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International Journal of Mining and Geo-Engineering

IJMGE

IJMGE 59-1 (2025) 11-20

DOI: 10.22059/IJMGE.2025.357550.595053

Pullout capacity of plus-shaped multi-plate horizontal anchors in sand

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Article History:

Received: 08 April 2023.

Revised: 15 December 2024.

Accepted: 16 January 2025.

ABSTRACT

In this study, the displacement finite element method was employed to evaluate the load-displacement response and estimate the ultimate pullout capacity of anchor plates. A detailed comparison was conducted between conventional and non-conventional shaped single-plate and multi-plate horizontal anchors. The analysis focused on square and plus-shaped anchors, examining the influence of anchor geometry, embedment depth, plate thickness, tie rod diameter, soil relative density, and spacing between plates on their pullout performance. The results indicated that pullout capacity increases with greater relative density, plate thickness, and embedment depth but decreases with larger tie rod diameters. Square anchors demonstrated 15–40% higher pullout capacities than plus-shaped anchors due to their larger contact area. Multi-plate configurations significantly improved pullout resistance compared to single plates, with critical plate spacing optimizing performance: 1.5b for square anchors and 1b for plus-shaped anchors. For dense sand, plus-shaped multi-plate anchors exhibited comparable pullout capacities to square single-plate anchors despite a 25% reduction in anchor area. At an embedment depth of 15 m, square triple-plate anchors achieved a pullout capacity of 360.6 MPa, while plus-shaped anchors reached 256.8 MPa. Stress distribution analysis revealed localized failure patterns above the anchors, with higher stress concentrations near the plates. These findings highlighted the effectiveness of multi-plate configurations and optimized geometries in improving anchor performance, offering practical solutions for geotechnical applications requiring high pullout resistance in sandy soils. Overall, plus-shaped double-plate and triple-plate anchors can effectively replace square-shaped single-plate anchors.

Keywords: *Square anchors; Plus-shaped anchors; Pullout capacity; Relative density; Embedment depth.*

1. Introduction

Several engineering constructions need foundation systems to resist vertical uplift or horizontal pullout stresses. In such situations, tension members can be used to create a design that is both aesthetically pleasing and cost-effective. These elements, known as soil anchors, are lightweight, underground structural elements designed to withstand pullout forces and overturning moments operating on geotechnical structures, such as submerged pipelines, offshore structures, retaining walls, and transmission towers. These soil anchors are resistant to tensile, wind, and wave forces. Depending on the load orientation and the type of structure that needs to be supported, plate anchors might be horizontal, vertical, or inclined. These soil anchors are installed by excavating the ground to the desired depth, placing the anchor, and attaching it to tie rods that may be driven or inserted through augured holes, followed by backfilling the area with earth mass. This kind of anchor was the topic of interest in this study.

2. Background

To provide a satisfactory background to further discussions, a summary of research on the behaviour of plate anchors is provided. An overview of prior research on horizontal single-plate and multi-plate anchors is divided into two parts: experimental and numerical-theoretical investigations. In experimental studies of plate anchor behaviour, generally, two methods have been adopted: conventional methods under "normal gravity" settings or centrifuge systems [1, 2]. However, both methodologies have benefits and drawbacks, which must be considered when evaluating the results of experimental studies of anchor behaviour. The pullout capacity of single-plate and multi-plate square and circular anchors with different configurations was studied experimentally, and researchers [2, 3] found that the embedment ratio and spacing between multiple plates had an impact on the anchor's pullout capacity. The study by the researchers [4] investigates the pullout capacity of horizontal plate anchors in granular soils, highlighting the influence of factors, such as embedment depth, sand type, slope, and geocell/geotextile reinforcement, with results showing that both embedment depth and reinforcement significantly enhance the uplift capacity. Researchers [5] conducted model studies to establish semi-empirical correlations that can be used to estimate the pullout capacity of plate anchors in cohesionless soil.

Several of these studies were primarily concerned with testing transmission tower foundations [6]. In most of these earlier studies, a failure mechanism was assumed, and the pullout capacity was then estimated by considering the equilibrium of the soil mass above the anchor and within the projected failure surface. Even though there are many experimental findings, only a small number of thorough numerical evaluations have been carried out to ascertain the pullout capacity of anchors in sand. The numerical analysis consists of a variety of anchor sizes, soil parameters, embedment ratios, and analysis methods to calculate the pullout capacity of anchors in cohesionless soil [7]. With more situations and more combinations that take the roughness of the plate anchor into account, numerical investigations open up more possibilities for understanding [8]. Researchers [9]

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evaluated the pullout capacity for different combinations of strip anchors for varied anchor embedment ratios, internal sand friction angles, and anchor-soil interface friction angles. Numerical research [10] was conducted on multi-plate anchors in a typical c–Φ soil. Researchers [11] used PLAXIS 2D to estimate the uplift capacity of double-plate anchors in cohesionless soil. It was discovered that when the embedment depth is increased, the vertical stress distributions of both the bottom and upper plates increase. The efficiency of the bottom plate was found at a separation of 3.5D (D = plate anchor diameter). The previous researchers [12–14] only considered a limit number of sizes, shapes, embedment ratios, and numbers of plate characteristics on multi-plate anchors.

Past studies have extensively investigated the pullout behavior of single and multi-plate anchors through experimental and numerical approaches. While conventional square and circular anchor plates have been the focus, research on non-conventional shapes and configurations remains sparse. Furthermore, the effect of multiple parameters, including spacing between plates, embedment depth, and relative density of sand, on the pullout capacity of multi-plate anchors has not been comprehensively addressed.

This study aims to bridge this gap by analyzing the pullout behavior of square and plus-shaped single and multi-plate anchors embedded in sand. A detailed numerical analysis using the finite element method was conducted to evaluate the load-displacement response, ultimate pullout capacity, and failure mechanisms under varying conditions of embedment depth, soil relative density, plate thickness, and tie rod diameter. By comparing the performance of square and plus-shaped anchor plates, this research seeks to provide novel insights into the design optimization of multi-plate anchors for enhanced stability and cost-effectiveness.

3. Problem definition

The study uses a variety of conventional and non-conventional shaped horizontal plate anchors embedded at varied depths in the sand with different relative densities. Generally, square and plus-shaped horizontal plate anchors made of mild steel are used. The configuration of three types of horizontal plate anchors is shown in Fig. 1. Multiple anchor plates are placed by separating them with varied spacing (s), which are equivalent to 0.5b, 1b, 1.5b, and 2b, where b is the width of the anchor plate. A three-dimensional numerical analysis was performed in ABAQUS using the finite element method to examine the pullout capacity of plus-shaped horizontal plate anchors and to draw a comparison with square plate anchors. For the analysis, square and plus-shaped horizontal plate anchors with the dimensions depicted in Fig. 2 are considered. To avoid boundary effects, the dimensions of the soil block must be at least 10 times the width of the anchor plate. Throughout the study, the following parameters were altered: (a) relative density of soil, (b) thickness of anchor plate, (c) diameter of tie rod, (d) embedment depth of anchor plate, and (e) spacing between the multiple plates in multi-plate anchors.

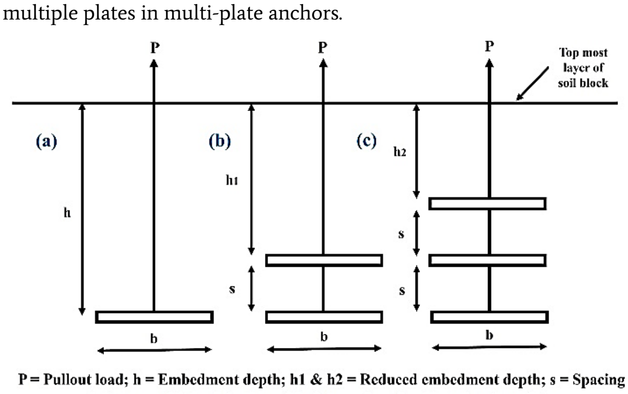


Fig. 1. Schematic sketch of the problem definition (a) SPA, (b) DPA, and (c) TPA.

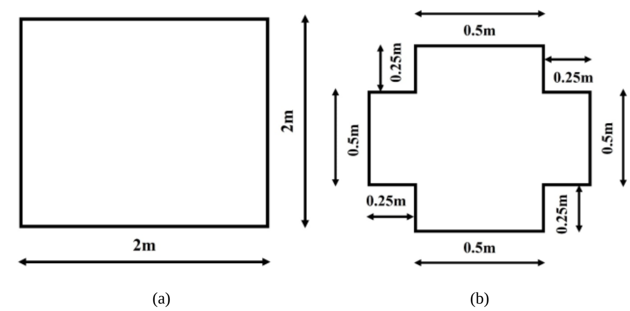


Fig. 2. Dimensions of horizontal plate anchors (a) Square-shaped anchor plate, and (b) Plus-shaped anchor plate

4. Soil and anchor parameters used for modelling

The soil parameters, including soil type, the relative density of soil, friction angle, dilation angle, Poisson's ratio, unit weight, and Young's modulus value, are described in Table 1. However, anchor properties, such as the type of anchor, the thickness of the anchor plate, the diameter of the tie rod, and spacing between multiple anchor plates are depicted in Table 2. The Young's modulus and the Poisson's ratio of anchor plates chosen for modelling were 210 GPa and 0.28, respectively.

5. Modelling, meshing and mesh convergence study

The analysis is conducted using ABAQUS software, which involves several steps. First, a sand domain is created with a size 10 times the width of the anchor plate to prevent boundary effects. The square-shaped or plus-shaped anchor plate is placed along the same vertical axis as the soil domain. In terms of material definition, the Mohr-Coulomb failure criterion is applied to the sand, with parameters including friction angle (φ), cohesion (c), Young's modulus (E), and Poisson's ratio (ν), while the anchor is modeled using a linear elastic material with defined values for Young's modulus and Poisson's ratio. For the soil-anchor interaction, the Tangential Contact method is used with a defined coefficient of friction (μ), typically ranging from 0.2 to 0.6. The boundary conditions fix the soil domain on all sides except the top, where the pullout load behavior is studied. A vertical upward displacement is applied to the top of the anchor (displacement-controlled loading), and the pullout load is determined from the reaction forces. Gravity loading or geostatic load is also applied to simulate the weight of the soil.

The size of the soil domain was chosen with the assumption that the stress and displacement gradients would reduce and approach zero towards the domain's boundaries so as not to influence the simulation's results. With this principle, square and plus-shaped plate anchors with dimensions shown in Fig. 2 were selected, and the dimensions of the soil block are such that it must be at least 10 times the width of the anchor plate. Using this approach, square and plus-shaped horizontal plate anchors with the measurements depicted in Fig. 2 were chosen, and the dimensions of the soil block must be at least 10 times the width of the anchor plate to provide satisfactory results. However, as per the soil-interaction properties, creating a direct contact between the anchor plate and soil mass is essential. The interaction property is described in terms of the interface friction coefficient between the anchor plate and the sand. Since the anchor plates are made of mild steel, they are assumed to have smooth surfaces. So, the sand-anchor friction coefficient is 0.2, as described by [15]. In addition, the sand anchor exhibits tangential behavior when the penalty contact method is used for numerical analysis. The sides of the soil block are confined on five sides, except for the topmost part, where the anchor plate is embedded. The model was subjected to geostatic stress to restrain it in all directions and simulate the actual soil conditions. The anchor plate was considered a rigid body during the finite element analysis. The finite element simulation was carried out using the Mohr-Coulomb failure criterion. As proposed by researchers [10], a higher concentration of components

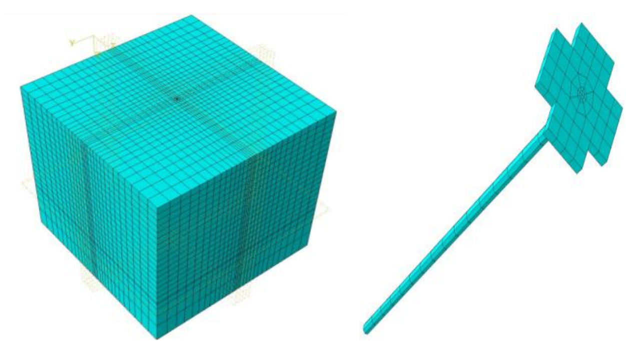
Table 1. Soil parameters used in the study [15].

Type of Soil	Relative Density (%)	Friction angle, ϕ (°)	Dilation angle, ψ (°)	Unit weight, γ (kN/m³)	Poisson's ratio, μ	Young's modulus of elasticity (MPa)
Loose sand	30	35	5	16.5	0.31	38.4
Medium sand	50	38	8	18	0.30	54.8
Dense sand	85	46	16	22	0.20	120

Table 2. Anchor parameters used in the study.

Type of anchor	Embedment depth, h (m)	Spacing between anchor plates, S	Thickness of anchor plate, t (mm)	Diameter of tie rod, d (mm)
Single-plate anchor	15,30,45	-	10, 25, 50	25, 32, 40
Double-plate anchor	15,30,45	0.5b,1b,1.5b,2b	10, 25, 50	25, 32, 40
Triple-plate anchor	15,30,45	0.5b,1b, 1.5b, 2b	10, 25, 50	25, 32, 40

was utilized in regions with a high-stress gradient. Hence, to ensure effective modelling, the elements nearer to the anchor had a decreased mesh size compared to the other elements. The mesh sensitivity study showed that the results obtained from extremely fine and fine mesh sizes were identical. However, the change from fine to coarse mesh produced a 3.2% variation in the results. Hence, finer mesh sizes are utilized nearer to the anchor plate, and coarser mesh sizes are employed towards the end of the soil block to maintain a balance between computational efficiency and the accuracy of the results. As per the convergence analysis, the optimal number of elements in the present study with a 15 m embedment depth was 24765. The discretized mesh and distribution of elements surrounding the anchor are shown in Fig. 3 (a) and Fig. 3(b), respectively.



(a) (b)

Fig. 3. Meshing (a) Soil block, (b) Plus-shaped anchor plate.

6. Results and discussions

6.1. Single plate anchors

The study employed square and plus-shaped SPA with thicknesses of 10, 25, and 50 mm and tie rod diameters of 25, 32, and 40 mm at an embedment depth of 15, 30, and 45 m in the sand having varied relative densities. The typical stress-displacement curve obtained from the numerical simulation corresponding to varying relative density of sand is shown in Fig. 4 (a) and Fig.4 (b). A numerical analysis was carried out on loose, medium, and dense sand having relative densities varying from 30%, 50%, and 85%. The square and plus-shaped SPA of thickness and the diameter of the tie rod, both 25mm, were embedded 15 meters deep in loose sand. Both square and plus-shaped anchor plates exhibit an increase in the pullout capacity with an increase in the relative density of sand. However, from Fig. 5 (a), it has been observed that the pullout capacity for the plus-shaped SPA is lower than that for the square single-plate anchor. The stress-displacement curve obtained from the numerical simulation corresponding to varying thickness of single-plate horizontal anchors is shown in Fig. 4 (c) and Fig.4 (d). A numerical analysis was carried out on the square and plus-shaped SPA, having thicknesses varying from 10, 25, and 50mm. The horizontal anchor plates, having a diameter of a tie rod of 25mm, are embedded at a depth of 15m in loose sand. It has been observed, based on the stress-displacement curve, that the pullout capacity of single-plate horizontal anchors increases with the increasing thickness of the anchor plate. However, Fig. 5 (c) demonstrates that the values obtained for plus-shaped single-plate anchors are lower than those for square-plate anchors. The stress-displacement curve obtained from the numerical simulation corresponding to varying diameters of tie rods is shown in Fig. 4 (e) and Fig. 4 (f). The displacement curve shows that the pullout capacity of both square and plus-shaped single plate anchors decreases as the diameter of the tie rod increases. The comparison of the pullout capacity of square-shaped and plus-shaped SPA with a varied diameter of the tie rod is presented in Fig. 5 (d). The stress-displacement curve obtained from the numerical simulation corresponding to varying embedment depth is shown in Fig. 4 (g) and Fig.4 (h). The curve shows an increase in the pullout capacity with an increase in embedment depth. The increasing trend can be attributed to the increased volume of soil contributing to the mobilization of passive resistance as the embedment depth increases. The variation of pullout capacities of square and plus-shaped SPA with embedment depth is depicted in Fig. 5 (b).

6.2. Double plate anchors

In this study, square and plus-shaped DPA with a thickness of 25 mm and tie rods with a diameter of 25 mm were embedded at depths of 15, 30, and 45 meters in loose sand. The spacing of multiple plates also varied from 0.5b, 1b, 1.5b, and 2b, where b is the width of the anchor plate. The typical stress-displacement curve obtained from the numerical simulation corresponding to varying embedment depth of DPA is shown in Fig. 6 (a) and Fig. 6(b). A numerical analysis was carried out on the square and plus-shaped DPA, which had depths of anchor plate varying from 15, 30, and 45m. The horizontal anchor plate has a thickness of 25mm and a diameter of a tie rod of 25mm. The spacing between the two plates is taken as 0.5b. From the stress-displacement curve, an increase in pullout capacity and an increase in embedment depth was observed in the case of the double-plate anchor in addition. However, Fig. 7(a) describes the variation of pullout capacity of square and plus-shaped DPA with change in embedment depth. The typical stress-displacement curve obtained from the numerical simulation corresponding to the varying spacing between double-plate anchors is shown in Fig. 6 (c) and Fig 6(d). A numerical analysis was carried out on the square and plus-shaped DPA, spaced between multi-plates varied from 0.5b, 1b, 1.5b, and 2b, where b is the width of the anchor plate. The horizontal anchor plates are 25mm thick, and the tie rod diameter is 25mm, embedded at a depth of 15m is loose sand. The stress-displacement curve demonstrates that the pullout capacity of DPA increases initially with increasing distance between two plates up to the critical spacing and then drops. However, the variation of pullout capacity of square and plus-shaped DPA with the increase in spacing between the multiple plates is shown in Fig. 7 (b).

6.3. Triple plate anchors

The study employed square and plus-shaped TPA with a thickness of 25mm and a tie rod diameter of 25mm at an embedment depth varying from 15, 30, and 45m in loose sand. The spacing between the multiple anchor plates also varies from 0.5b, 1b, 1.5b, and 2b, where b is the width of the anchor plate. The typical stress-displacement curve obtained from

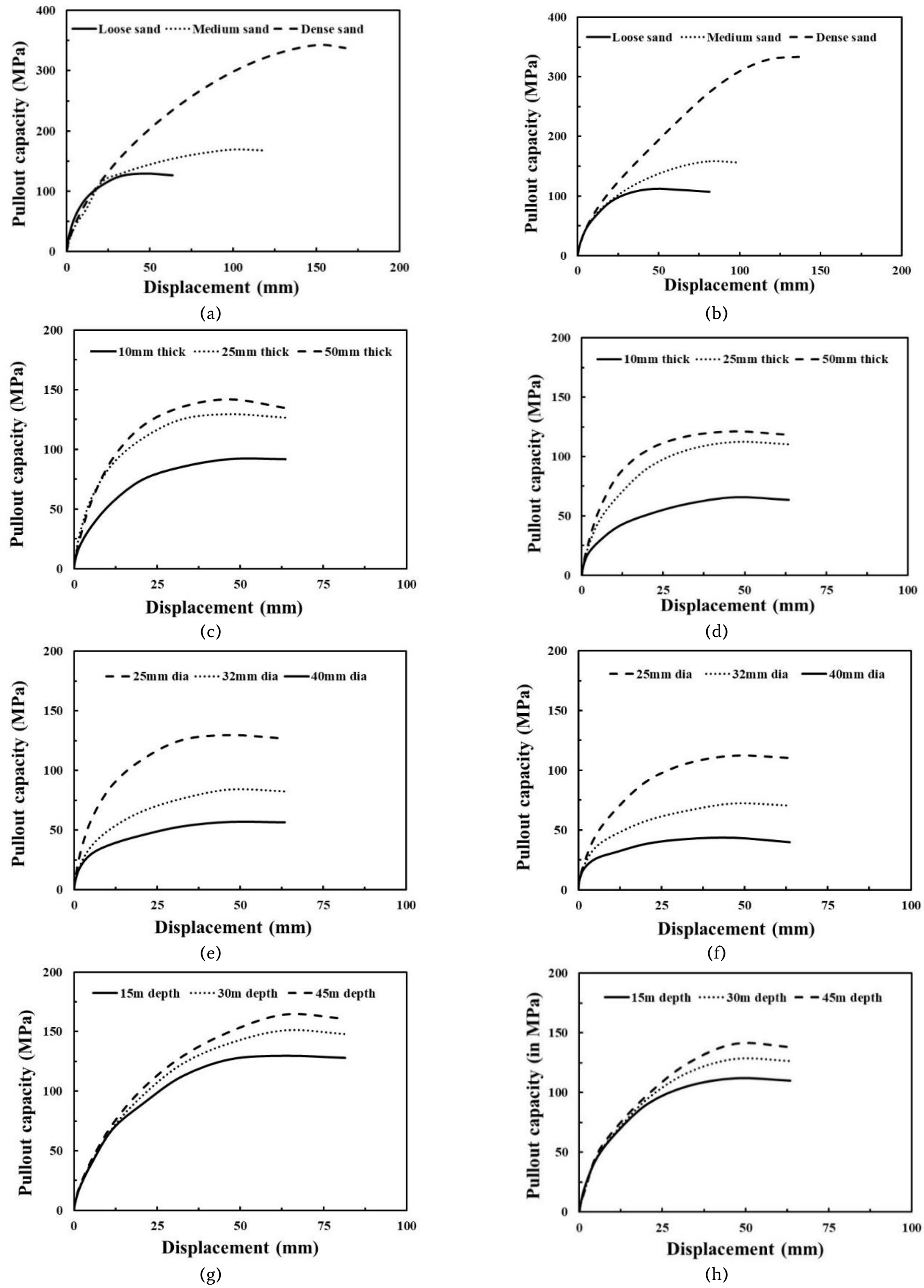


Fig. 4. Pullout capacity versus displacement curves (a) Square SPA with varying relative density, (b) Plus-shaped SPA with varying relative density, (c) Square SPA with varying thickness of the anchor, (d) Plus-shaped SPA with varying thickness of the anchor, (e) Square SPA with varying diameter of the tie rod, (f) Plus-shaped SPA with varying diameter of tie rod, (g) Square SPA with varying embedment depth, and (h) Plus-shaped SPA with varying embedment depth.

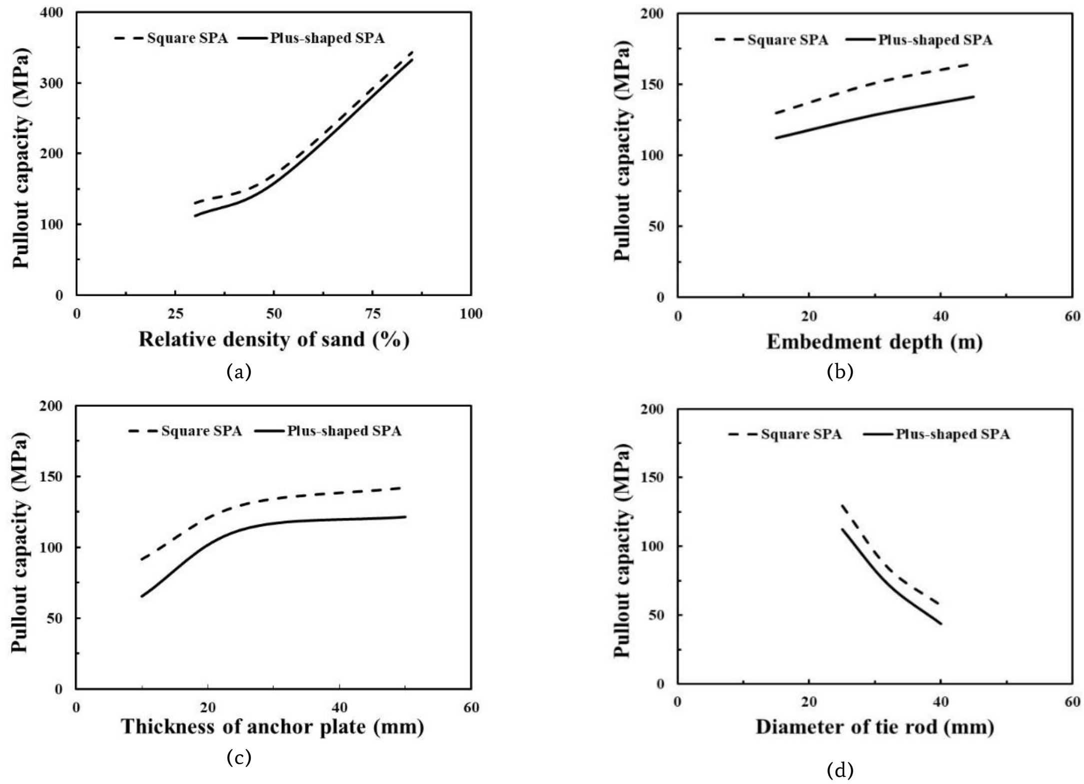


Fig. 5. Variation in pullout capacity of SPA with different parameters (a) Variation with the relative density of sand, (b) Variation with the embedment depth, (c) Variation with the thickness of anchor plate, and (d) Variation with the diameter of tie rod

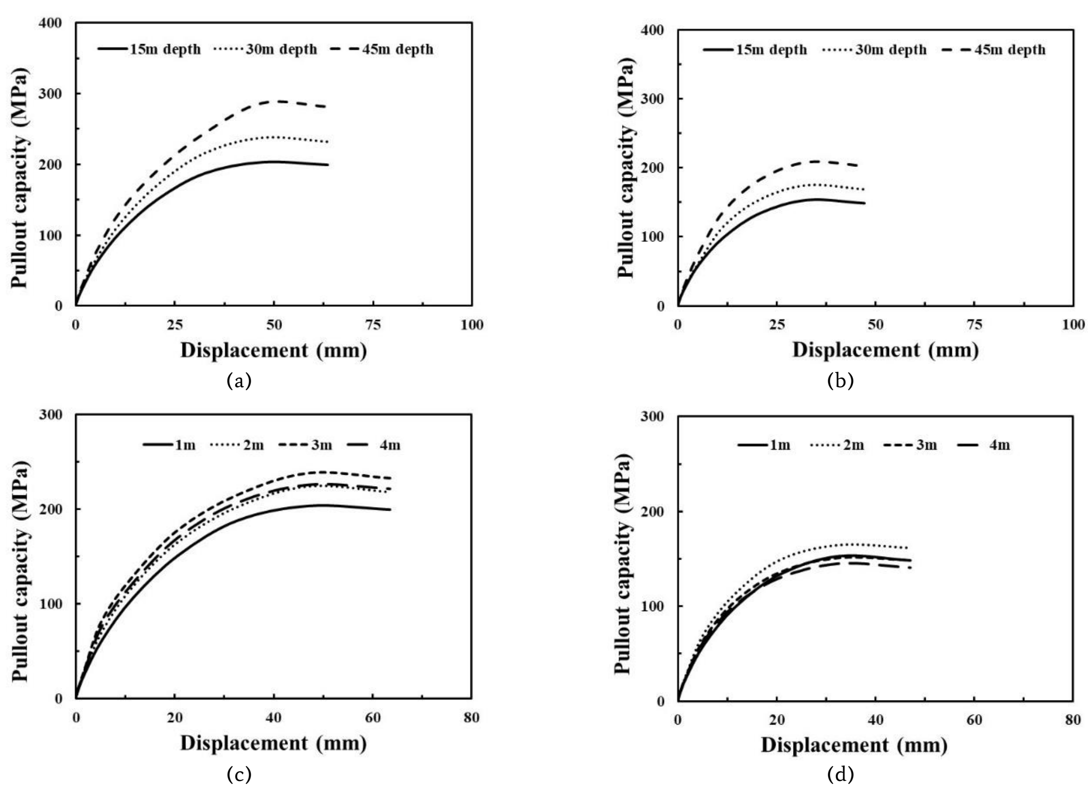
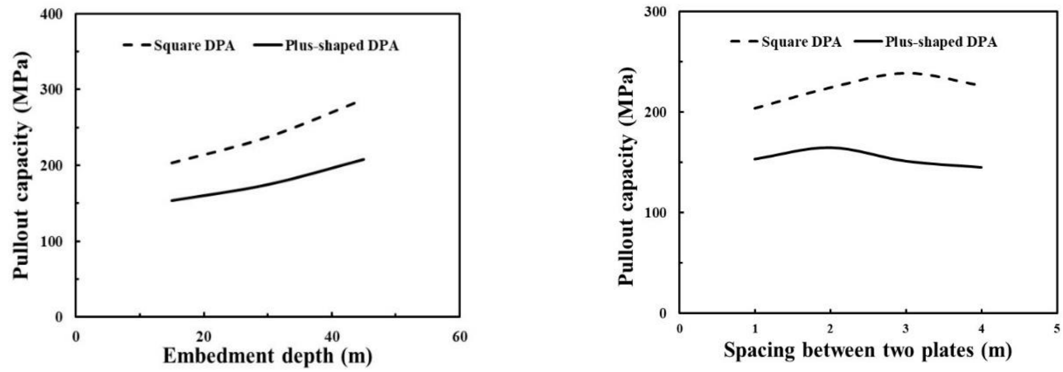


Fig. 6. Pullout capacity versus displacement curves (a) Square DPA with varying embedment depth, (b) Plus-shaped DPA with varying embedment depth, (c) Square DPA with varying spacing, and (d) Plus-shaped DPA with varying spacing.



(a) (b)

Fig. 7. Variation in Pullout capacity of DPA with different parameters (a) Variation with embedment depth, and (b) Variation with spacing between two plates.

the numerical simulation corresponding to varying embedment depth of triple plate anchors is shown in Fig. 8 (a) and Fig. 8 (b). A numerical analysis was carried out on the square and plus-shaped TPA, which had a depth of anchor plate varying from 15, 30, and 45m in loose sand. The horizontal anchor plate, which has a thickness of 25mm and a diameter of a tie rod of 25mm, is used for analysis. The spacing between the multiple anchor plates is taken as 0.5b. An increase in pullout capacity and embedment depth was observed in the triple-plate anchor from the stress-displacement curve. The variation of pullout capacity of square and plus-shaped triple plate anchors with embedment depth is depicted in Fig. 9 (a). The stress-displacement curve obtained from the numerical simulation corresponding to the varying spacing between multiple anchor plates is presented in Fig. 8 (c) and Fig. 8 (d). A numerical analysis was carried out on the square and plus-shaped TPA spaced between multi-plates ranging from 0.5b, 1b, 1.5b, and 2b. The horizontal anchor plates having a thickness of 25mm and a diameter of a tie rod of 25mm embedded at a depth of 15m are loose sand. From the curve, it was observed that the pullout capacity of TPA increases initially with increasing distance between multi-plates up to the critical spacing and then drops, similarly to the case of DPA. However, Fig. 9 (b) shows the variation of pullout capacity of square and plus-shaped TPA with the increase in spacing between the multiple plates.

6.4. Comparison

Figure 10 shows the comparative study of square-shaped and plus-shaped single and multi-plate horizontal anchors. The study shows that the plus-shaped horizontal anchor plates have lower pullout capacity values than square-shaped single and multi-plate anchors. The reduction in area for plus-shaped anchors is nearly 25% greater than that for square plate anchors. Nonetheless, differences in pullout capacity are not notably large.

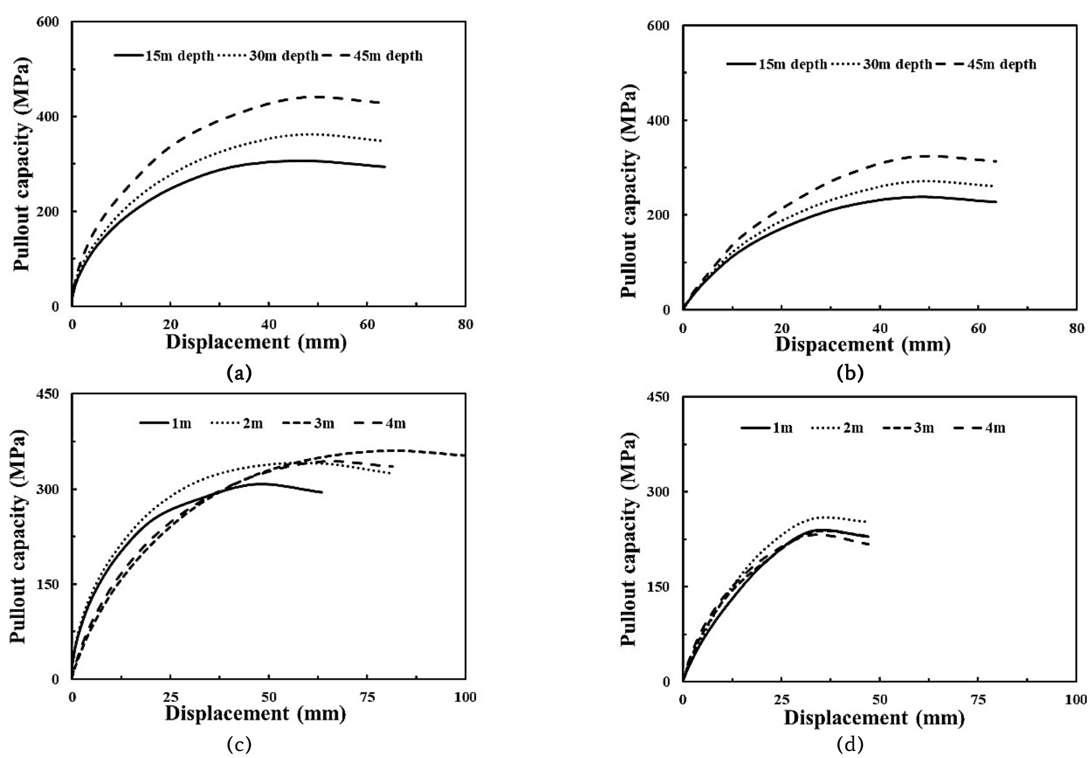


Fig. 8 Pullout capacity versus displacement curves (a) Square TPA with varying embedment depth, (b) Plus-shaped TPA with varying embedment depth, (c) Square TPA with varying spacing, and (d) Plus-shaped TPA with varying spacing

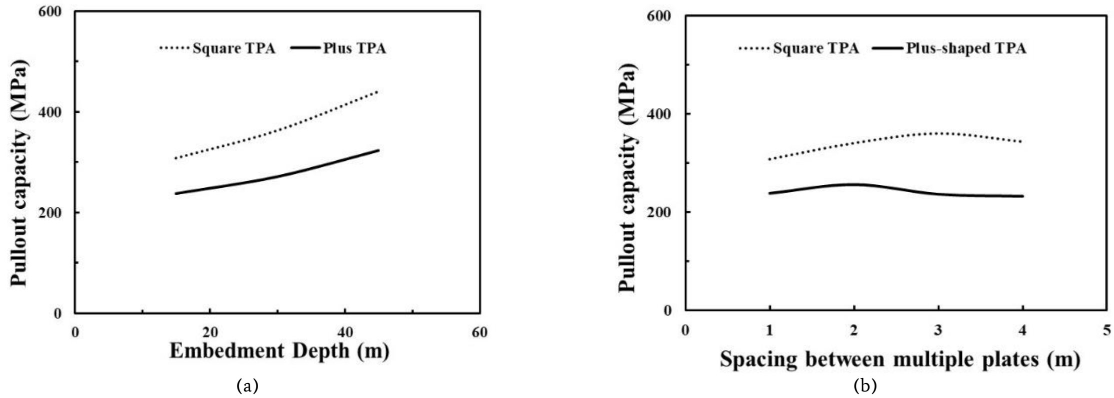


Fig. 9. Variation in pullout capacity of TPA with different parameters (a) Variation with embedment depth, and (b) Variation with spacing between multiple plates.

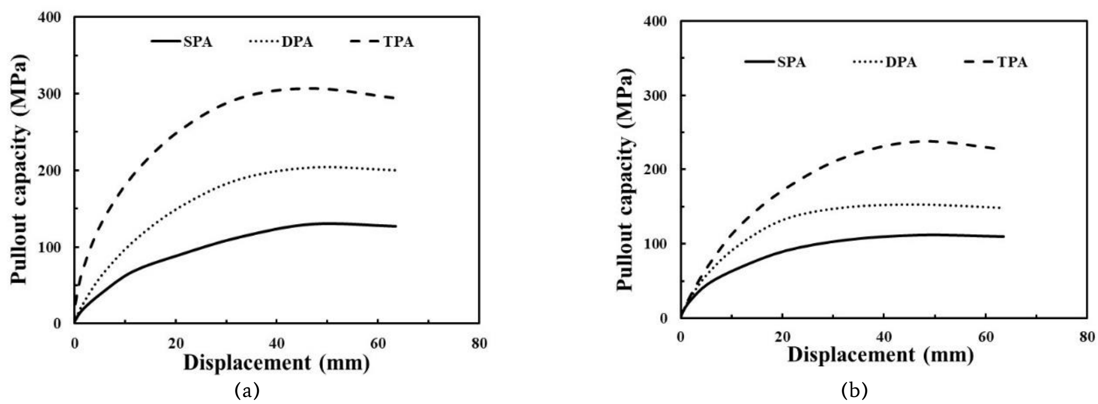


Fig. 10. Pullout capacity versus displacement curves (a) Square-shaped anchor plate, and (b) Plus-shaped anchor plate.

However, the pullout capacities of square and plus-shaped single and multi-plate anchors exhibit similar behavior to varying soil types, the anchor plate's thickness, the tie rod's diameter, embedment depth, and spacing between multiple plates in multi-plate anchors. In the case of loose sand, the plus-shaped SPA's pullout capacity is reduced by a maximum of 15.58 % compared to the square single-plate anchor. This percentage reduction, however, decreases to 3.09 % as soil density increases. The percentage reduction in pullout capacity of plus-shaped SPA from square SPA with varying thickness ranges from 40.13% to 15.58%. However, this value varies with diameter from 30.35% to 15.58%. The minimum variance in pullout capacity is when the thickness and diameter of the anchor plate are taken as 25mm. Since the pullout capacity increases with an increase in embedment depth for both square and plus-shaped SPA. However, the percentage reduction in these values varies between 15.58% and 17.50% as the embedment depth changes. In the case of multi-plate anchors, the percentage reduction in pullout capacity of plus-shaped anchors with varying embedment depth ranges from 32.98% to 37.91% for DPA and 29.06% to 36.45% in the case of TPA. However, the minimum change in pullout capabilities is observed at an embedment depth of 15m. The variation in pullout capacities with spacing of multiple plates in multi-plate anchors is somewhat different, as the pullout capacity first increases with increasing spacing and then decreases. The pullout capacity for multi-plate square anchors increases up to a spacing of 3m or 1.5b. However, this value only increases up to a spacing of 2m or 1b and then decreases in the case of plus-shaped multi-plate anchors. In the case of DPA, the percentage reduction of pullout capacities ranges from 32.98% to 57.76%, and for TPA, this value ranges from 29.06% to 52.68%. The variance in percentage reduction is minimal when the spacing between multiple anchor plates is kept at 1m or 0.5b. Table 3 and Table 4 summarize the finite element analysis performed on square and plus-shaped single-plate and multi-edges multi-plate anchors embedded in sand.

6.5. Comparison with literature

In the experimental investigation conducted by the researcher [2]. The soil parameters used were as follows: sand friction angle was 34°, the relative density of sand was 65%, and the dry unit weight was 14.8 kN/m^3. The dimensions of the test tank were 1100mm x 1100mm x 750mm, made up of a 6mm thick rigid steel plate. The square anchor plate made up of mild steel had dimensions 50mm x 50mm and a thickness of 5mm. However, in the present numerical analysis, the Poisson's ratio, friction angle, elastic modulus, and dry unit weight of loose sand were 0.31, 35°, 38.4MPa, and 16.50 kN/m3, respectively, whereas the modulus of elasticity and poison's ratio of the plate anchor used were 210GPa and 0.28, respectively.

Table 5 compares the pullout capacity of the anchor plate determined by the current study with the experimental investigation conducted by the researcher [2] in terms of a non-dimensional factor called the breakout factor. The dimensionless breakout factor is derived as given in the equation.

$$N = P/\gamma AL \tag{1}$$

Table 5 shows the variations in the breakout factor for square and plus-shaped anchor plates. The discrepancy in the results may be due to the modelling parameters chosen for the sand in the present study.

6.6. Failure pattern

The typical failure patterns of single square and plus-shaped plate anchors embedded at a depth of 15m in the sand are presented in Figs. 11 (a) and 11(b), respectively.

Similarly, the failure pattern for the double and triple square-shaped plate anchors is shown in Fig. 11 (c) and Fig. 11(d), and plus-shaped plate anchors are shown in Fig. 11 (e) and Fig. 11(f).

Table 3. Summary of ultimate pullout capacity of single-plate anchors.

Soil Type	Embedment depth (mm)	Thickness of anchor plate (mm)	Diameter of tie rod (mm)	Pullout capacity (MPa)		% change in pullout capacity
				Square SPA	Plus-shaped SPA	
Variation with Relative density of sand						
Loose	15	25	25	129.641	112.163	15.58
Medium	15	25	25	169.705	158.301	7.20
Dense	15	25	25	343.194	332.917	3.09
Variation with thickness of anchor plate						
Loose	15	10	25	91.773	65.49	40.13
Loose	15	25	25	129.641	112.163	15.58
Loose	15	50	25	142.019	121.371	17.01
Variation with diameter of tie rod						
Loose	15	25	25	129.641	112.163	15.58
Loose	15	25	32	84.058	72.083	16.61
Loose	15	25	40	56.8322	43.598	30.35
Variation with Embedment depth						
Loose	15	25	25	129.641	112.163	15.58
Loose	30	25	25	150.902	128.425	17.50
Loose	45	25	25	164.638	141.07	16.70

Table 4. Summary of ultimate pullout capacity of multi-plate anchors.

Type of anchor plate	Embedment depth (mm)	Spacing between anchor plates (m)	Pullout capacity (MPa)		% change in pullout capacity
			Square plate anchor	Plus-shaped anchor	
Variation with Embedment depth (DPA)					
DPA-0.5b	15	1	203.597	153.094	32.98
DPA-0.5b	30	1	237.51	174.527	36.08
DPA-0.5b	45	1	287.143	208.208	37.91
Variation with Spacing (DPA)					
DPA-0.5b	15	1	203.597	153.094	32.98
DPA-1b	15	2	223.956	164.576	36.28
DPA-1.5b	15	3	238.208	150.985	57.76
DPA-2b	15	4	225.992	144.759	56.11
Variation with Embedment depth (TPA)					
TPA-0.5b	15	1	307.286	238.094	29.06
TPA-0.5b	30	1	362.587	271.427	33.58
TPA-0.5b	45	1	440.735	322.998	36.45
Variation with Spacing (TPA)					
TPA-0.5b	15	1	307.286	238.094	29.06
TPA-1b	15	2	340.545	256.765	32.63
TPA-1.5b	15	3	360.571	236.158	52.68
TPA-2b	15	4	343.449	231.568	48.31

Table 5. Pullout capacity of anchor plates in terms of breakout factor (N).

	Square plate anchor [2]			Present study					
				Square plate anchor			Plus-shaped plate anchor		
h/d	SPA	DPA-1b	TPA-1b	SPA	DPA-1b	TPA-1b	SPA	DPA -1b	TPA-1b
2	3.78	2.16	-	2.7	4.25	6.41	2.34	3.19	4.97
4	6.35	4.86	3.78	3.15	4.95	7.56	2.68	3.64	5.66
6	7.21	7.48	6.76	3.44	5.99	9.19	2.94	4.34	6.74

Fig. 11 depicts the total contour of the stress, and their importance is to assess the actual stress upon applying the pullout load. This type of information is required to verify whether the stress in the sand above the anchor plate is within acceptable limits or not upon application of pullout load. The stress contours in both the instances shown in Fig. 11 (a) and Fig. 11 (b) demonstrate that the square single plate anchor is more resistant to pullout than the plus-shaped single plate anchor. However, in the case of multi-plate square and plus-shaped anchors, the square multi-plate anchors exhibited greater resistance to pullout loads than plus-shaped multi-plate anchors. In contrast, a localized failure mechanism produces a failure surface that engulfs only a portion of the soil above the horizontal anchor plate. Further, the failure surface does not extend to the top surface of the sand stratum. A close examination of Fig. 11 reveals that the stress contours remained well established within the selected lateral and vertical boundaries for the square and multi-edges multi-plate anchors. Further analysis of this figure reveals that the maximum stress was observed immediately above the anchor plate. However, the overall failure mode was the local shear failure above the plates in all the cases studied for the square and multi-edges multi-plate anchors.

7. CONCLUSIONS

This study determined the pullout capacity of single and multi-plate square and plus-shaped anchors in sandy soils using finite element analysis. The major conclusions that can be drawn from the findings of this study are as follows:

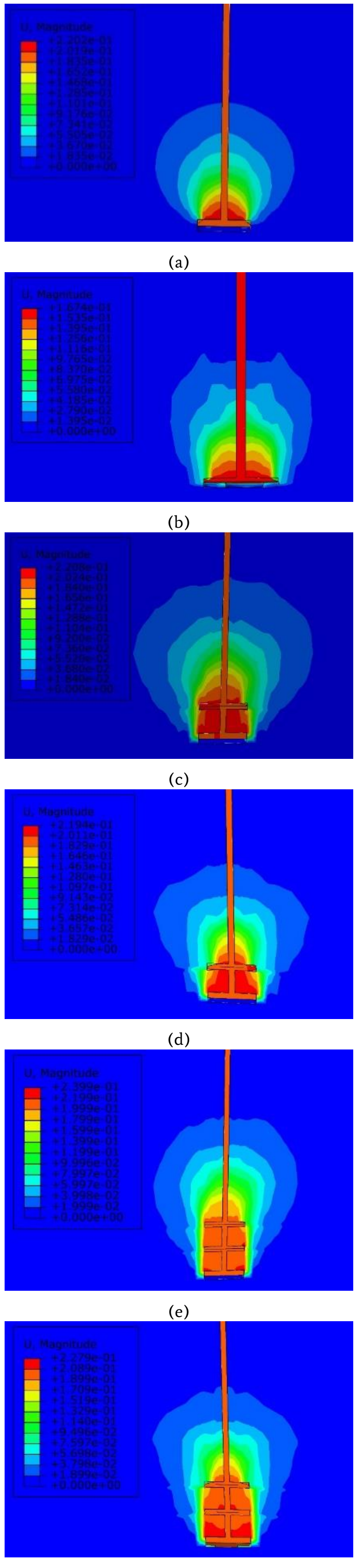


Fig. 11. Failure pattern of horizontal anchor plates embedded at a depth of 15m in the sand (a) square SPA, (b) plus-shaped SPA, (c) square DPA, (d) plus-shaped DPA, (e) square TPA, and (f) plus-shaped TPA.

1- Square plate anchors exhibited a 15.58% higher pullout capacity than plus-shaped anchors in loose sand. The difference was reduced to 7.20% in medium sand and 3.09% in dense sand, indicating the influence of soil density on anchor performance.

2- The pullout capacity increased with the thickness of the anchor plate. For instance, square single-plate anchors in loose sand had pullout capacities of 91.77 MPa, 129.64 MPa, and 142.02 MPa for plate thicknesses of 10 mm, 25 mm, and 50 mm, respectively, reflecting a maximum increase of 54.74%. Plus-shaped anchors followed a similar trend but showed a lower capacity, with reductions ranging from 15.58% to 40.13%.

3- Increasing the tie rod diameter decreased the pullout capacity. For square single-plate anchors in loose sand, the pullout capacity decreased from 129.64 MPa for a 25 mm rod to 84.05 MPa for a 32 mm rod and 56.83 MPa for a 40 mm rod. Plus-shaped anchors showed similar trends with a maximum reduction of 30.35%.

4- An increase in embedment depth significantly enhanced the pullout capacity. For square single-plate anchors in loose sand, capacities rose from 129.64 MPa at 15 m to 150.90 MPa at 30 m and 164.64 MPa at 45 m, reflecting a 27% improvement. Plus-shaped anchors showed a slightly lower increase, with reductions between 15.58% and 17.50%.

5. Double-plate anchors achieved their maximum pullout capacity at 1.5b spacing, with square anchors showing capacities up to 238.21 MPa at 3 m spacing, while plus-shaped anchors achieved their peak at 1b spacing with 164.58 MPa. The reduction in pullout capacity for plus-shaped double-plate anchors ranged from 32.98% to 57.76% compared to square anchors.

6. Triple-plate anchors followed a similar trend, with maximum pullout capacities of 360.57 MPa for square anchors at 1.5b spacing and 256.77 MPa for plus-shaped anchors at 1b spacing.

7. Despite a 25% reduction in area compared to square plates, plus-shaped double and triple-plate anchors demonstrated higher pullout capacities than single square-plate anchors. This makes them a viable alternative for reducing material usage while maintaining performance.

The practical implications of the findings of this research paper are significant for geotechnical applications requiring high pullout resistance in sandy soils, such as submerged pipelines and offshore structures. Optimized multi-plate configurations and plus-shaped anchors can reduce material usage without significantly compromising performance. This study has several limitations that warrant consideration. The numerical model simplifies soil behavior by assuming it to be isotropic, homogeneous, and elastic-plastic, which may not accurately represent real-world conditions. In practice, even cohesionless soils exhibit distinct properties, such as those of calcareous sand and terrigenous sand, which are not accounted for in this study. Calcareous sand, predominantly composed of marine organism debris like coral reefs and seaweeds, exhibits unique characteristics, including a fragile particle structure, high porosity, irregular grain shapes, and lower bearing capacity compared to terrigenous sands [16, 17]. In regions where calcareous sands are prevalent, these properties can significantly impact the performance of anchor plates, necessitating enhanced optimization in anchor design. This includes refining geometry, embedment depth, and plate configurations to ensure sufficient pullout capacity under such challenging conditions.

Additionally, critical factors, such as moisture content, temperature effects, and anchor-soil interactions are represented in an idealized manner, limiting the applicability of the findings to field conditions. The simulated loading rates also differ from the dynamic or gradual loading typically encountered in practice. While finer mesh sizes improve the accuracy of numerical simulations, they substantially increase computational demands, posing challenges in achieving an optimal balance between precision and efficiency. Addressing these limitations in future work would further enhance the robustness and applicability of the findings.

To address these limitations and advance this research, future studies could incorporate advanced material models, such as critical state or particle-based models, explore hybrid or bio-inspired anchor designs, and include real-world factors, including groundwater flow and temperature changes. Automation of simulations using scripting and AI/ML integration could further enhance efficiency and predictive capabilities.

Abbreviations

b = Width of the anchor plate
d = Diameter of tie rod
h = Embedment depth
E = Modulus of elasticity
L = Length of tie rod
N = Breakout factor
S = Spacing between multiple plates
t = Thickness of anchor plate
γ = Dry unit weight of sand
ϕ = Friction angle
μ = Poisson's ratio
ψ = Dilation angle

Acknowledgement

The opportunity to employ the ABAQUS explicit software for this investigation was made possible by the NIT Hamirpur, for which the authors would like to express special gratitude.

References

[1]. Dickin EA, Laman M (2007) Uplift response of strip anchors in cohesionless soil. Advances in Engineering Software 38:618–625. https://doi.org/10.1016/j.advengsoft.2006.08.041

[2]. Tilak BV, Samadhiya NK (2021) Pullout capacity of multi-plate horizontal anchors in sand: an experimental study. Acta Geotech 16:2851–2875. https://doi.org/10.1007/s11440-021-01173-1

[3]. Tilak VB, Samadhiya NK (2023) Pullout capacity of Circular Multi-plate Inclined Anchors in Sand: An Experimental Study. Geotech Geol Eng 41:2427–2449. https://doi.org/10.1007/s10706-023-02407-7

[4]. Aliasgharzadeh M, Yousefzadehfard M, Atrchian M, Bayat M (2023) Experimental Study on Pullout Capacity of Geocell and Geotextile-Reinforced Horizontal Plate Anchors Embedded in Granular Soil. Int J of Geosynth and Ground Eng 9:6. https://doi.org/10.1007/s40891-023-00428-z

[5]. Das BM, Seeley GR (1975) Breakout Resistance of Shallow Horizontal Anchors. J Geotech Engrg Div 101:999–1003. https://doi.org/10.1061/AJGEB6.0000202

[6]. Ball AJ (1961) The resistance to breaking-out of mushroom foundations for pylons

[7]. Bhattacharya P, Roy A (2016) Variation of Horizontal Pullout Capacity with Width of Vertical Anchor Plate. Int J Geomech 16:06016002. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000639

[8]. Feng T, Zong J, Jiang W, et al (2020) Ultimate Pullout Capacity of a Square Plate Anchor in Clay with an Interbedded Stiff Layer. Advances in Civil Engineering 2020:8867678. https://doi.org/10.1155/2020/8867678

[9]. Kumar J, Sahoo JP (2012) Upper Bound Solution for Pullout Capacity of Vertical Anchors in Sand Using Finite Elements and Limit Analysis. Int J Geomech 12:333–337. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000160

[10]. Merifield RS, Sloan SW (2006) The ultimate pullout capacity of anchors in frictional soils. Can Geotech J 43:852–868. https://doi.org/10.1139/t06-052

[11]. Karamanoglu Mehmetbey University, Turkey, Misir G (2018) Predicting the uplift capacity of vertically located two-plate anchors. AGS 15:47–57. https://doi.org/10.18690/actageotechslov.15.2.47-57.2018

[12]. Mokhbi H, Mellas M, Mabrouki A, Pereira J-M (2018) Three-dimensional numerical and analytical study of horizontal group of square anchor plates in sand. Acta Geotech 13:159–174. https://doi.org/10.1007/s11440-017-0557-x

[13]. Jadid R, Shahriar AR, Rahman MR, Imtiaz T (2019) Evaluation of Theoretical Models to Predict the Pullout Capacity of a Vertical Anchor Embedded in Cohesionless Soil. Geotech Geol Eng 37:3567–3586. https://doi.org/10.1007/s10706-019-00870-9

[14]. Das A, Bera AK (2019) Ultimate Uplift Capacity of Bell-Shaped Anchor in River Sand Using Finite Element Software "ABAQUS." Geotech Geol Eng 37:4121–4133. https://doi.org/10.1007/s10706-019-00897-y

[15]. Panwar V, Dutta RK (2021) Bearing capacity of rectangular footing on layered sand under inclined loading. Journal of Achievements in Materials and Manufacturing Engineering 108:49–62. https://doi.org/10.5604/01.3001.0015.5064

[16]. Rawat V, Satyam N (2024) Effect of fibre-reinforced microbial-induced calcite precipitation on the mechanical properties of coastal soil. Soil Use and Management 40:e13078. https://doi.org/10.1111/sum.13078

[17]. Rawat V, Satyam N (2024) Enhancing the durability of coastal soil treated with fiber-reinforced microbial-induced calcite precipitation (MICP). Applied Ocean Research 150:104106. https://doi.org/10.1016/j.apor.2024.104106