because of the enlarged base at the bottom, which will give more resistance in vertical uplift than in oblique loading. The volume of soil covered in vertical loading is higher than the volume of soil column developed under oblique loading. Usually, the failure zones will extend completely up to the top of the sand bed; hence resistance will be more in vertical loading. In case of oblique loading, the failure zones will not extend up to the top of the sand bed, and the failures internally collapse, so the volume of the soil column reduces; hence the uplift load reduces under oblique loading.

The model piles are made up of aluminum. Aluminum is a lightweight metal, which helps with easy operation during installation and removal. The uplift load is a combination of the self-weight of the pile and the frictional resistance of the pile. Since the pile surface is smooth, the frictional resistance is also very negligible. In this present study, when the load is applied to the conventional tapered pile, the sand column developed will be cylindrical. The cylindrical sand column fails easily without taking much load under vertical pullout. Since the pile is tapered, which means the maximum diameter will be at the top and lesser diameter will be provided at the bottom, hence there will be easy uplift of the pile occurring without taking much load. In case of inclined loads, the sand column developed will be resisted by lateral sand, which increases the horizontal component; hence as the oblique angle increases, the uplift capacity also increases in case of tapered piles.

From graphs 11 and 12, it is clear that as the oblique angle increases, the uplift capacity of the pile decreases. Since the tilting of the pile with the vertical axis leads to the collapse of the soil column in the failure zone, the soil formed in the failure zone resists the upward movement against the uplift force. Hence, the tilting of the pile occurs due to the application of inclined loads; these loads decrease the uplift capacity of piles, and special attention should be given in case of oblique loads. Therefore, the oblique uplift loads are not significant for pile foundations.

From Figures *13* and 14, it is clear that the piles with a diametric ratio of 1.5 and 2 are performing well at a load inclination angle of 0 degree. The pullout capacity of the pile decreases as the oblique angle increases and further, as the bell angle increases, the pullout capacity also increases.

From the graphs 15 and 16, it is clearly observed that as the oblique angle increases, the pullout capacity decreases and further, as bell angle increases the uplift capacity increases. This behavior is due to the enlarged base at the bottom; hence the enlarged base at the bottom leads to the development of a larger soil column within the failure zone.

From the graphs 17 and 18, as the bell angle increases, the uplift capacity significantly increases, and as the D_b/D_{avg} ratio increases, the uplift capacity increases. This behavior is due to the enlarged base at the bottom of the pile. The increase in Db/Ds ratio is optimal in case of vertical uplift and it reduces in oblique loading of 30 and 45 degree load inclination. The behavior is similar to comparison of overall results by Kong et al. and it is suggested that, belled-wedge piles provide more uplift capacity than tapered piles. Hence belled-wedge piles perform much better under uplift loads.

From Figure *19*, it is noted that an increase in taper angle will reduce the uplift capacity by 25% to 45% in tapered piles. the pullout capacity was increased from 9 to 19% as the oblique angle increased. Patra and Pise also observed the same kind of behavior.

From Figure *20*, it is noted that the uplift capacity increases as bell angle increases and uplift capacity decreases as oblique angle increases. The uplift capacity is also affected by varying D_b/D_{avg} ratios. This kind of behavior was also observed by Binu Sharma and Poly Buragohain [25].

In case of belled-wedge piles, as bell angle increases from 30 to 60 degrees, the uplift capacity was found to increase by 7%-15%.

Also, as the ratio of D_b/D_{avg} (diameter of bell to average diameter of shaft) increases, the uplift capacity was found to increase by 3%-25%.

The uplift capacity of 1 degree tapered pile is 8% to 34% higher than 2 degree tapered belled-wedge pile under different bell angles and oblique angles. This behavior was also noticed by Dhatrak et al. and Kong et al.

The percentage of vertical deformation of the belled-wedge pile was observed to vary between 2% and 18% of pile diameter to reach the ultimate pullout capacity.

The percentage of horizontal movement of the pile was observed to vary between 10% and 50% of pile diameter to reach the ultimate pullout capacity.

Conclusions

In the present study, a series of model tests on belled-wedge piles subjected to vertical and oblique pullout capacity have been carried out. The following conclusions are drawn:

The pile of 1 degree taper angle performs better than 2 degree taper angle in resisting axial and oblique pullout loads, for both tapered and belled-wedge pile. For tapered pile, the ultimate axial pullout load of 42 N decreased to 2 N when taper angle increased from 1 degree to 2 degrees.

In case of tapered pile, the pullout capacity was found to increase with an increase in oblique loading angle and the maximum capacity is attained at 45 degrees. The ultimate pullout load of 1 degree tapered pile has increased from 42 N to 50 N as oblique angle increased from 0 degree to 45 degrees.

In case of belled-wedge piles, the pullout capacity was found to decrease with an increase in oblique loading angle and the maximum capacity is attained at 0 degree. The ultimate pullout load of 1 degree belled-wedge pile has increased from 298 N to 200 N when oblique angle increased from 0 degree to 45 degrees.

The use of a bell at the bottom of tapered pile has significantly increased both axial and oblique pullout capacity. The axial pullout capacity of the pile increased from 42 N to 298 N by the use of 30 degree bell at the bottom of 1 degree tapered pile.

As bell angle increases, the ultimate axial and oblique pullout capacity was found to increase in all the combinations. For belled-wedge pile, the ultimate axial pullout load of 298 N increased to 351 N when bell angle increased from 30 degrees to 60 degrees.

As the diameter (D_b/D_{avg}) ratio increases, both the axial and oblique pullout capacity of belled-wedge pile were found to increase. At 60 degree bell, for belled-wedge pile the ultimate axial pullout load of 248 N increased to 283 N when D_b/D_{avg} increased from 1.5 to 2 degrees.

The present study will be useful in designing foundations subjected to significant uplift loads and oblique pullout loads, as in the case of solar panels, wind turbines, transmission towers, and offshore structures, and other similar applications.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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