The efficiency of the opening multi-plate anchors with different configurations

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ABSTRACT: The pullout capacity of the mechanical anchors is a key point of onshore and offshore anchorage systems, with many influential factors, including depth of embedment (H), anchor width (B), and shape. Multi-plate anchors can be an alternative that presents higher pullout capacity compared to single plate anchors. For multi-plate expansive anchors, it is essential to consider the pullout capacity in a dimensionless form named efficiency (E), considering single plates' pullout capacities and space ratio (s/B) parameter defined as the space between the plates (s) to plates' widths (B). In the present study, pullout tests have been performed on three opening multi-plate anchors with different configurations to evaluate the effects of deeper plate width on anchors' pullout capacity. To observe the interaction of different plates and the surrounding soil, the soil formation zone in the maximum pullout load is illustrated for multi-plate anchors using the PIV technique. Moreover, to investigate the efficiency (E) of multi-plate anchors, several pullout tests have been conducted on single plate anchors, and pullout capacity results have been used to calculate efficiency (E). It can be concluded that increasing the deeper plate size leads to an increase in pullout capacity, while the Efficiency (E) approximately remains constant due to a low space ratio (s/B).

1 INTRODUCTION

In geotechnical engineering, anchors are used to resist tensile and uplift forces (Hanna, 1982). Expansive plate anchors consist of a shaft and one or more opening plates are installed by being driven in to the ground. Easy and quick installation and immediate activation are among the advantages of these anchors. Moreover, expansive plate anchors are applicable in a wide range of soils and underwater (Das and Shukla, 2013).

Many experimental studies indicate that plate anchors' optimum design is affected by considering key parameters including size and depth of the anchor and subsoil condition like density or strength (Ganesh and Sahoo, 2016; Moghadas Tafreshi et al., 2019). Main results of 1-g experimental researches on influencing parameters on plate anchors' behaviour are summarized in practical tables (Tilak and Samadhiya, 2021) in literature.

Considering an efficient spacing, adding one or more plates to a single plate anchor is an alternative to acquiring a higher pullout capacity (Ghaly et al., 1991). Mitsch and Clemence (1985) considered the cylindrical shear failure mechanism and expressed that the space ratio, defined as the space between two plates (s) to the plate's width (B), significantly affects the anchor pullout capacity (P_u) (Mooney 1985). Kulhawy (1991) noted that if the space ratio (s/B) is high enough, the single plates act independently and the multi-plate anchor pullout capacity (P_u) can be equal to the sum of its single plate anchors. Lutenegger (2011) investigated multi-helix screw anchors behavior in sandy soil and performed a series of full-scale pullout tests and observed that while the space ratio (s/B) is about 3, the cylindrical shear failure mechanism changes to independent plate failure mechanism. Tsuha et al. (2012) investigated the effects of soil density and the number of helices (N) on the pullout capacity of multi-plate anchors with various configurations. The study found that in the case of double- and triple-helix anchors, as the diameter of the plates or the relative density of the sand increases, the impact of the second and third plates on the overall pullout capacity of the anchor diminishes. Hao et al. (2018) focused on the interaction of the plates of multi-helix anchors with various space ratios in sand and concluded that extra plates will only contribute in anchor pullout capacity if they are positioned outside the soil zone mobilized in the other plates' failure mechanisms. Mohammadkhanifard et al. (2022) examined the performance of double-plate anchors with different space ratios in sand. The results indicated that adding an extra plate to a single-plate anchor in loose sand, enhances the pullout capacity compared to using a single plate anchor. The space ratio equal to 1 was recommended for achieving greater pullout capacity. Conversely, Tilak and Samadhiya (2021) suggested that the space ratio equal to 3 would lead a higher pullout capacity.

2 SETUP AND MATERIALS

The experimental setup includes plane strain box, opening plate anchor, sandy soil, and data acquisition system including data logger, digital encoder, and loadcell.

2.1 Plane strain box

The box features a width of 1.8 m, a height of 2.2 m, and an outer thickness of 0.1 m. The wide glass side of the box facilitated improved observation of the sand deformation zone and the movement of the anchors.

The two narrower side walls are made from steel, while the two larger sides are made from thick, unbreakable glass, which offered superior clarity compared to Plexiglas for monitoring the displacement field from both sides. The 10-mm thickness of the glass ensured that it functioned as rigid walls and prevented any deformation, thus enabling the simulation of the plane strain condition. The box is bolted to the ground and does not move during the pullout tests. The plane strain box is depicted in Figure 1.

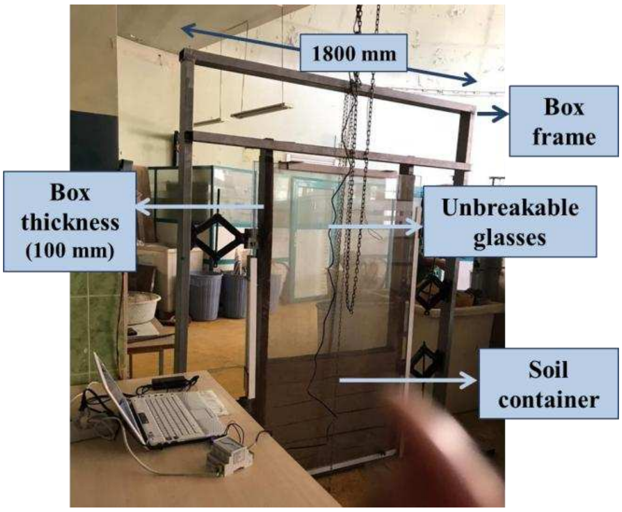

Figure 1. The plane strain box

2.2 Opening plate anchor

The opening plate anchor, which extends its bearing area during pullout is studied in this paper. The design of the opening plate anchor consists of a rod and one or more pairs of wings as shown in Figure 2. These wings can be closed and, facilitating its pushing into the soil. Once the wings are released, the springs located between the rod and wings cause the wings to open. The final angle formed between the wings is 120 degrees, which aligns with the anchor's width (B). To regulate the angle's magnitude, a cable is incorporated to link the two wings, capping the maximum angle at 120 degrees.

To monitor the anchor's position and movement within the soil during testing, three magnets were fixed on the anchor. Additionally, three more magnets were positioned on the glass sidewall in front of the camera, aligned with the magnet locations on the anchor. The movement of the magnets on the glass indicated the movement of the anchor in the soil. Figure 2 depicts the details of the opening plate anchor.

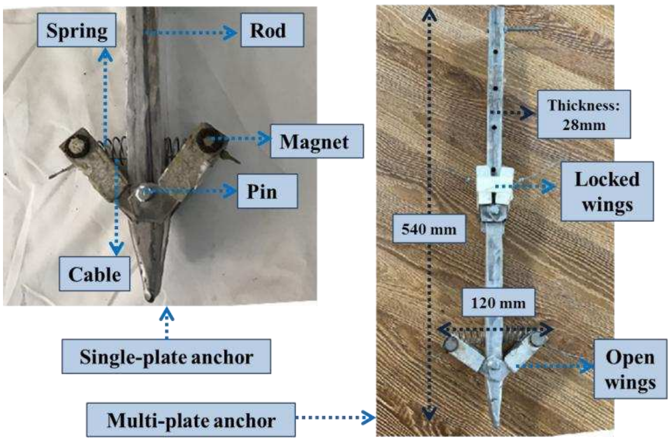

Figure 2. The opening plate anchor

2.3 Soil properties

In this study, Firoozkooh sand #161 is used which is light brown and artificially produced using crushers. According to the Unified Soil Classification System (D422 2002), it is classified as poorly graded sand (SP). The soil characteristics are summarized in Table 1. It should be noted that the presented results have been achieved through 1g reduced scale models and may be subject to scale effects of different nature.

Table 1. Properties of Firoozkooh sand #161

Soil property	Value
Dry unit weight, $\boldsymbol{\gamma_d}$ (kN/$\mathbf{m^3}$)	15.34
Critical friction angle, $\boldsymbol{\varphi}$	32 °
Relative density, $\boldsymbol{D_R}$(%)	75%
$\boldsymbol{d_{50}}$	0.38mm
Void ratio (e)	0.68

3 SCHEDULE OF THE TESTS

3.1 Single-plate anchors

Three series of tests were performed on opening single-plate anchors to study the effects of the anchor width (B) and anchor embedment ratio (R = H/B) on anchors' behaviour, pullout capacity of the anchor (Pu), and the corresponding anchor displacement (du). The tests schedule is presented in Table 2.

Table 2. Scheme of pullout tests on the opening single-plate anchors

Anchor width (B)	Embedment depth (H)	Embedment ratio (R)	Test name	Pu (N)	du/B
B=120 mm	600 mm	5	B12R5	378.7	0.55
	720 mm	6	B12R6	490.0	0.57
	840 mm	7	B12R7	613.0	0.59
B=150 mm	600 mm	4	B15R4	359.4	0.54
	750 mm	5	B15R5	485.5	0.57
	900 mm	6	B15R6	631.8	0.59
B=180 mm	540 mm	3	B18R3	343.6	0.53
	720 mm	4	B18R4	479.3	0.55
	900 mm	5	B18R5	637.5	0.60

3.2 Multi-plate anchors

Three tests were implemented on multi-plate opening anchors to investigate the effects anchor configuration. The details of studied configurations of the opening multi-plate anchors are illustrated in Figure 3. In this paper, three multi-plate anchors with two plates are studied. In these anchors, the average of two anchor plates' widths ($\boldsymbol{B_{ave}}$) is 150 mm and space ratio (s/$\boldsymbol{B_{ave}}$) is equal to 2. It should be noted that all these three anchors are embedded in depth of 900 mm. Hence, the embedment ratio (R=H/$\boldsymbol{B_{ave}}$) can be considered as 6.

The scheme of pullout tests on the opening multi-plate anchors is presented in Table 3.

Table 3. Scheme of pullout tests on the opening multi-plate anchors

Test name	Plates' parameters			
	position	width (B)	Embedment depth (H)	Embedment ratio (R)
2B1218	shallow	180	600	3.34
	deep	120	900	7.5
2B1515	shallow	150	600	5
	deep	150	900	7
2B1812	shallow	120	600	5
	deep	180	900	5

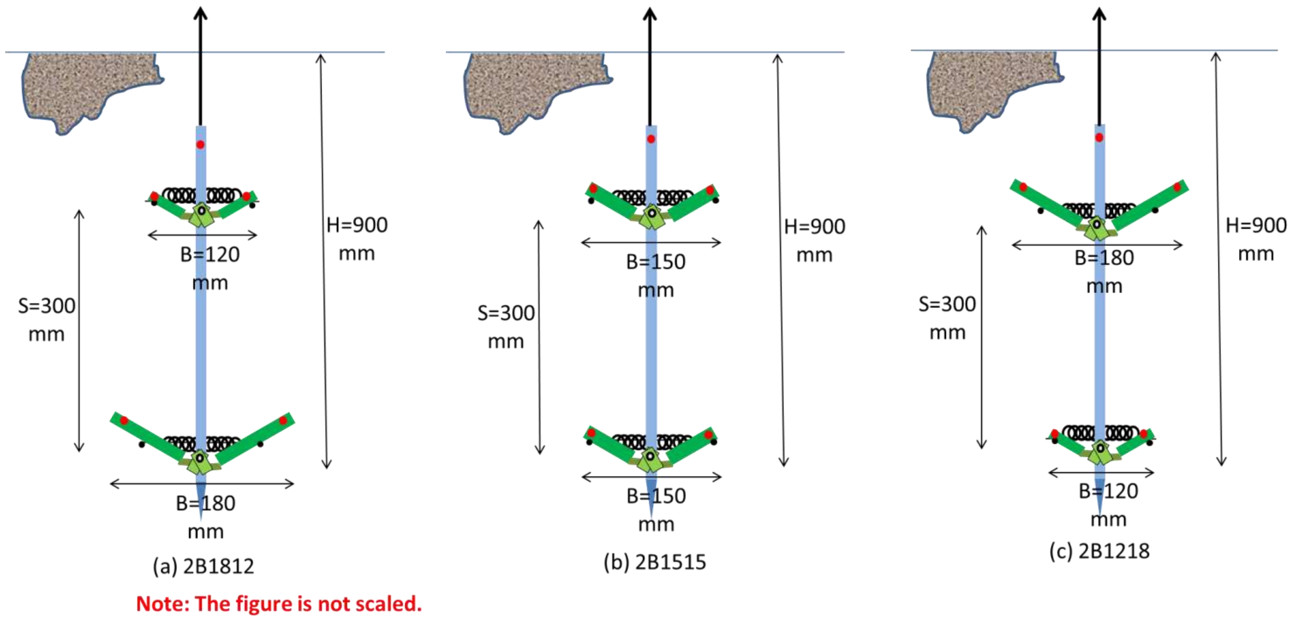

Figure 3. The details of studied opening multi-plate anchors

4 DISCUSSION AND RESULTS

4.1 Pullout load-displacement diagrams

The relationship between pullout load and displacement for an opening single- anchor with varying embedment ratios and anchor widths is illustrated in Figure 4. The overall pattern of all curves are consistent, although significant differences are noted between the shallow and deep anchors' behaviors. In the case of the shallow anchor systems (low embedment ratio) a sharp peak in pullout load is observed at displacements about 0.55

of anchors' width. Following this peak, a significant reduction in pullout load is noted. Conversely, in the deep anchor system with a high embedment ratio, stable pullout resistance is observed after the peak load, with no considerable reduction in uplift loading occurring post-peak.

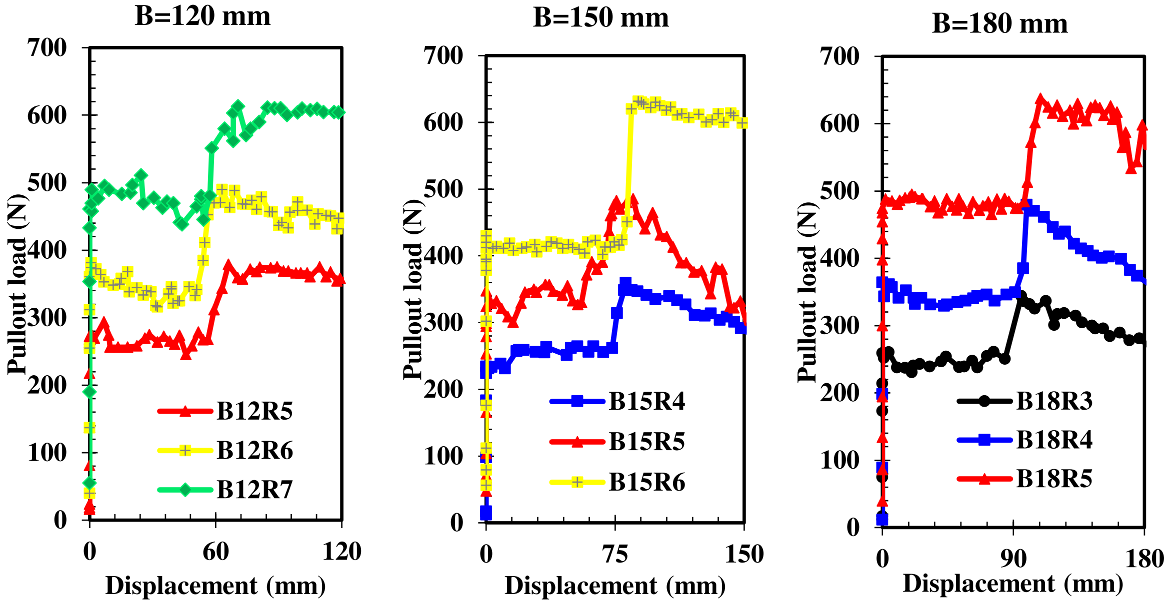

Figure 4. Pullout load vs. displacement of single-plate anchors with different widths and embedment ratios

For opening double-plate anchors, the relationship between pullout load and displacement is depicted in Figure 5. According to Figure 3, the embedment depth of deeper plates in all these three anchors is equal to 900mm. For 2B1218 anchor, the individual deeper plate's width is 120mm and its embedment ratio is high and equal to 7.5. Conclusively, the 2B1218 curve in Figure 5 is similar to deep anchors curve, as explained in the latter paragraph. For 2B1812 anchor, the individual deeper plate's width is 180mm and its embedment ratio is low and equal to 5. Conclusively, the 2B1812 curve in Figure 5 is similar to shallow anchors curve, and after reaching a sharp peak, a significant reduction is observed in pullout load with increasing displacement. For 2B1515 anchor, the individual deeper plate's width is 150mm and its embedment ratio is equal to 6. In Figure 5, the residual pullout load after reaching the sharp peak is not completely steady and decreases insignificantly during the pullout test.

4.2 Pullout capacity (P_u)

For single-plate anchors, Figure 6 demonstrates that the pullout capacity (P_u) rises nearly linearly in relation to the embedment ratio across various anchor widths. For all anchor widths (B= 120, 150, and 180mm), the pullout capacity (P_u) increases with embedment ratio, although the increase in pullout capacity (P_u) is more significant for wider anchors.

For multi-plate anchors, Figure 7 indicates that the pullout capacity (P_u) increases as deeper plate width (B_{deeper}) increases. The pullout capacity (P_u) is equal to the effective weight of the soil in the failure zone and the shear resistance acting along the failure surfaces. When the wider plate's embedment depth increases, the effective weight of the soil in the failure zone and conclusively, pullout capacity (P_u) increases. In other words, when wider plate is located in lower position, the pullout capacity rises.

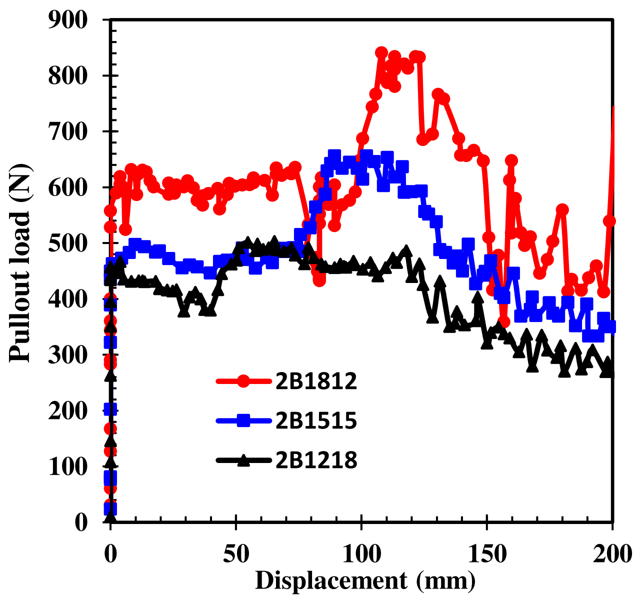

Figure 5. Pullout load vs. displacement of multi-plate anchors

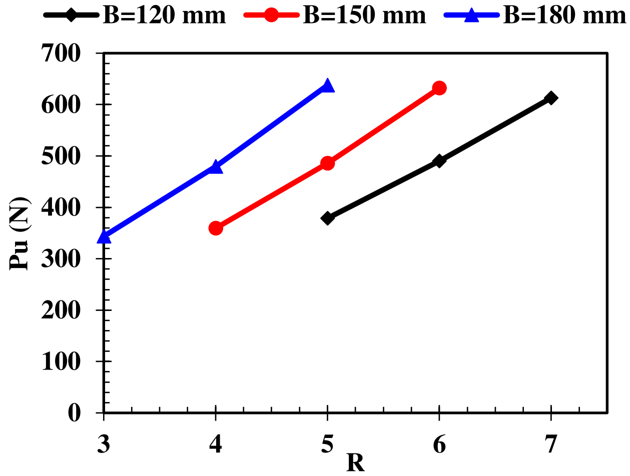

Figure 6. Pullout capacity vs. embedment ratio for single plate anchors

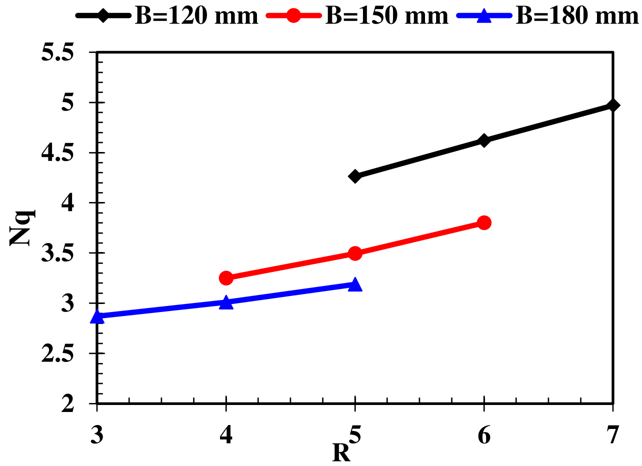

Figure 8. Pullout capacity vs. embedment ratio for single plate anchors

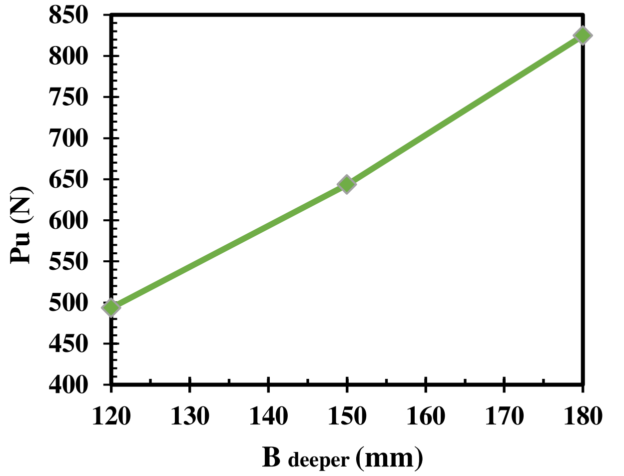

Figure 7. Pullout capacity vs. deeper plate width for double plate anchors

4.3 Breakout factor

The pullout capacity is represented using the dimensionless breakout factor (Nq), which is defined in the following way:

$$N_q = \frac{P_u}{\gamma AH} \tag{1}$$

Where P_u is the anchor pullout capacity, γ is the soil unit weight, A is the area of the anchor and H is embedment depth (Meyerhof and Adams, 1968).

Figure 8 illustrates the relationship between the breakout factor and the embedment ratio for varying anchor widths. As indicated, the breakout factor rises as the embedment ratio increased, aligning with earlier observations. For a given embedment ratio, increasing the anchor width (B) decreases the breakout factor (Nq).

4.4 Efficiency

The Efficiency of an opening plate anchor (E) can be defined as the ratio of the pullout capacity of a multi-plate anchor to pullout capacity of its individual plate anchors with one wing (Lutenegger 2011). The pullout capacity of the opening multi-plate anchors, their individual plates pullout capacities, and calculate efficiency (E) are presented in Table 4.

Table 4. The details of efficiency (E) calculation

Test name	P_u (N)	Individual plates‘ parameters			Efficiency (E%)
		B (mm)	R	P_u (N)	
2B1218	493.4	180	3.34	388.9*	$\frac{493.4}{388.9+666.4}$ =46.8
		120	7.5	666.4*	
2B1515	643.3	150	5	485.5	$\frac{643.3}{485.5+742}$ =52.4
		150	7	742*	
2B1812	824.6	120	5	378.8	$\frac{824.6}{378.8+637.6}$ =81.1
		180	5	637.6	
* **Note**: For B18R3.34 and B12R7.5 individual plates, the Pu results were calculated using interpolation and extrapolation, respectively. For B15R7, the Pu result is reported based on an experimental test.					

Figure 9 illustrates the efficiency of multi plate anchors (E) across deeper plate widths (B_{deeper}). It can be observed that the efficiency (E) rises as deeper plate width (B_{deeper}) increases. It should be noted that in this paper, the space ratio (s/B) is low. Therefore, two adjacent plates cannot develop their pullout capacity individually and without each other interference. According to Figure 9, it is not efficient to locate the wider plate in lower embedment depth.

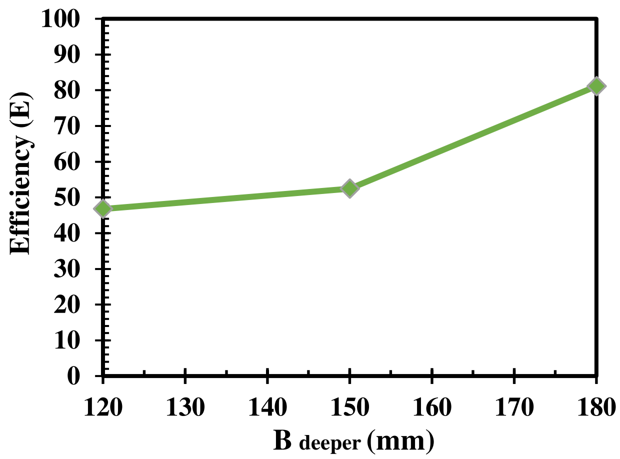

Figure 9. Efficiency vs. deeper plate width

5 SOIL DEFORMATION ZONE

5.1 PIV technique

PIV (Particle Image Velocimetry) is an image processing technique that is suggested for investigating soil deformation within the field of geotechnical engineering (White et al., 2003). Nowadays this technique is widely used to investigate anchors and their surrounding soil movements (Sabermahani and shojaee, 2021; Abrifam et al., 2024). The PIV system comprises three components: tracer particles, an image capturing system, and an image analysis system (Duan et al., 2018). In this study, the tracer particles consisted of soil particles and colored soil lines. Additionally, free magnets placed on the sidewalls of the test box are used as tracer particles. A digital camera with 4K resolution is employed to capture images. Furthermore, the image processing system developed by White et al. (2003) is utilized for the PIV analysis.

5.2 Soil deformation zone around the anchor

Figure 10 shows the displacement field at the peak point for opening multi-plate anchors with different configurations, using PIV. It can be inferred that plates are positioned in the area of soil mobilized in the failure mechanism of the each other. Thus, it can be concluded that space ratio equal to 2 leads to plates interactions. Besides, when wider plate is located deeper, mobilized soil zone is much more massive and subsequently pullout capacity will be higher.

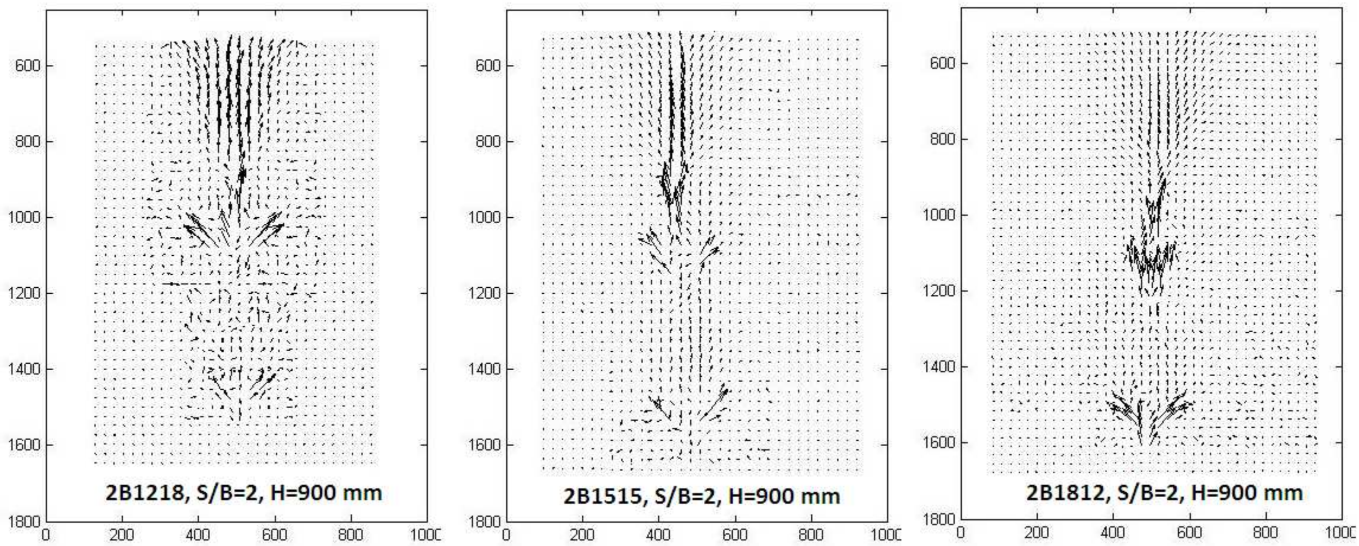

Figure 10. Displacement field around the opening multi-plate anchors

6 CONCLUSIONS

The paper outlines the findings from two series of experiments using scaled models on opening single-plate and multi-plate plate anchors with different configurations and embedment depths. Additionally, the PIV technique is used to analyse the sand displacement field surrounding the anchor and to examine the soil failure lines. It is important to highlight that investigating all three dimensions of the anchor during experimental tests or conducting a field study will yield more accurate results and conclusions. Furthermore, the findings have been obtained through 1g reduced scale models and may be influenced by different types of scale effects. The outcomes are as follows:

- For single-plate anchors for a given embedment ratio, increasing anchor width, increases pullout capacity.
- For single-plate anchors, pullout capacity increases almost linearly with the embedment ratio for different anchor widths, although the enhancement in pullout capacity is more pronounced for wider anchors.
- In the case of multi-plate anchors, as the width of the deeper plate enhances, the pullout capacity also increases. This means that when a wider plate is positioned lower, the pullout capacity increases.
- For single-plate anchors, the breakout factor increases with a higher embedment ratio, consistent with previous findings. For the investigated ranges of anchor widths and embedment ratios, for a given embedment ratio, wider anchors result in lower breakout factors.
- In the case of multi-plate anchors, the efficiency increases as the width of the deeper plate increases. It is important to highlight that this study involves a low space ratio (s/B=2). Consequently, two adjacent plates are unable to establish their pullout capacity independently, as they interfere with one another. In the case of multi-plate anchors with space ratio equal to two, the PIV results show that plates are positioned in the area of soil mobilized in the failure mechanism of the each other. Thus, it can be concluded that space ratio equal to 2 results in plates' interactions.
- Positioning the wider plate at a shallower embedment depth is not effective. Positioning the wider plate in deeper embedment ratio can increase the efficiency about more than 70%.

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DESCRIPTION OF ABBREVIATIONS

Parameter	Description
B	Width of anchor (mm)

d	Anchor displacement
d_{50}	particle size corresponding to the cumulative frequency of 50% (mm)
D_R	Relative density (%)
e	Porosity ratio
E	Efficiency (%)
H	Embedment depth of anchor (mm)
N	Number of helixes
N_q	Breakout factor

P_u	Ultimate pullout load (kg)
R	R=H/B, Embedment ratio
s	Space between plates (mm)
s/B	Space ratio
γ_d	Sample dry unit weight (kN/m^3)
$\gamma_{d_{max}}$	Maximum dry unit weight (kN/m^3)
$\gamma_{d_{min}}$	Minimum dry unit weight (kN/m^3)
φ	Angle of soil friction (degree)