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Finite Element Analysis on Behavior of Single Battered Pile in Sandy Soil Under Pullout Loading

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ABSTRACT

Batter piles are the piles driven in the soil at an inclination with the vertical to withstand oblique loads or large horizontal loads and have been widely used to support high buildings, offshore buildings, and bridges. These constructions are risky because of the exposure to moments and overturning resulting from winds, waves, and ship impact. A 3D FEA using PLAXIS 3D software was used to investigate the effect of several variables that affect the behavior of single batter piles under pull-out loads. The study is achieved on a steel pipe pile model embedded in a dry sandy soil with three relative densities (loose, medium, and dense) at different inclination angles and three embedment ratios, L/D of 25, 37.5, and 50, respectively. The numerical results showed that the ultimate pull-out resistance of the battered pile raise as the battered angle increases reaches a maximum value, then decreases. The ultimate pull-out load capacity of a single battered pile is directly proportional to the slenderness ratio and relative density; the ultimate pull-out load increases with the increase in the ratio of slenderness and relative density. The ultimate uplift load of the battered pile was less affected by the free-standing length. Vertical and battered piles at a battered angle of (10^{o} and 20^{o}) and free-standing lengths equal to zero have higher ultimate pull-out capacity; by increasing the free-standing length, the ultimate pull-out capacity decreased.

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1. INTRODUCTION

Batter piles are used to support marine structures, towers, bridges, and tall chimneys since the type of structures are subjected to lateral load, pullout load, and/or overturning moments due to wind, waves, and ship impact. Battered piles transfer the induced overturning moment and the lateral load partially into compression or/and tension forces. A few studies have been carried out experimentally as well as numerically to evaluate the batter piles capacity under pullout loading.

Zhang et al. [1] performed an experimental investigation to study the effect of the batter pile angle in addition to sand density on the lateral load capacity of a battered pile. Results showed that the batter pile angle and soil density affect lateral pile capacity. Bose and Krishnan [2] performed experimental tests on vertical and batter model piles constructed in sandy soil and subjected to pullout loads to investigate the effect of pile inclination and pile length. The results showed that the ultimate pullout capacity increases with an increase in a length to diameter ratio; also, the ultimate pullout capacity increases with increasing pile batter angle attain a maximum value and then decreases.

Rahimi and Bargi [3] carried out a three-dimensional finite element analysis using ABAQUS software to study the effect of pile inclination angle. The results showed that the change in the pile inclination could significantly influence the distribution of pile forces and moments; as the pile inclination angle increases, the pile displacement decreases.

Nazir and Nasr [4] conducted tests on the steel pipe pile model in loose, medium, and dense sand with different embedded lengths and with various batter angles to study the effect of different parameters on the ultimate pullout load capacity of battered pile. The results indicated that when the batter angle increases, the ultimate pullout capacity of a battered pile constructed in

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dense and medium sand increases, while in loose sand, the ultimate pullout capacity decreases with an increase in the pile batter angle. The ultimate pullout capacity increases with an increase in the embedment ratio and relative density of sand.

Gaaver [5] conducted experimental model tests on single piles and pile in groups embedded in the sand and subjected to uplift loading to investigate the effect of pile embedment depth, relative density of soil, and piles arrangement in a group on the uplift capacity. The results concluded that the pile capacity increased with an increase in the relative density of the soil and the pile embedment ratio.

Al-Neami et al. [6] studied the ultimate capacity of a single pile model subjected to a compression load. The results indicate that an increase in battered angle would increase the pile capacity until it reached the peak value at 20°; then, the capacity decreased. Also, they studied the effect of relative density and slenderness ratio on pile load capacity. Increasing the relative density of the sand by 1.5 times will increase the pile load capacity twice, and the load capacity of the battered pile is less affected by an embedded ratio (L/D). Gebrselassie [7] presented FEA to investigate the response of a battered pile under horizontal, vertical, and oblique loads. It was noted that when the batter angle increases, a pile load-carrying lateral capacity increases until the angle reaches -20°; then, the resistance decrease and as the load inclination angle increased, the total and lateral deformation increases. Vali [8] studied the effects of the water table changes on the behavior of a geogrid reinforced soil-footing system on marine soft soil layers in Qeshm Island, Iran. The impacts of the water table and the geogrid layer specifications were evaluated by the finite element analysis to investigate the system's behaviors. The results indicate that water tables played a substantial role in the behaviors of the soil-footing systems. By decreasing the water table, the settlement decreased while the safety factor of the soil-footing system increased. Increasing the tensile strength of the geogrid layer resulted in decreasing the soil-footing system settlement and improving the safety factor of the system. Russo et al. [9] investigated the mechanical behavior of three hybrid piles equipped with strain gauges along the shaft via three loading tests. A new installation procedure for a foundation pile of a new Mall under design in a disused factory area and numerical simulations of the energy hybrid pile behavior was presented. The FEM package PLAXIS 2D was demonstrated to be capable of modeling the most important features of the complex behavior of a heat exchanger pile even with simple constitutive models for soil. The FE package PLAXIS 2D was used to simulate the behavior of an isolated hybrid energy pile installed in pyroclastic sandy soils and subjected to both thermal and mechanical loadings. In the technical literature, many studies were limited to permanent situations where only the maximum temperature variations were considered.

Many factors influence batter piles under pullout loads. Thus, it becomes necessary in geotechnical engineering to understand how they behave and know the variables that affect the design of the pullout capacity of batter piles. Therefore, further investigation is required to provide insight into the influence of different parameters on the batter pile response. In this study, the behavior of the batter pile under a pullout load embedded in the sand is evaluated under different parameters (relative densities, embedment ratio, battered angles, and free-standing length). The recent paper will focus on the behavior of batter piles subjected to pullout loading driven in dry sandy soil by conducting three-dimensional numerical model tests using PLAXIS software on a full scale.

2. VALIDATION OF NUMERICAL MODEL

To check the validity of PLAXIS software, the research carried out by Al-Neami et al. [6] was used. The problem represents pile models with five different inclinations of 0, 10°, 20°, 30°, and 40° constructed in dense sand with a relative density of 80%. The model's domain used in the analysis was 100 cm in length, 75 cm in width, and 70 cm in depth. The dry unit weight of soil is 18.7 kN/m^3, and the internal friction angle equals 40°. The soil was modeled using the Mohr-Coulomb model. The pile used is circular steel solid with a cross-section of 20 mm in diameter pile and an embedment ratio equal to 15. The single vertical and batter piles were modeled as an embedded beam element which is discretized with solid elements. The interface strength reduction factor (R_{inter}) was taken as a manual, and it equals 0.7 as reported by Waterman [10]. A fine mesh was used to obtain accurate numerical results. Figure 1 shows the finite element mesh for soil and pile.

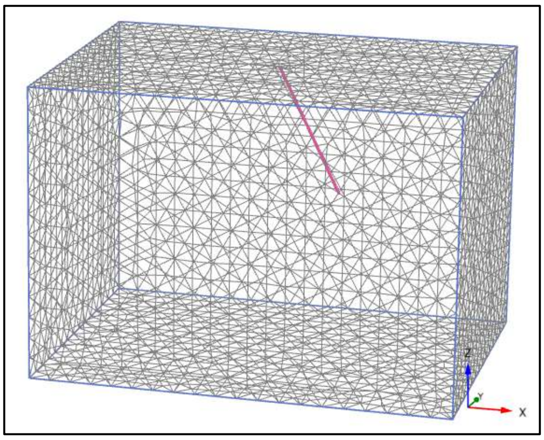


Figure 1. Problem finite element mesh

The load-settlement curves estimated from the numerical model compared with the experimental results of Al-Neami et al [6] as shown in Figure 2 . PLAXIS-3D analysis resulted in excellent agreement with the experimental results.

3. PARAMETRIC STUDY

3. 1. Method of Analysis The pullout capacity of a battered pile is predicated by using PLAXIS 3D software that works on the finite element approach. PLAXIS 3D software is a 3D finite-element analysis program for the nonlinear properties of soil and rock and soil-structure interaction problems. In this studying, the loading is applied axially through a prescribed displacement equal to 0.1D, (where D diameter of the pile) instead of applying the axial load for a better comparison of the results.

3. 2. Soil Modeling The properties of the sand used in this analysis are taken directly from laboratory tests carried out by Al-Neami et al. [6]. The soil is assumed to obey the advanced Mohr-Coulomb yield criterion. The soil properties used are listed in Table 1.

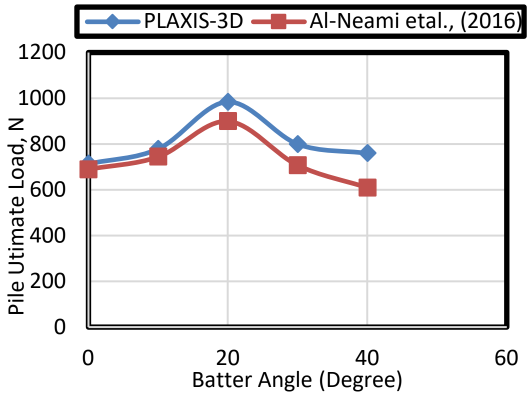


Figure 2. Validation of the result obtained from PLAXIS-3D and Al-Neami et al. [6]

TABLE 1. Properties of soil

Parameters	Unit	Loose sand	Medium sand	Dense sand
Relative density, RD	%	40	60	
Dry weight, γ_d	kN/m^3	17.3	18	18.7
Internal friction angle, φ	°	33	37	40
Dilaatancy angle, ψ	°	3	7	10
Young's modulus, E	kN/m^2	10000	20000	30000
Poisson's ratio, μ	-	0.15	0.2	0.25

*assumed values from Budhu [11].

3. 3. Pile Modeling The pile used in this study is a circular pipe with a 0.4 m diameter, and the corresponding lengths are 10, 20, and 30 m. The pile has been modeled as elastic; where the elastic model describes the pile material. The pipe pile is modeled as closed-ended from top and bottom. The strength reduction factor R_{inter} is assumed to be 0.7 based on the interaction between steel and sand, which ranges from (0.6 - 0.7) depending on the surface roughness of the pile Waterman [10]. The input parameters of the pile in PLAXIS 3D analysis are listed in Table 2.

3. 4. Geometry and Boundary Conditions The testing box geometry was constructed by dimensions of 60 m x 60 m in the x-axis and y-axis. The soil layer's top boundary is at a depth of z equals zero, while the soil layer's bottom boundary is at a depth of z = 40 m, then the soil characteristics were identified as the soil block. The simulation is performed under drained conditions where the phreatic level is kept at the bottom of the soil.

4. MESH GENERATION

Mesh is a term used to describe a collection of finite elements. PLAXIS allows for a fully automatic generation of finite element mesh. So to acquire precise numerical results, the mesh should be fine enough. Extremely fine meshes must be avoided because they would result in excessive calculation. To perform the finite element computations in this numerical study; the geometry of the model was divided into the numbers of finite elements to be fully defined. The soil elements of the 3D-finite element mesh are the 10-node tetrahedral elements. Figure 3 shows the soil model, pile geometry, and mesh generated in PLAXIS 3D.

5. RESULT AND DISCUSSION

5. 1. Single Pile Load-Displacement Curve The ultimate axial pullout load of vertical and batter pile was obtained from load-displacement curves. The

TABLE 2. Properties of the pile

Parameters	Unit	Value
Material type	-	Steel
Diameter, D	m	0.4
Wall thickness, t	m	0.01
Unit weight,	kN/m^3	78
Young's modulus, E	kN/m^2	200x10^6
Poisson's ratio	-	0.3

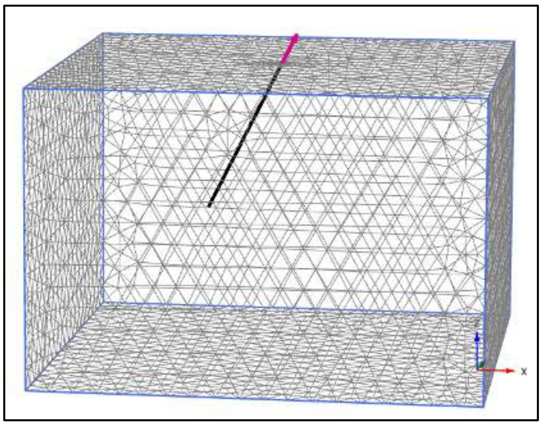
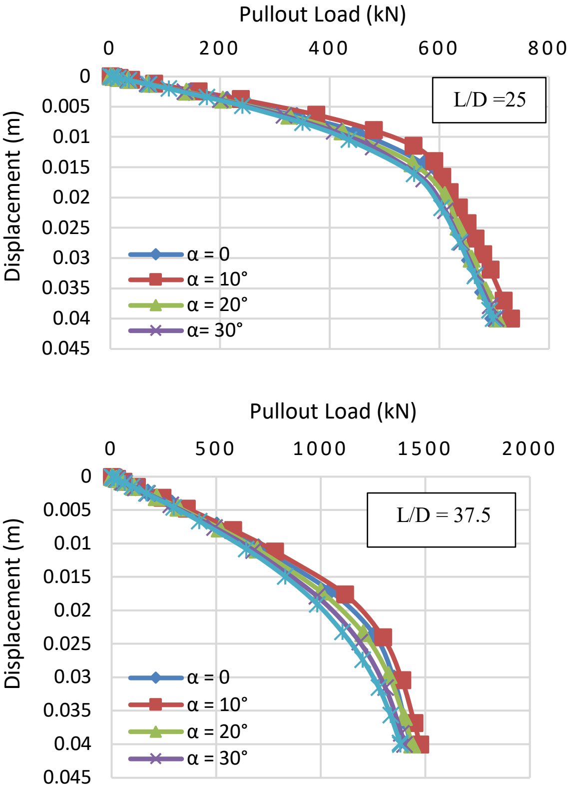


Figure 3. 3D FE mesh for soil and pile

ultimate pullout capacity of the pile is obtained from the load-displacement curve as 10% D (Where D is the pile diameter). Figures 4-6 show the axial pullout load versus displacement for piles having different L/D ratios for different batter angles in soil with different relative densities.

5. 2. Effect of Pile Batter Angle The effect of battered angle (α) on the ultimate pullout load capacity is investigated through a selection of vertical and inclined piles with angles (10°, 20°, 30°, 40°) installed in the



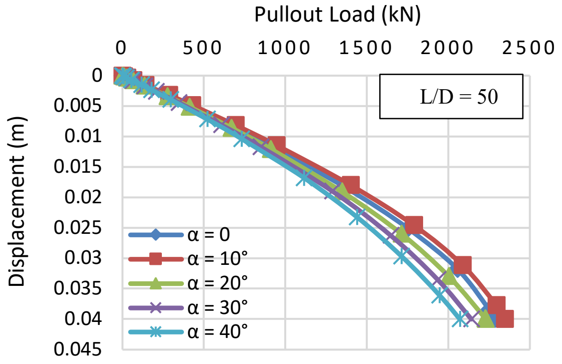


Figure 4. Load-displacement curve for vertical and batter pile under different embedment ratio in loose sand RD = 40%

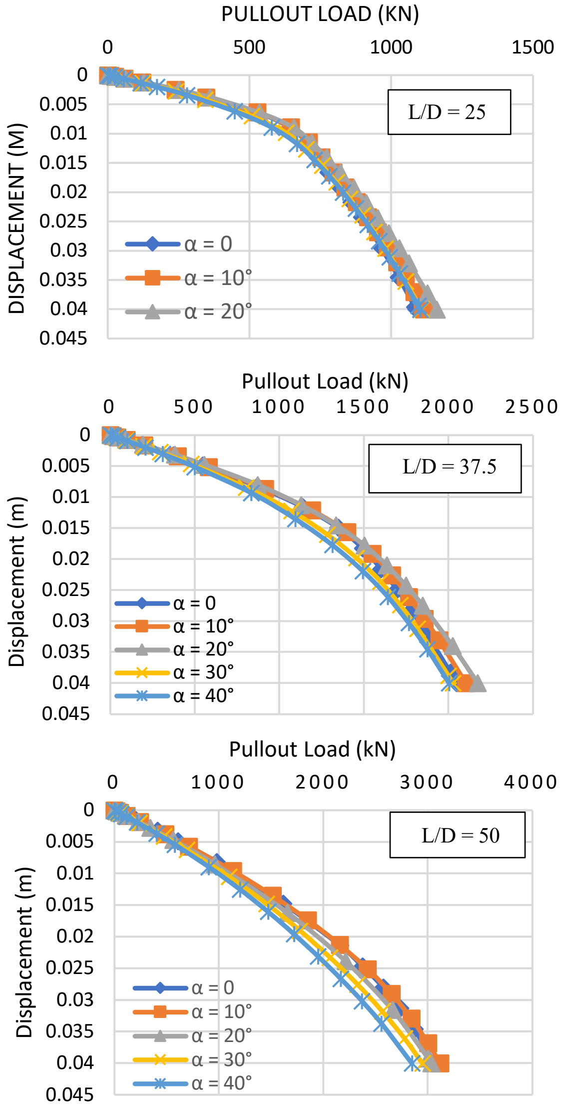


Figure 5. Load-displacement curve for vertical and batter pile under different embedment ratio in medium sand RD = 60%

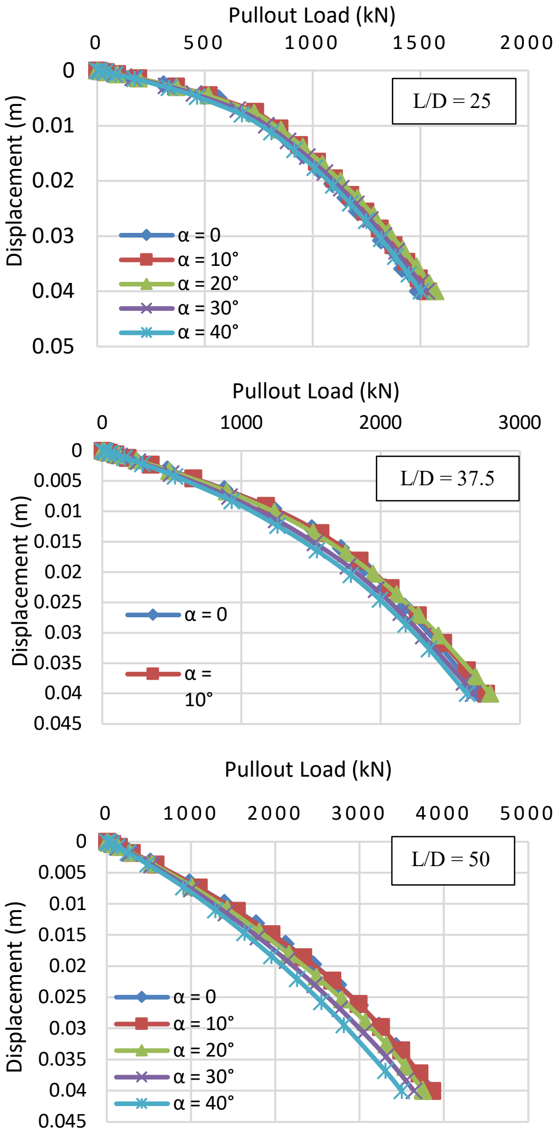


Figure 6. Load-displacement curve for vertical and batter pile under different embedment ratio in dense sand RD = 80%

loose, medium, and dense sand with different embedment ratio (L/D) equals 25, 37.5, and 50. Figure 7 shows the variation of the ultimate pullout load with batter angle. It is seen that the ultimate pullout load capacity increases with an increase in batter angle, reaches its maximum value, and then decreases. For piles constructed in loose sand, RD = 40% maximum value is attained at batter angle equal to 10° for all L/D ratios, and it is about 2.6 to 4.5 % higher than that of the vertical pile. For piles constructed in medium and dense sand, the increasing of battered angles increases the pile load capacity until the maximum value is attained at angle 20°, after which the resistance decreases for L/D ratio equal to 25 and 37.5. The increased percentage of the battered pile at 20° ranges between (3.08-6.67) % higher than that of the vertical piles. Results obtained were close to the finding of Nazir and Nasr [4].

5. 3. Effect of Pile Embedment Ratio

Three different L/D ratios (25, 37.5, and 50) were used to study the effect of the pile embedment ratio of vertical and batter piles. Figure 8 gives the relationship between the ultimate pull out capacity and pile embedment ratios L/D with different batter angles at 40%, 60%, and 80% relative densities. The embedment ratio has a major

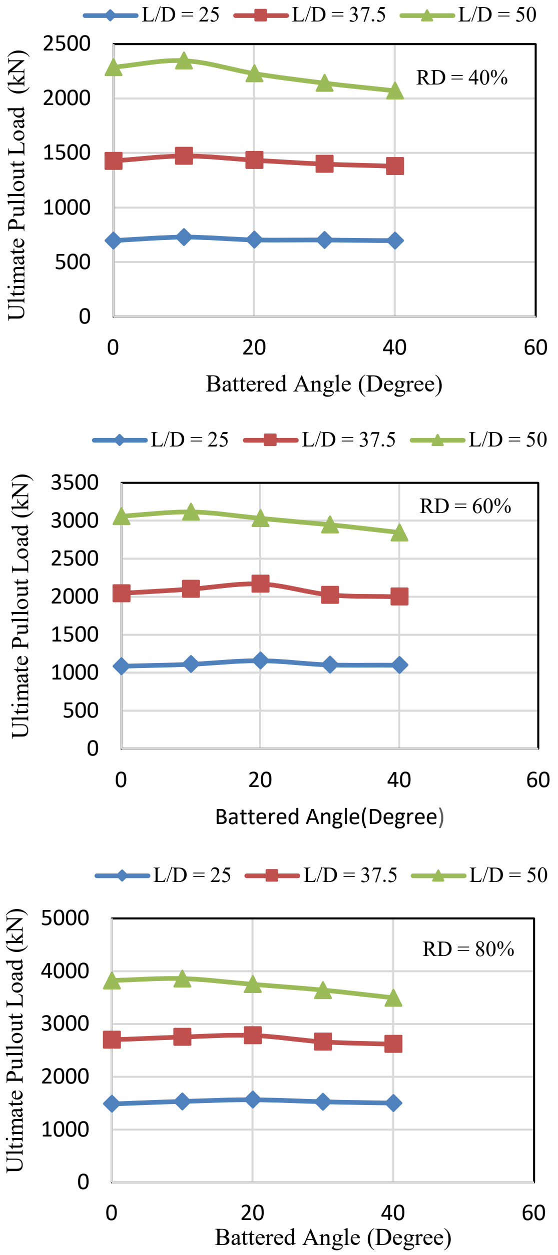


Figure 7. Ultimate pullout load capacity variation with batter angle under different embedment ratios

influence on a single pile's ultimate pull out load capacity. Results obtained were close to the finding of Gaaver's [5].

5. 4. Effect of Relative Density of Sand Figure 9 shows the ultimate pull out load capacity variation with a batter angle for different sand densities. The figure confirmed that an increase in the relative density improves the ultimate pull out load capacity of vertical and batter piles for all L/D values.

When the relative density of sand increases from 40% to 60%, the ultimate pulls out load capacity increases by about 34-56% for vertical pile and 36-64% for battered pile at angle 20°. When the relative density of sand increases from 40% to 80%, the ultimate pulls out load capacity improves by 67-112% for vertical piles, and 68-122% for batter piles at an angle of 20°. When relative density increases, the angle of friction between the soil

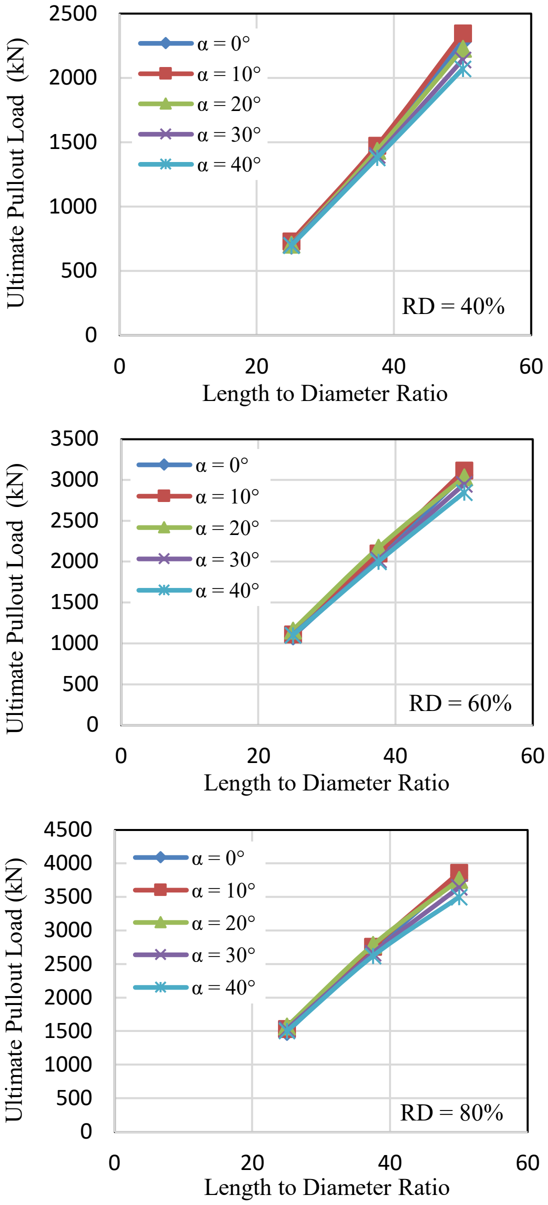


Figure 8. Ultimate pullout load capacity with length to diameter ratio under different batter angles

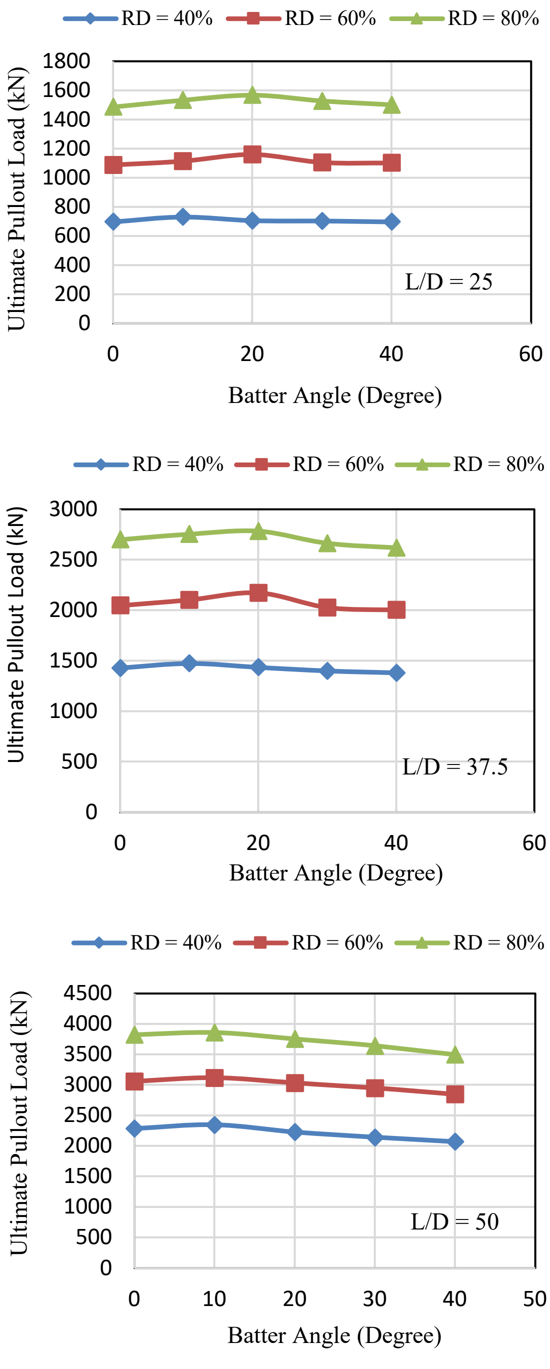


Figure 9. Ultimate pullout load capacity variation with batter angle under different relative densities

and pile increases, and thus, the effective stress and skin friction also increase. These results are conjugated with Al-Neami et al. [6] results.

5. 5. Effect of Free-Standing Length Free-standing of the pile (unsupported pile length) is the pile height above the ground level, in which the pile cap doesn't in contact with the underlying soil. The effect of free-standing length e on the ultimate pull out load capacity has been studied for single vertical and batter piles. PLAXIS 3D model has built for the sandy soil of 80% relative density; the pile length has kept a constant and equal to 15m, while the free-standing length was varied (e = 0.0, 10 cm, and 20 cm) as shown in Figure 10.

Figure 11 shows the ultimate pull out load capacity variation with the free-standing length for different batter pile angles.

It can be found that the vertical pile at zero free-standing has a higher ultimate pull out load capacity, while for batter piles, the pull out load is the highest at the batter angle of 20° and the free-standing length is zero. After which, the pull out load starts decreasing with an increase in the free-standing length. When the angle of inclination reaches more than 20° (30° or 40°), it can be noticed that the pull out load decreases at zero free-standing, and when the (e) increases to 0.1 m, the pull out load increases, then it shows a slight decrease at 10cm e.

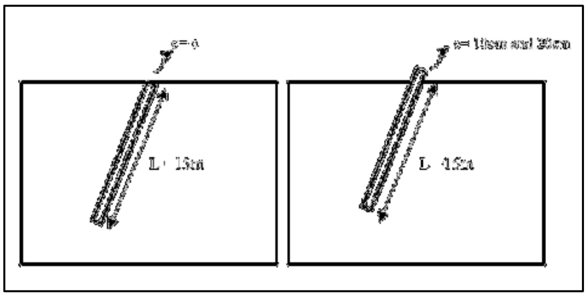


Figure 10. Free-standing length, e.

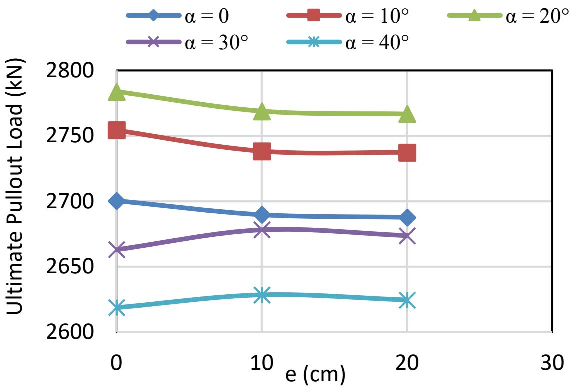


Figure 11. Variation of ultimate pull-out load capacity with free-standing length, RD = 80%

This behavior is attributed to the surrounding soil that will provide sufficient support to the embedded pile. Therefore, the free-standing slightly affects ultimate pull out load capacity due to mobilizing the skin friction.

6. CONCLUSION

This research implicated a 3D FEA to study the influence of several parameters affecting the pullout capacity of battered piles. The overall results may be ordered as follows:

1. The ultimate pullout load capacity of a single battered pile increases with an increase in batter angle α, reaches its maximum value, and then decreases. The maximum value of ultimate pullout load capacity corresponds to batter angle α, dependent on the relative density of soil and the length to diameter ratio L/D of the pile.
2. For piles constructed in loose sand, the batter angle that equal to 10° has the highest pullout load capacity for all L/D ratios, and it is about 2.6 to 4.5 % higher than that of the vertical pile
3. In medium and dense sand with a slenderness ratio equal to 25 and 37.5, the ultimate pullout load value is at a battered angle of 20°. While for batter pile with L/D equal to 50, the ultimate value is at 10°.
4. The increse in the ultimate pullout load capacity with increasing the pile inclination angle has occurred as a result of the interfacial bonding effect due to the increase of the friction angle between the pile shaft and surrounding soil.
5. The slenderness ratio influences the ultimate pullout load resistance of vertical and battered piles; the increase of ultimate uplift capacity when L/D increased from 25 to 50 was approximately doubled.
6. The ultimate pullout capacity of vertical pile bent in loose sand was increased about 227% when the L/D was increased from 25 to 50, while in dense sand, the increase in ultimate pullout capacity was 157%.
7. The increase in ultimate pullout capacity with an increased L/D ratio is due to the increase in the skin friction resistance between the soil and the pile; when the slenderness ratio increases, the shaft resistance increases. The increase in the shaft resistance is due to the increase in the overburden pressure with the slenderness ratio generates the horizontal earth pressure that acts as a normal force on the pile shaft.
8. The relative density has an impact on the ultimate resistance pullout load capacity of vertical and battered piles. When the relative density of sand increases from 40 % to 60%, the ultimate pullout capacity increases by about 34-56% for vertical pile and 36-64% for battered pile at an angle of 20°.

When the relative density of sand increases from 40% to 80%, the ultimate pullout capacity improves by 67-112% for vertical piles and 68-122% for batter piles at an angle of 20°.

9. The relative density of sand greatly affects the ultimate load pullout capacity. When relative density increases, the friction angle between the pile and soil increases, and thus, the effective stress and skin friction also increase.
10. Vertical and batter pile at a battered angle (10^o and 20^o) and free-standing lengths equal to zero have higher ultimate pullout capacity; by increasing the free-standing length, the ultimate pull-out capacity decreased. This behavior is attributed to the surrounding soil that will provide sufficient support to the embedded pile. Therefore, the free-standing slightly affects ultimate pullout load capacity due to mobilizing the skin friction.
11. The ultimate pullout load capacity of the battered pile was less affected by the free-standing length.

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Persian Abstract

چکیده

شمع های خمیر شمع هایی هستند که در خاک با شیب عمودی رانده می شوند تا بارهای مورب یا بارهای افقی بزرگ را تحمل کنند و به طور گسترده برای حمایت از ساختمان های مرتفع، ساختمان های فراساحلی و پل ها استفاده می شوند. این سازه‌ها به دلیل قرار گرفتن در معرض لحظات و واژگونی ناشی از باد، امواج و برخورد کشتی خطرناک هستند. یک FEA سه بعدی با استفاده از نرم افزار PLAXIS 3D برای بررسی اثر چندین متغیر که بر رفتار شمع های خمیر منفرد تحت بارهای کششی تأثیر می گذارد، استفاده شد. این مطالعه بر روی یک مدل شمع لوله فولادی تعبیه شده در خاک شنی خشک با سه تراکم نسبی (سست، متوسط و متراکم) در زوایای شیب مختلف و سه نسبت تعبیه، L/D به ترتیب ۲۵، ۳۷.۵ و ۵۰ به دست آمد. نتایج عددی نشان داد که مقاومت نهایی شمع ضربه‌خورده با افزایش زاویه ضربه‌خورده به یک مقدار حداکثر می‌رسد و سپس کاهش می‌یابد. ظرفیت بارکشی نهایی یک شمع کوبیده شده مستقیماً با نسبت باریکی و چگالی نسبی متناسب است. بار کشش نهایی با افزایش نسبت باریکی و چگالی نسبی افزایش می یابد. بار بالابر نهایی شمع ضربه خورده کمتر تحت تأثیر طول ایستاده آزاد قرار گرفت. شمع‌های عمودی و ضربه‌خورده با زاویه ضربه‌خورده (۱۰ و ۲۰ درجه) و طول‌های ایستاده برابر با صفر ظرفیت بیرون‌کشی نهایی بالاتری دارند. با افزایش طول ایستادن، ظرفیت خروجی نهایی کاهش یافت.