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A Numerical Analysis on Pullout Capacity of Batter Pile Groups in Sandy Soil

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HIGHLIGHTS

- The pullout capacity of a batter pile group attains maximum value at a 20° batter angle
- Batter piles have a higher lateral load resistance than vertical piles.
- The pullout load capacity of groups increases with the increase in the embedment ratio
- Pullout capacity of vertical and batter piles improves significantly with increasing RD
- The negative batter pile group has more load capacity than the positive batter pile group

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ABSTRACT

Batter piles or raker piles are the piles driven in the soil at an inclination with the vertical to resist inclined forces or large lateral loads. Battered piles are widely utilized to support offshore buildings, towers, and bridges since these structures are risky due to the exposure to overturning moments resulting from winds, waves, and ship impact. This paper used a three-dimensional finite element analysis using PLAXIS 3D software to study the effect of several variables that affect the behavior of batter piles in a group under pullout loads. The study is conducted on a steel pipe pile model embedded in a dry sandy soil with three different relative densities (loose, medium, and dense sand) at different inclination angles and three embedment ratios L/D of 25, 37.5, and 50, respectively. The finite element model was carried out on a pile group of 2×1 with different configurations. The numerical results indicated that for all pile configurations, the pullout capacity of the batter pile group increased when the embedded ratio and relative density increased, and the maximum value was attained at a 20° batter angle. Furthermore, batter pile groups with BB (group with two battered piles) configuration of (-20°, +20°) gave a high resistance to the pullout load compared to other configurations of the pile group. In addition, pile Groups with battered piles marked the resistance to the pullout load more than pile groups that contain only the vertical piles.

1. Introduction

Batter piles have a higher lateral load resistance than vertical piles. Vertical piles resist the lateral loadings exclusively through the shear and bending, while battered piles carry lateral loads partially in axial compression or/and tension. As a result, batter piles have a higher lateral bearing capacity and stiffness than vertical piles. The angle formed by the pile with the vertical is known as the batter degree. Batter or the negative batter piles are formed when the lateral loads act in the batter inclination direction with the vertical, whereas out the batter or positive batter piles are formed when the lateral loading acts in the opposite direction of the batter inclination with the vertical. Several investigations have been carried out experimentally and numerically to evaluate the batter piles' capacity. Atici [1] developed a 3D numerical study to investigate the resistance of a single batter pile in the sand under uplift loadings using "ABAQUS" version 6.6. The study concluded that the shaft capacity of the single pile was reduced with the increase of inclination angle α, and the shaft resistance was highly dependent on pile dimension (diameter and length) and the friction interface angle. A three-dimensional finite-difference analysis using FLAC3D was performed by Hazzar et al. [2] to study the behavior of laterally loaded battered piles in sand. The results showed that increasing batter angle and soil density significantly increases battered pile lateral capacity for negative batter angles. The lateral capacity is slightly reduced for positive batter angles, and the total capacity is moderately increased. The influence of relative density and embedded length of piles on the ultimate load of single and pile groups with two configurations (1x2) and (2x2) was investigated by Rahil et al. [3]. The results showed that as the relative density increased, the ultimate load of the single and pile groups increased. The increase in the pile embedded length causes a higher ultimate load capacity and a lower settlement ratio. Parthipan and Kumar [4] found that the single pile behavior under pullout loads mainly depends on the L/D ratio and the soil's relative density. In contrast, pile behavior in a group under pullout loading mainly depends on the soil's relative density and piles arrangement in the group.

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Singh and Arora [5] conducted 66 tests on batter pile groups in the sand to investigate the effect of the pile inclination direction and the batter angle influence on the load-carrying capacity of the batter pile group. The results indicated that negative batter piles showed more resistance than positive batter piles. The study also found that the effect of batter angle is parabolic; increasing the batter angle causes a reduction in the load-carrying capacity. Naveen et al. [6] presented a laboratory study on groups containing batter piles to investigate the influence configuration of the pile group, batter angle, sand density effect, and loading direction on ultimate uplift resistance. It was concluded that the increase in soil relative density and inclination angle led to increased uplift pile capacity. The batter pile group gives more resistance than the vertical pile group, and the positive batter pile groups give less load capacity than the negative batter pile groups. Sabbagh et al. [7] studied the arrangement effect of pile groups on the lateral response of 1×2 capped battered pile groups with different configurations. The study showed that the batter pile groups with positive and negative batter pile configurations of (−10°, +10°) give a higher resistance to the lateral load than other pile groups with the same pile spacing. Gebrselassie [8] presented a 3D finite element analysis using PLAXIS software to study the behavior of batter and vertical piles subjected to the lateral, axial, and inclined loads. The study attempted to examine the effect of battered angle on the ultimate lateral and axial load capacity. It noted that when the batter angle increased, a pile load-carrying capacity increased until the battered angle reached 20°. Then, the resistance started to decrease. The vertical monotonic load effect on the ultimate vertical load capacity of the batter pile group has been investigated using fourteen steel solid pile models by Al-Neami et al. [9]. The results show that the slenderness ratio (L/D) has a major impact on the ultimate load capacity of pile groups. For both batter and vertical pile groups, the load capacity has been improved as the relative density of soil is increased.

Most previous studies focused only on the behavior of batter piles under lateral loads. However, little research dealt with the behavior of batter piles under pullout loads. Therefore, this research analyzes the behavior of pile groups embedded in sandy soil under pullout loads under several circumstances.

The recent numerical study aims to investigate the influence of embedment ratio, soil relative density, and batter pile arrangement in the group on the pullout load resistance of the batter pile group embedded in sandy soil with different configurations using PLAXIS 3D software.

2. Method of Analysis

The pullout capacity of the batter pile group is predicated using PLAXIS 3D software based on the finite element approach. PLAXIS 3D software is a three-dimensional finite-element analysis program for the nonlinear properties analysis of rock and soil. To study the batter pile group behavior under a pullout load in the sand, the pile groups were evaluated under different (relative densities, embedment ratio, and pile groups configuration). In this analysis, the loading was applied axially through a surface displacement of 0.1D (where D was a pile diameter) instead of applying the axial load for a better comparison of the results. This simulation was to obtain pullout loads and load-settlement curves to study the behavior of batter piles.

2.1 Soil Modeling

The properties of the sand used in this analysis are obtained from those reported in Al-Neami et al. model tests [10]. The soil was assumed to follow the advanced Mohr-Coulomb yield criterion. The soil properties used in the analysis are presented in Table 1.

Table 1: Sand soil properties used

Parameter	Unit	Loose sand	Medium sand	Dense sand
Relative density, RD	[%]	40	60	80
Dry unit weight, γ_d	[kN/m^3]	17.3	18	18.7
The angle of internal friction, ϕ	[°]	33	37	40
Dilatancy angle, ψ	[°]	3	7	10
Young's modulus, E_s	[kN/m^2]	10000*	20000*	30000*
Poisson's ratio, μ	-	0.15*	0.2*	0.25*

*assumed values from Budhu [11].

2.2 Pile Properties

The pile model used in this study was a circular pipe with 0.4 m in diameter, and the corresponding lengths are 10, 20, and 30 m. The pipe pile was modeled as closed-ended from top and bottom. The strength reduction factor R_{inter} was 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. The input parameters of the pile in PLAXIS 3D analysis are listed in Table 2.

Table 2: : Pile properties

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

The pullout response has been analyzed for closely spaced batter pile groups of 2x1 with a minimum c./c. Spacing of 3D. The different configurations of piles used for the numerical models, as shown in Figure 1, are encoded as follows:

- Vertical – Vertical (VV), (0°, 0°);
- Vertical – Batter (VB), (0°, +α);
- Batter – Vertical (BV), (-α, 0°);
- Batter – Batter (BB), (-α, +α).

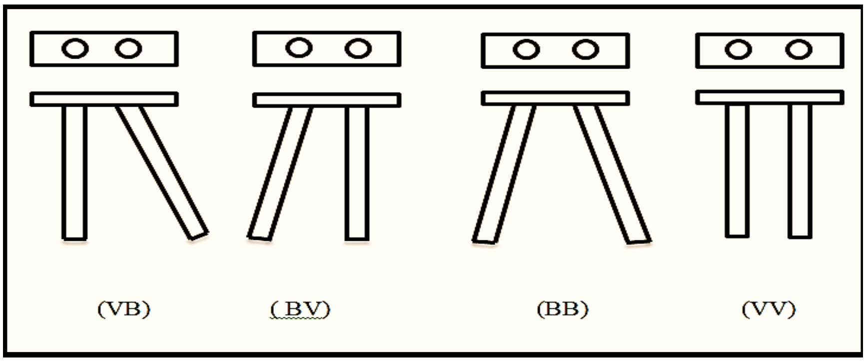


Figure 1: 1x2 pile group configurations

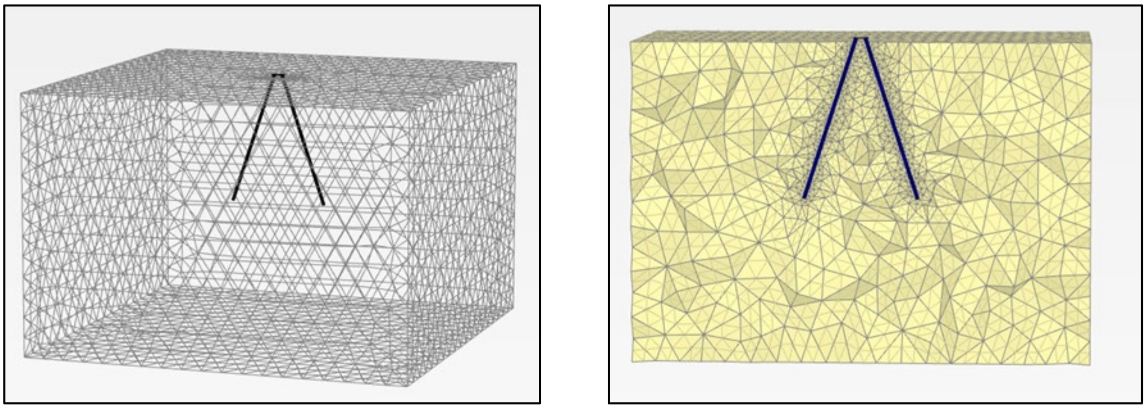


Figure 2: FE mesh for soil and pile

2.3 Geometry and Boundary Conditions

The testing box geometry was constructed by dimensions of 60 m x 60 m on the x-axis and y-axis. The top boundary of the soil layer was at a depth of z equal to zero, and the bottom boundary of the soil layer was at a depth of z equal to 40 m. Then the soil characteristics were identified as a soil block. The simulation is performed under a drained condition at which the phreatic level is kept at the soil's bottom.

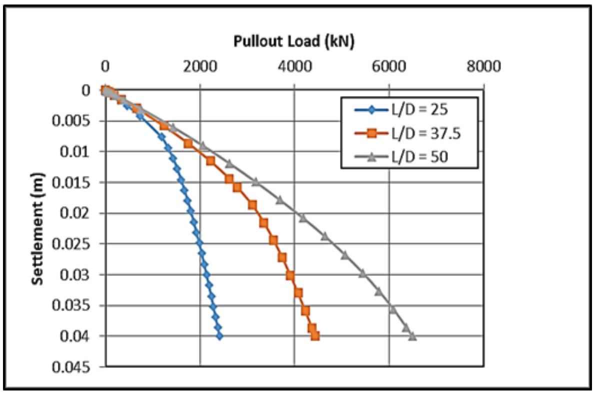
2.4 Mesh Generation

Mesh is a term used to describe a collection of finite elements. PLAXIS allows for a fully automatic generation of finite element mesh. Therfore, to acquire precise numerical results, the mesh should be fine enough. On the other hand, extremely fine meshes must be avoided because they would result in excessive calculation. To perform the finite element computations in this numerical study, the model's geometry 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 2 shows the soil model, pile geometry, and mesh generated in PLAXIS 3D.

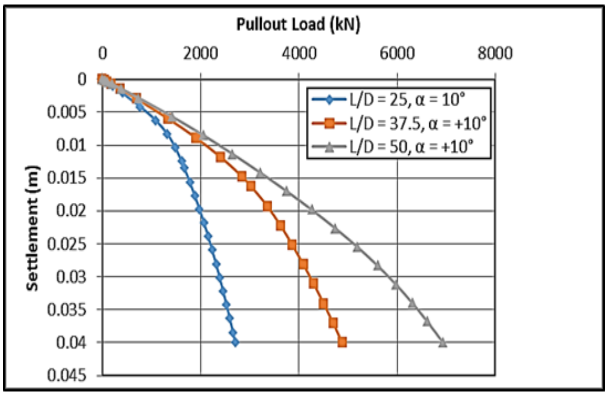
3. Results and Discussion

3.1 Effect of Embedment Ratio

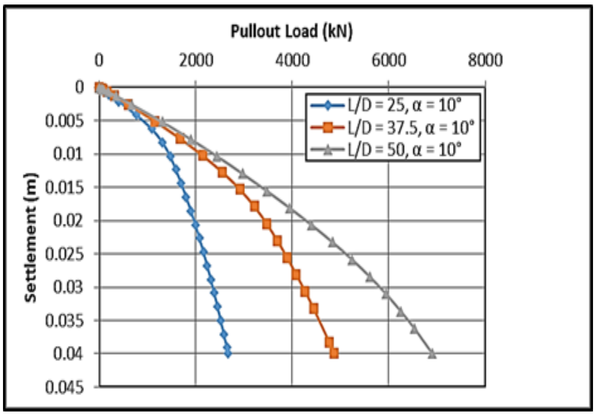
The pile embedment ratio (L/D) affects the ultimate pullout load capacity of the pile group. Resistances increase dramatically as this ratio rises. Three ratios of the L/D (25, 37.5, and 50) were tested. Figure 3 represents a relationship between the pullout load and the settlement for 2×1 group piles embedded in dense sand. For the same relative density, pile group configuration, and at the same batter angle, it can seem that the increase in pullout load of pile groups is doubled with the L/D ratio increase. This increase occurred due to increased skin friction resistance along the pile shaft. This increase is due to the increase of the overburden pressure with the embedment depth that generates the horizontal earth pressure that acts as a normal force on the pile shaft. When the L/D ratio increased from 25 to 37.5, the ultimate load capacity increased about 80-83% for VV, VB, BV, and BB configurations. When the L/D ratio increased from 25 to 50, the ultimate load capacity of pile groups ranged between 1.52 and 1.7 times. A pile with L/D equal to 25 has less ultimate pullout resistance than other L/D ratios. This observation agrees Al-Neami et al. [9] and Al-Neami et al. [12], who reported that the ultimate load increased with an increasing L/D ratio.



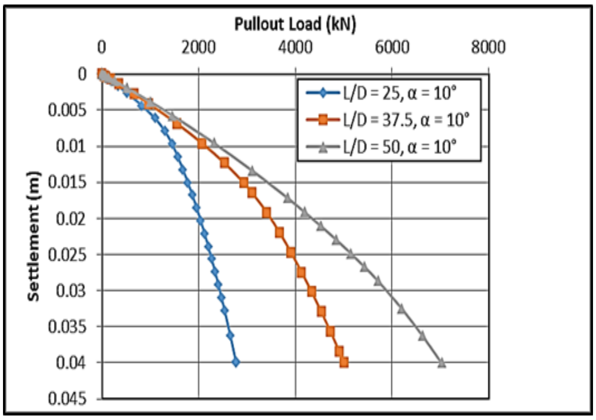
(a) VV



(b) VB



(c) BV

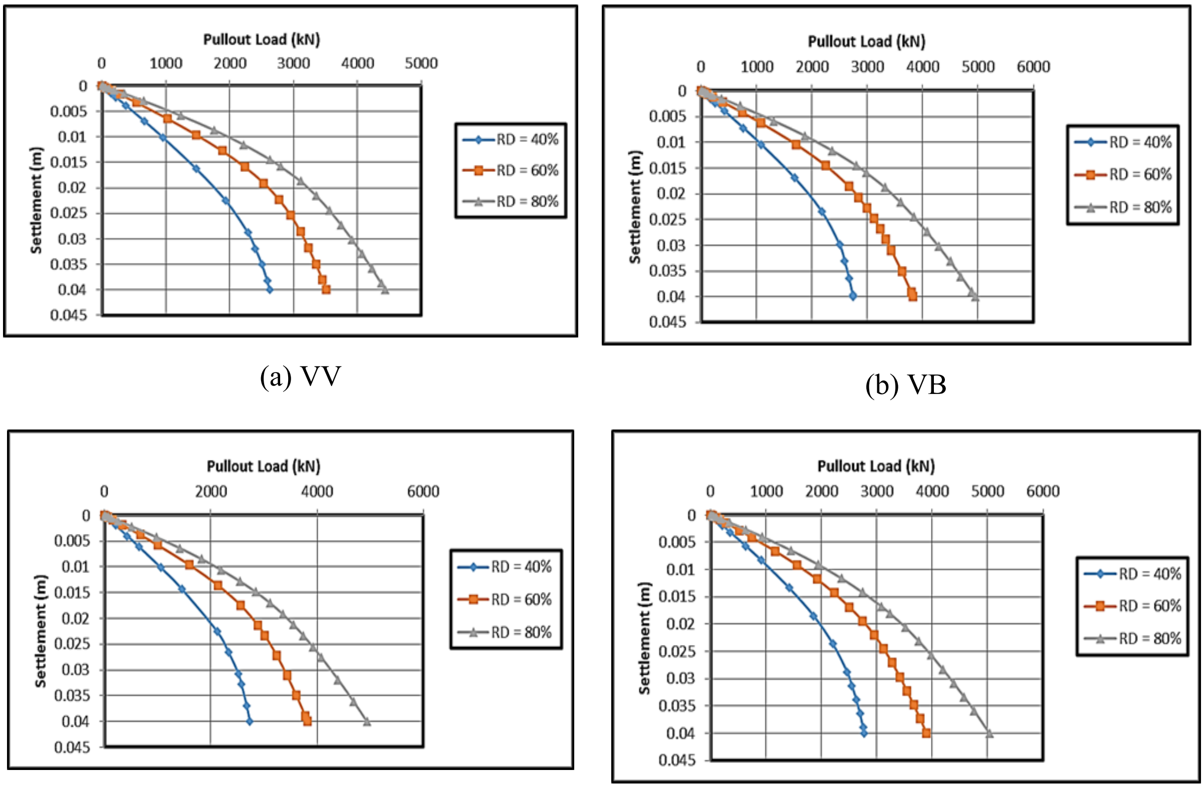


(d) BB

Figure 3: Load-settlement curves for 2x1 pile groups constructed in soil with RD = 80% at α = 10°: a) VV, b) VB c), BV d), BB

3.2 The Influence of Relative Density of Sand

Figure 4 represents the influence of the relative density of sand on the pile group capacity for four pile group configurations. The sand relative density affects the pullout capacity of piles, increasing the relative density of sand from 40% to 60 %, leading to an increase in the ultimate pullout capacity of about 34% and 39% for VV and VB configurations, and 40% for both BV and BB configurations. When the RD increases from 40% to 80%, the ultimate pullout capacity increases about 69% for VV, 76% for BB, and 80% for other configurations (VB and BV). The pullout capacity of the pile significantly improved with the increase in the relative density of sand for vertical and batter piles. This increase occurred because the increase in the relative density of sand led to increased friction forces between grain particles surrounding the pile shaft. Therefore, the group load capacity also increased. This is in agreement with Hazzar et al. [2], Rahil et al. [3], and Al-Neami et al. [13], which reported that the ultimate load increased as the relative density of sand increased.



(a) VV (b) VB

(c) BV (d) BB

Figure 4: Load-settlement curves for 2x1 pile groups under different relative densities at α = 20 and L/d = 37.5: a) VV, b) VB c), BV d), BB

3.3 Effect of Pile Groups Configuration

Figure 5 shows the variation of ultimate pullout load with batter pile angle for the 2x1 group pile with different configurations. Comparing alternative pile group configurations with the same pile spacing leads to a conclusion that the batter pile groups with (BB) configuration of (-20°, +20°) have a higher ultimate pullout capacity.

The pullout capacity of the batter pile group increased as the batter angle increased, attained maximum value at = 20°, and then decreased. When the results are compared with the vertical pile group (VV), as shown in Figure 6, it can find out that the battered pile offers 11%, 12%, and 14% more resistance for BV, VB, and BB configuration respectively than VV group configurations. This occurred due to the interfacial bonding effect due to the increase of friction angle between pile shaft and surrounding soil when the batter angle of pile increases.

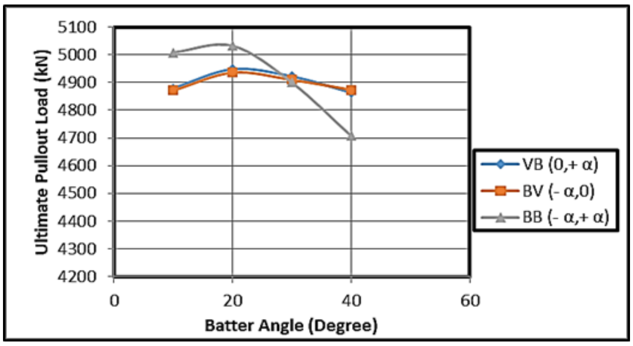


Figure 5: Ultimate pullout load variation with batter angle for BV, VB, BB configuration, RD = 80% and L/d = 37.5

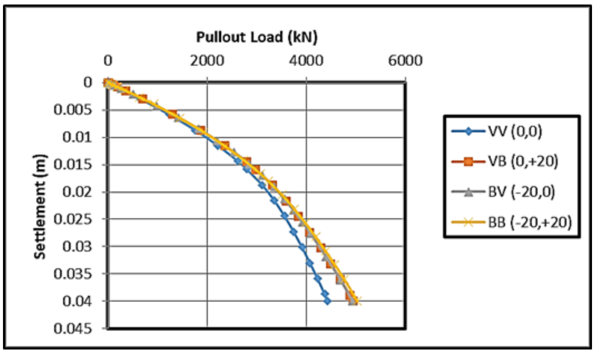


Figure 6: Load-settlement curves for 2x1 pile groups

4. Conclusion

This paper included a three-dimensional analysis to investigate the effect of several variables affecting the pullout capacity of batter pile groups' behavior. The general findings may be outlined as follows:

1) The embedded ratio highly influences the ultimate pullout capacity of pile groups. A pullout capacity of the batter pile group increases with the increase in the embedded ratio. When the L/D ratio increased from 25 to 37.5, the ultimate load capacity increased by about (80-83) %. When the L/D ratio increased from 25 to 50, pile groups' ultimate pullout load capacity increased by about (152-156) %.
2) The pile group pullout capacity increases as the sand relative density increases for all configurations. Increasing the relative density of sand from 40% to 60 % leads to an increase in the ultimate pullout capacity of about 34% and 39% for VV and VB configurations and 40% for both BV and BB configurations. When the RD increases from 40% to 80%, the ultimate pullout capacity increases about 69% for VV, 76% for BB, and 80% for other configurations (VB and BV).
3) The batter pile group's pullout capacity increases as the batter angle increases. The maximum value attains at = 20° and then decreases.
4) A group pile with a BB configuration of (-20°, +20°) gives a high resistance to pullout load more than other pile group configurations with the same pile length, spacing, and batter angle.
5) Pile groups with VV configuration offered the least resistance to the pullout load.
6) Battered pile groups offer 11%, 12%, and 14% more resistance for BV, VB, and BB configurations than VV group configurations.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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