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Investigating the behavior of opening plate anchor by 2D and 3D physical models

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ABSTRACT: Horizontal plate anchors as efficient and reliable systems can provide uplift resistance where the foundations must sustain tensile forces. Expansive plate anchors are commonly implemented in infrastructure applications due to their advantages of immediate loading capability and rapid installation. A better comprehension of expansive plate anchor behavior can lead to confidence in design and also wider acceptance as a foundation alternative. The primary aim of this research is describing failure mechanisms during pullout tests. Therefore, to observe soil deformation zone, first series of pullout tests were conducted in a special plane-strain thin box with transparent side walls (2D models). Then Particle Image Velocimetry (PIV) was used to illustrate sand deformation zone comprehensively and precisely. In second part, pullout tests were conducted in a typical cubic chamber box (3D models). Finally, by applying observed failure surfaces characteristics in theorical methods and verifying the analytical findings with experimental results of second part of the study, two equations were presented to evaluate the anchor's pullout capacity in application conditions. Furthermore, the paper provides a brief discussion on the anchor's embedment ratio and scale effects on the pullout capacity.

KEYWORDS: Opening plate anchor, Pullout capacity, physical model, Embedment ratio, Failure mechanism, PIV.

1 INTRODUCTION

Nowadays, various types of anchors with wide loading conditions are implemented in geotechnical engineering projects (Das and Shukla 2013). Generally, anchors can be categorized into three main groups: grout anchors, mechanical anchors, and combination of them (Hanna 1982). Mechanical anchors are divided into helical, drag, and plate anchors. Among all mentioned anchors, plate anchors have attracted the attention of researchers due to their flexibility in design and minimum environmental disturbance. The plate anchors can be used in wind farms, foundations, retaining walls and marine structures (Das and Shukla 2013; Randolph and Gourvenec 2017). Jalali Moghadam et al. (2022) summarized all types of plate anchors, their common applications, advantages, and disadvantages. There are many different factors that can affect the pullout capacity and displacement of anchors, such as anchor size, shape, and embedment depth and soil condition (Ganesh and Sahoo 2016; Ouria and Mahmoudi 2018). The shape of plate anchors plays an important role as it affects pullout load capacity and installation parameters. Therefore, new generation of expansive plate anchors were introduced. Giampa et al. (2019) investigate the effect of plate shape on the pullout capacity of plate anchors embedded in sand implementing 1g physical model tests. It was indicated that circular plate anchors had the highest pullout capacity, which was about 50% to 70% higher than that of square anchors. Other shapes including kite-shaped and triangular anchors exhibited pullout capacities between those of circular and square anchors. Tilak and Samadhiya (2021) studied the effect of plate shape on the pullout capacity of plate anchors embedded in sand and reported similar results. Sabermahani and shojaee (2020) introduced an expansive plate anchor called "opening plate anchor" that can be pushed to the desired depth. After installation, the anchor can be unlocked and activated and its bearing area increases during pullout process. Jalali Moghadam et al. (2022) introduced a new type of mechanical anchors called Expandable Mechanical Plate Anchors with movable plates and easy and quick installation. Various studies have focused on expansive plate anchors characteristics (including size, shape, number and angle of plates) and pullout tests conditions (such as soil particle size and density, velocity of penetration and pullout process) on anchor pullout capacity and displacement (Mohamadkhanifard et al. 2022; Azadimanesh et al. 2023; Abrifam et al. 2024).

The proposed paper presents two series of small-scaled physical model tests in 2D and 3D conditions. In first series of tests, test specimens were prepared using Plane Strain Box regarded as 2D condition. Pullout tests and anchor-soil movements were accurately observed using PIV techniques. In second series of tests, pullout tests are performed in a common chamber box regarded as 3D condition tests. In final part of the paper, 2 equations are presented to predict the pullout capacity for both conditions.

2 TESTING PROGRAM

In this study, two series of pullout tests are implemented on opening plate anchor using 2D and 3D physical models. The tests schedule is expressed in Table 1.

Table 1. Testing Schedule

Series Condition	Embedment Depth (H)	Embedment Ratio (R)	Test Name
2D condition	300 mm	2	B15R2-2D
	450 mm	3	B15R3-2D
	600 mm	4	B15R4-2D
	750 mm	5	B15R5-2D
3D condition	300 mm	2	B15R2-3D
	450 mm	3	B15R3-3D
	600 mm	4	B15R4-3D

Note:
The anchor width (B) is equal to 150 mm.
Embedment ratio (R) is defined as embedment depth (H) to anchor width (B).

3 EXPERIMENTAL SETUP AND MATERIALS

The experimental setup consists of experimental boxes for 2D and 3D physical modeling, data acquisition system (including load cell, linear encoder, and computer), the opening plate anchor, and PIV photo capturing system

3.1 *Opening plate anchor*

The "Opening plate anchor" is a mechanical anchor with exceeding bearing area during pullout. It consists of a rod and a pair of wings made of steel. The wings can be closed and tightened the rod, which allows the anchor to be pushed axially into the soil. When the wings are unlocked, the springs between the wings and rod help the wings to open. The final opening angle between wings is 120, which corresponds to anchor width B. In order to control the magnitude of the angle, a cable was installed to connect the two wings at a maximum angle of 120. In this paper, anchor width (B) is equal to 150 mm. The anchor acts rigidly during pullout tests.

3.2 *Soil properties*

In the proposed study, Firoozkooh sand #161 is used. Soil properties are summerized in Table 1. The dry unit weight is equal to 15.34 (kN⁄$\mathbf{m^3}$corresponding to relative density of 75%. The friction angle is 32°.

Table 2. Soil properties of Firoozkooh sand #161

USCS name	SP
Dry unit weight, γ_d (kN⁄$\mathbf{m^3}$)	15.34
Relative density, D_R(%)	75%
Internal friction angle, φ	32 °
void ratio (*e*)	0.68
d_{50}	0.38 mm

Figure 1 shows the opening plate anchor in the Firoozkooh sand #161.

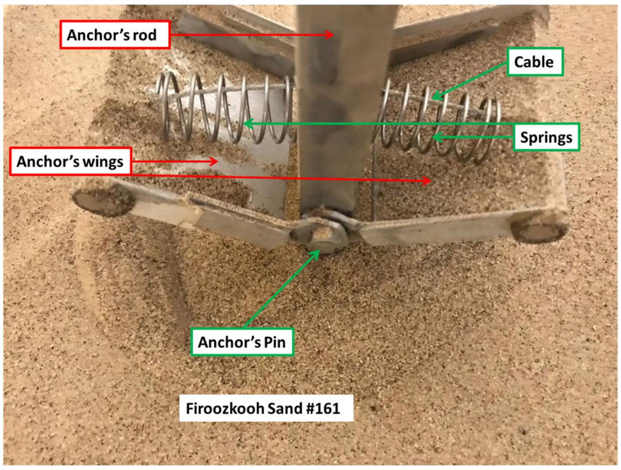

Figure 1. The opening plate anchor in the Firoozkooh sand #161.

3.3 *Plane Strain Box-2D physical modeling*

An experimental box with height of 2.2 m, width of 1.8 m, and inner thickness of 0.08 m was used to model 2D condition. The small thickness of the box and its glass side walls allowed a better observation of the sand deformation field and the anchor movements during uplift tests. The 10-mm thickness of the glass walls allowed them to serve as rigid walls with no deformation, which allowed simulation of the plane strain condition. Therefore, the pullout tests performed in Plane Strain Box are considered as 2D tests. Figure 2 shows the specimen of the B15R2-2D test prepared in Plane Strain Box.

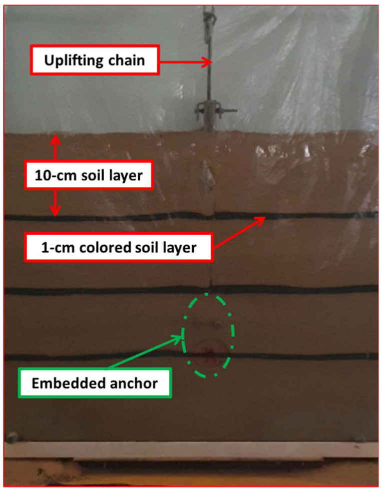

Figure 2. The B15R2-2D test specimen

3.4 *Chamber-3D physical modeling*

A chamber with width of 700 mm was used to perform common pullout tests in 3D condition. It should be noted that no PIV analysis was performed on 3D pullout tests as the failure surfaces were not observable. The 3D test chamber is illustrated in Figure 3.

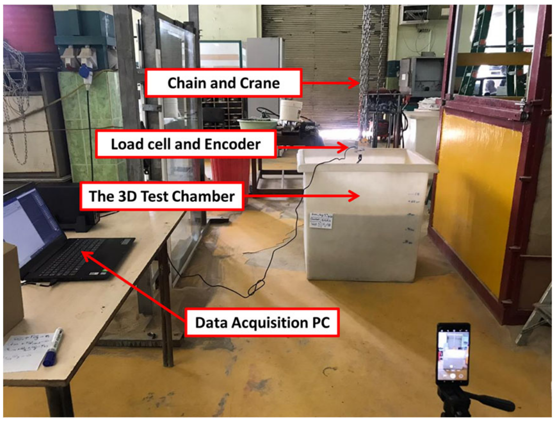

Figure 3. The 3D test chamber

4 PIV SYSTEM

Particle Image Velocimetry (PIV) is an Image Processing technique developed by Adrian (1990) in the 1980s to observe the flow of fluids. As soil deformations can be regarded as slow fluid flow, PIV technique is generalized to geotechnical engineering (White et al., 2003). Briefly, a PIV system consists of tracer particles, an image capturing system and an image processing program (Duan et al., 2019).

Observing soil deformation surfaces obtained by PIV technique leads to a more precise understanding of soil and anchor interactions and a more accurate analytical study of anchor's behavior.

5 EXPERIMENTAL RESULTS

5.1 *Pullout load-displacement diagrams*

The pullout load-displacement curves of the opening plate anchor with different embedment ratios for 2D condition are illustrated in Figure 4. As embedment ratio is low, all tested anchors act as shallow anchors. For these shallow anchors (low embedment ratios), a sharp peak in pullout load is observed. After the peak point, a considerable decrease in the pullout load is indicated. A thorough description about pullout load-displacement diagram in three phases is presented by Sabermahani and Shojaee (2021).

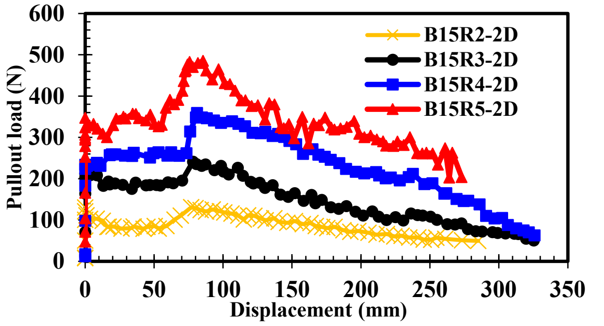

Figure 4. Pullout load vs. displacement of opening plate anchor in 2D condition

5.2 *Pullout capacity*

Figure 5 depicts the variation of maximum pullout load (P_u) as a function of embedment ratio (R) for 2D and 3D conditions. It can be observed that pullout capacity (P_u) increases with embedment ratio in both 2D and 3D conditions. Furthermore, in a given embedment ratio, pullout capacity (P_u) is much greater in 3D condition rather than that of 2D condition as uplifted soil mass and shear resistance acting along the failure surfaces are greater in 3D condition.

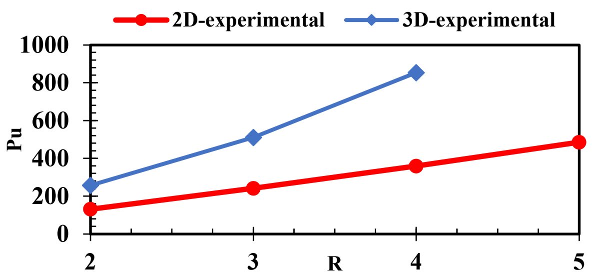

Figure 5. Pullout capacity vs. embedment ratio

Figure 6 shows that embedment ratio do not affect relative displacement (d_u/B) significantly. For all anchors in 2D condition with shallow behavior, relative displacement ranged from 0.51 to 0.57.

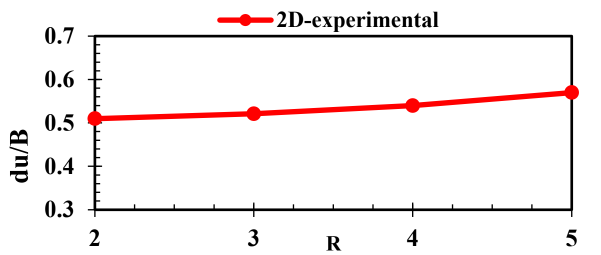

Figure 6. Relative displacement vs. embedment ratio

5.3 *Breakout factor (N_q)*

Breakout factor is the common dimensionless form of pullout capacity defined as follows:

$$N_q = \frac{P_u}{\gamma AH} \qquad (1)$$

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

Figure 7 presents the Breakout factor versus the embedment ratio for both 2D and 3D conditions. As shown in Figure 7, the Breakout factor increases as the embedment ratio increases. Furthermore, at a given embedment ratio, Breakout factor is higher in 3D condition compared to 2D condition.

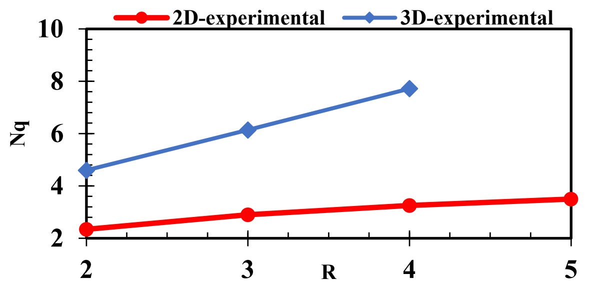

Figure 7. Breakout factor vs. Embedment ratio

6 SOIL DEFORMATION ZONE AROUND UPLIFTING ANCHOR

To improve the understanding of the opening plate anchor behavior, it is vital to observe the soil deformation zone around the anchor during the pullout test. In 2D condition, soil displacement field around the opening plate anchor at instance of maximum pullout load for two presented tests (B15R3-2D and B15R5-2D) are depicted in Figure 8. According to Figure 8, for these two shallow anchors (R=3 and R=5) failure surfaces start from the edge of anchor and cross the soil surface.

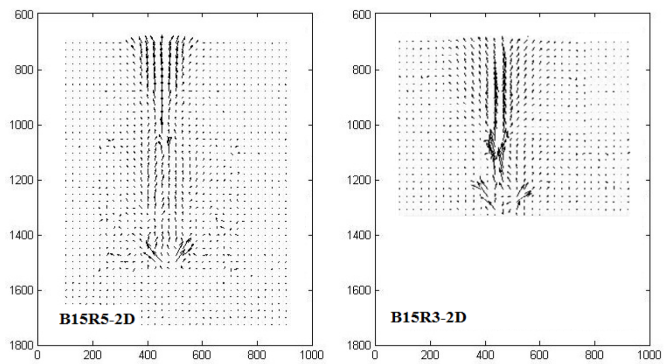

Figure 8. Soil deformation field around the uplifting anchor

7 ESTIMATION OF PULLOUT CAPACITY FOR SHALLOW ANCHORS

The pullout capacity is equal to the effective weight of the soil inside the failure zone and the shear resistance acting along the failure surface (Meyehof and Adams 1968; Giampa et al 2017). Thus:

$$P_u = P_s + W \qquad (2)$$

where P_s is the shear resistance mobilized along the failure surfaces and W is the weight of the soil inside the failure zone. The analytical pullout capacity equation for shallow opening plate anchors was reported by Sabermahani and Shojaee (2021) as follows:

$$P_u = \gamma LBH(1 + RK_u \tan\varphi) \qquad (3)$$

where B and L are anchor's plan dimensions and K_u is the nominal uplift coefficient (Meyerhof and Adams 1968).

Equation (4) is obtained by generalizing Equation (3) from 2D to 3D condition as follow:

$$P_u = \gamma LBH(1 + RK_u \tan\varphi + \frac{B}{L} RK_u \tan\varphi) \qquad (4)$$

The experimental and analytical results of pullout capacity for 2D and 3D condition are depicted in Figure 9.

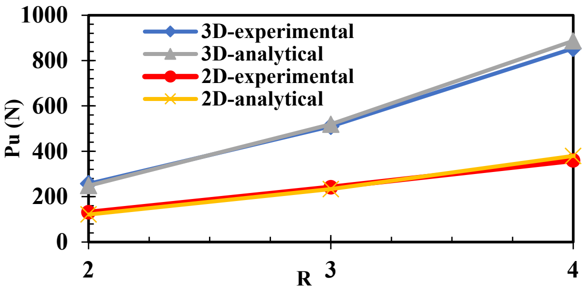

Figure 9. Comparison of experimental and analytical pullout capacities as a function of embedment ratio

Experimental Breakout factors are compared with analytical ones for 2D and 3D condition in Figure 10. According to Figure 9 and Figure 10, analytical results are in good agreement with experimental ones.

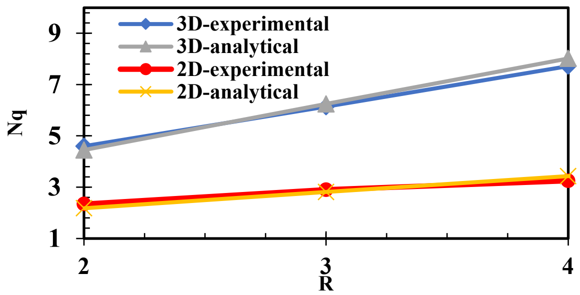

Figure 10. Comparison of experimental and analytical Breakout factors as a function of embedment ratio

It should be considered that in this paper, the stress level is low. Accordingly, the presented results are affected by low stress levels in the 1g tests. Several investigations have suggested that conventional 1-g model tests can be used to simulate prototype behavior if the results are presented in dimensionless form and the constitutive response of the soil is similar to the prototype (Bradshaw et al. 2016). However, some soil behaviors may depend on the stress level, and dimensionless parameters do not regard this. This matter leads to overestimations in small-scale 1g model tests results.

8 CONCLUSIONS

This paper presents the results of two series of scale-model experiments and analytical models performed on opening plate anchors embedded in sand having different embedment ratios in 2D and 3D conditions. The results are as follows:

- For shallow opening plate anchors with width of 150 mm, as embedment ratio increases, pullout capacity increases significantly, while relative displacement ranges from 0.51 to 0.57.
- PIV demonstrated that for anchors with width of 150 mm and embedment ratio of up to 5, the anchors act as shallow anchors and the failure surfaces reach the free soil surface.
- Pullout capacity and subsequently Breakout factor is much higher in 3D condition rather than 2D condition due to participation of the third dimension in soil mass and shear resistance along failure surfaces.
- Two equations are suggested for calculating the pullout capacity for shallow opening plate anchors in 2D and 3D conditions.

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