scientific reports

OPEN

Performance of vertical steel plate anchor in layered cohesionless soil

Alireza Parsa[1] & Hamed Niroumand[1,2]✉

This study investigated the performance of steel vertical anchor plates in multi-layered cohesionless soils. The research evaluated the effects of various parameters, such as soil density, number of layers, and anchor embedment depth, on the pullout capacity of the anchors. For the research, a container with the dimensions of was filled with sand at two different densities (dense and loose) up to a height of 80 cm. The study used steel plate anchor. Plate anchor underwent 12 tests with different embedment depths. In this research, steel plate anchors with equal dimensions of 150 × 50 × 8 mm, with L/d ratios of 1–4 and H/d ratios of 1–4 were used. The research showed that increasing the distance of the steel anchor from the soil wall increased the pullout force. For example, embedding a steel anchor at a depth of tripled the pullout force. Finally, the study indicated that soil parameters and anchor embedment geometry directly influenced the pullout behavior of the anchors.

Keywords Vertical anchor plate, Steel plate, Multi-layered, Cohesionless soil, Pull-out

List of symbols

B	Anchor width
Cc	Uniformity coefficient
Cu	Curvature coefficient
D_r	Soil relative density
D_{10}	Diameter of soil particles finer than 10 percent of the soil
D_{30}	Diameter of soil particles finer than 30 percent of the soil
D_{60}	Diameter of soil particles finer than 60 percent of the soil
D_{85}	Diameter of soil particles finer than 85 percent of the soil
H	Anchor embedment depth from the soil surface
h or d	Anchor height
L	Distance of the embedded anchor from the box wall
$M_{\gamma q}$	Pullout force coefficient
Q_u	Ultimate pullout load
γ	Unit weight of the soil
H_1 and H_2	The thickness of each soil layer

Engineers have been using vertical plate anchors for a long time to strengthen geotechnical structures. These anchors are usually made of steel, concrete, or wood and have different shapes, such as rectangular, square, or circular, depending on the site of application. The main purpose of these anchors is to resist the lateral movement of soil and the horizontal tensile force on structures such as retaining walls, bridge supports, and piles. The pullout capacity of these anchors is crucial for the overall performance of the structures they reinforce[1,2]. Much research has been done on the pullout capacity of these anchors, considering various factors that can affect it, such as the shape of the anchor, the type of soil, and the embedment depth[3].

A study by Choudhary and Dash explored the behavior of vertical plate anchors in granular soil. Their findings showed that the load-carrying capacity and failure displacement of the anchor depend on the embedment depth and soil density. The study also emphasized that increasing the embedment depth can change the failure mechanism from the general state to the localized failure around the anchor[4]. Similar results were obtained by Das et al.[5] and Dickin and Leung[6] in their respective studies.

Moreover, Yue et al. found in their research that the anchor embedment ratio has a significant role in the anchor load-carrying capacity under lateral loading in the sand. Their study concluded that increasing the anchor embedment depth can increase the anchor's load-carrying capacity[7]. Overall, previous studies on the pullout capacity of vertical plate anchors have suggested a direct relationship between the failure surface and

[1]Department of Civil Engineering, Faculty of Engineering, Buein Zahra Technical University (IKIU-BZ), Qazvin, Iran. [2]Department of Geotechnical and Hydraulic Engineering, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland. ✉email: niroumand.mrud@gmail.com

the embedment depth. Shallow anchors, due to general shear failure, have a failure surface that reaches the soil surface, while deeper anchors with increased embedment depth lead to local failure around the anchor[8,3,9–12].

Numerous articles have examined the performance of plate anchors and effective parameters in single-layer soil in the laboratory[13–19], but there is limited research worldwide on multi-layer cohesionless soils[20]. Therefore, the importance of this research lies in investigating the performance of plate anchors in multi-layer soils on a laboratory scale. Finding homogeneous soil in nature can be difficult, which makes it necessary to investigate the behavior of vertical plate anchors in multi-layered soils. This approach will provide a more realistic representation of real-world conditions and help us better understand the effectiveness of these anchors. Therefore, the research focuses on evaluating the behavior of vertical plate anchors in double-layer sand. The goal of this research is to investigate the performance of these vertical steel anchors in multi-layered cohesionless soils.

Materials and methods

Figure 1 shows the schematic shape of the instrument used to study the pullout behavior of horizontal anchors. This instrument consisted of a wooden box, a loading system, a monitoring system, and a plate anchor. The built wooden box had the dimensions of 1 × 1 × 1, which was secured with steel corners around the box. The box's dimensions matched those chosen by other researchers and the ASTM D6706-1 (2013) standard[21]. To avoid the effect of the sample's dimensions on the test results, the test box's dimensions should not be smaller than 610 × 460 × 610[22–24]. In this standard, the minimum width of the recommended box is twenty times 85 or six times the largest diameter of the soil aggregate. To eliminate the friction between the soil and the box wall, the minimum distance between the anchor and the wall should be 150 mm and if this distance is not met, it is necessary to reduce the friction between the box and the soil by lubricating the box wall or using appropriate covers[21]. It is necessary to reduce the friction between the box and the soil by lubricating the box wall or using appropriate covers, as recommended by ASTM Standard D6706-01 (2021) for measuring pullout resistance in soil[21]. Regarding most research done in the physical modeling of anchors, the minimum dimensions of the model are considered one-tenth of the actual dimensions, which is to minimize the effects of boundary conditions on the results[3].

The loading system consists of a winch motor, which connects to a plate anchor using a steel cable with a diameter of 10 mm, and applies the pullout force to the anchor. The monitoring system includes a load cell and a linear variable displacement transducer (LVDT) to measure force and displacement, respectively. The load cell is an S-shaped tool with a capacity of 2 tons, and the LVDT can measure with an accuracy of 10 cm. A digital data logger was used in this research to record and collect the force and displacement data from the experiments. The data logger is a 24-bit Advantech 4704 type with a sampling rate of 1000 samples per second, which has a sensor and stores the measured data in its internal memory. The data is connected to the computer through the USB interface. Moreover, strain gauges with an accuracy of 0.03 mm were used to evaluate the soil surface deformations when applying pullout force. To account for the soil heterogeneity in nature, an attempt was made to use two-layer soil with different relative densities. For this purpose, the first and second layers were prepared

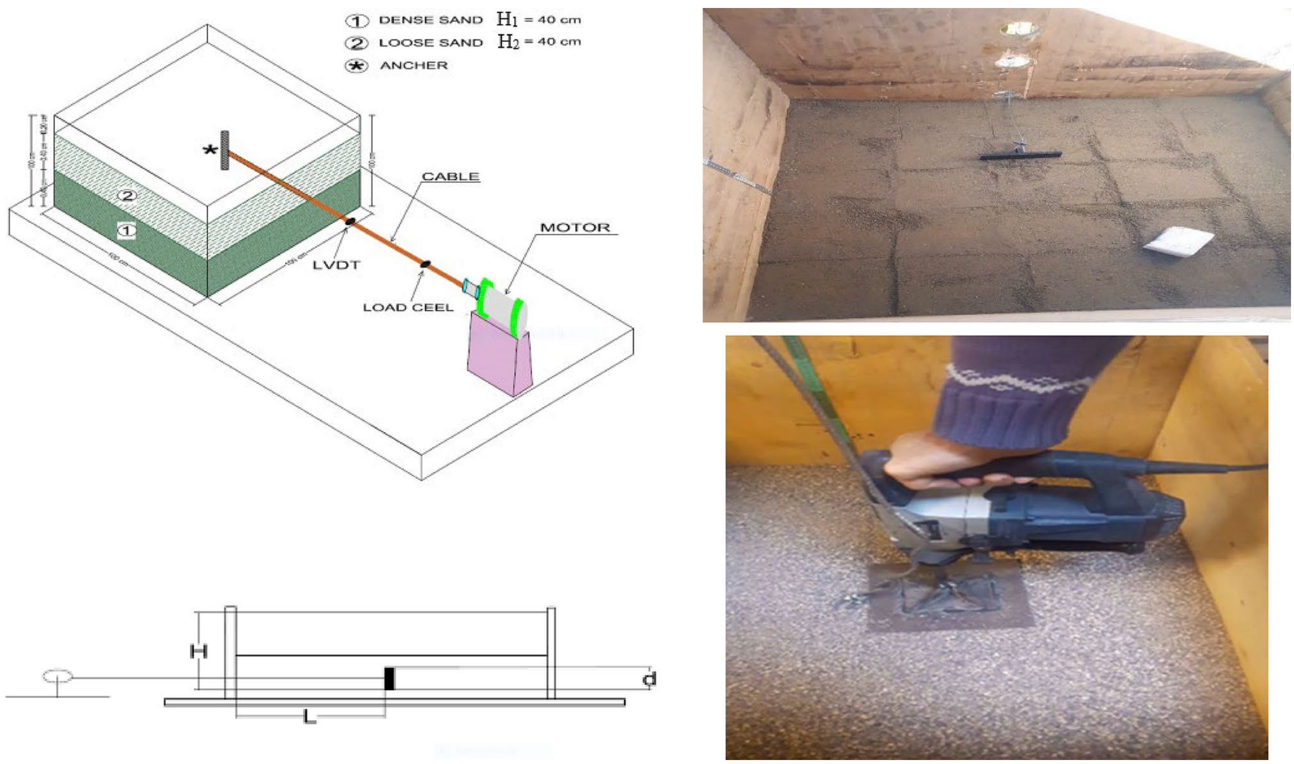

Fig. 1. Schematic of the chamber box.

L/d	1–4
H/d	1–4
Steel plate anchors with dimensions	150 × 50 × 8 mm

Table 1. Experimental details.

Fig. 2. Steel plate anchors used in the present research.

using dense and loose sands, respectively. The ASTM D4253 (2006) standard was used to make the dense layer[25]. The sand was poured into the box in four stages, each of which was compacted using an electric vibrating compactor to prepare a dense layer with a height of 40 cm and a relative density of = 95%. The loose layer (< 35%) was placed on the dense layer in four stages to a total height of 40 cm, so that the sample's total height reached 80 cm. To prepare a loose layer, sand was poured from a very close height to avoid compaction due to the soil's weight. The sand used in this research was river sand, with a grain size distribution between 0.075 and 4.75 mm (according to the grain size analysis test), and $D_{10} = 0.42$ mm, $D_{60} = 2.1$ mm, and $D_{30} = 2.1$ mm.

In this research, steel plate anchors with dimensions of 150 × 50 × 8 mm were used, featuring L/d ratios ranging from 1 to 4 and H/d ratios ranging from 1 to 4 (Table 1). Figure 2 shows a schematic of steel plate anchors. To evaluate the effect of the depth and height of the anchor embedment in the soil, the anchors were placed at three different depths and three different heights in the soil. Since the embankment process is related to the plate anchor embedment process, these anchors were installed inside the box during the embankment so that the anchors were placed at the predetermined embedment depths and then the embankment process continued. Due to the sensitivity of loading and the effect of changes in the load direction angle on the anchor pullout force, any eccentricity in relation to the loading direction was checked during the embedding of the anchor and before continuing the embankment process, and the anchor was installed vertically without any angle in the center of the loading area in the soil. Furthermore, the anchors were installed at four depths of 150, 300, 450, and 600 mm from the box side wall and at three heights of 200, 400, and 600 mm from the soil surface, which were the middle of the loose layer, the border of the loose and dense layer, and the middle of the dense layer, respectively. Therefore, the effect of the distance of the anchor from the wall and the ground surface and the change in soil density on the anchor pullout force could be evaluated.

The anchor pullout operation was performed by a winch motor that could adjust the loading speed. After the anchor was installed and embedded at the expected depth, it was connected to a load cell by a hook. Then, the anchor was loaded at an average speed of 15 mm/min, and the load and displacement were recorded by a displacement gauge and a load cell. Additionally, a series of strain gauges were installed on the samples' finished surface to evaluate the soil surface displacements when applying pullout force. This study aimed to evaluate the pullout capacity of steel plate anchors in different states. Moreover, the changes in the anchors' pullout force coefficients were studied as an important parameter in the anchors' pullout topic. The pullout force coefficient of plate anchors was obtained using the theory of Neely et al., which was presented in 1973 for single vertical anchors under horizontal force[1]. Equation 1 shows how to calculate the pullout force coefficient of horizontal plate anchors.

$$M_{\gamma q} = \frac{Q_u}{\gamma B h^2}$$

where $M_{\gamma q}$ represents the pullout force coefficient, Q_u indicates the ultimate pullout load, shows the unit weight of the soil, B is the width of the anchor, and h is the height of the anchor although d used as height of anchor in this research paper.

Results and discussion

In this study, 12 series of tests were performed for steel anchors with different embedment depths. In the presented diagrams, L represents the distance of the embedded anchor from the box wall, H indicates the embedment depth from the soil surface, and d represents the length of the anchor. Figures 3, 4 and 5 show force-displacement diagrams of the steel plate anchor at three embedment depths (H) of 200, 400, and 600 mm and four distance ratios of (L/d) 1, 2, 3, and 4. As observed, the pullout force of the anchors increases with the distance of the anchors from the soil wall in all three embedment depths (H). The main reason is the increase in the soil mass available in front of the anchor by increasing the embedment depth, which causes more resistance during pullout. For instance, increasing the distance from the box wall by four times increases the pullout force in all three heights (H) by 2 to 3 times. Moreover, the highest pullout force was recorded at a depth of 600 mm from the soil surface. The increase in soil density and the frictional force between the soil and the anchor increase the anchor resistance against pullout and reach its maximum value. The anchor embedded at the boundary between the dense and loose layers has a lower pullout force than the anchor placed in the dense layer. Besides, the pullout force of the anchor reaches its minimum value in the loose layer because the soil's internal friction angle is lower, and the space between the soil grains allows the anchor to move more easily in the soil. Similar results were obtained in the research of Choudhary and Dash (2018)[4]. They conducted experiments on plate anchors in three types of dense, semi-dense, and loose soils and observed that the increase in soil density increases the ultimate pullout force, and the rate of this force increase rises with the increase in the anchor embedment depth, which is attributed to the soil failure behavior. According to the experiments, the increase in soil density increases the size of the failure surface, which is more evident at a greater depth. Therefore, the performance of the system is improved due to the increased soil mass involved in the anchor force[4]. Ilamparuthi et al. (2002) achieved similar results by studying horizontal anchors embedded in sandy soil[26]. Figure 6 shows the diagram of steel plate anchors' pullout force coefficient versus the embedment depth ratio (H/d). As shown, the pullout force coefficient of the anchors increases with the distance between the anchors and the box wall. Furthermore, the pullout force coefficient of the anchors increases with the embedment depth ratio (H/d), which is due to the increase of surcharge on the anchor with the increase in depth. On the other hand, the increase in depth (H) raises the soil density, which is directly related to its internal friction angle. In this regard, the increase in density increases the internal friction angle, which causes more interactions between the soil and the anchor

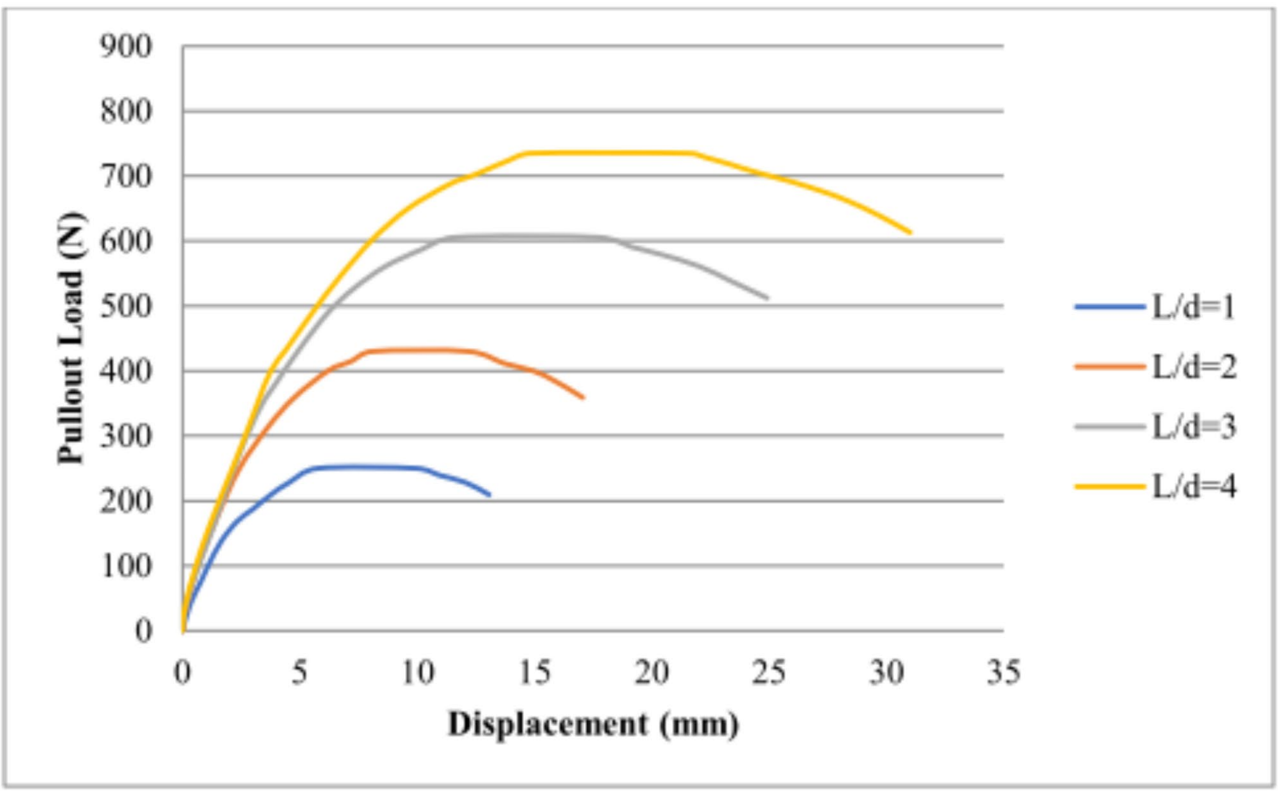

Fig. 3. Force-displacement diagram of steel plate anchor in loose layer (H= 200 mm).

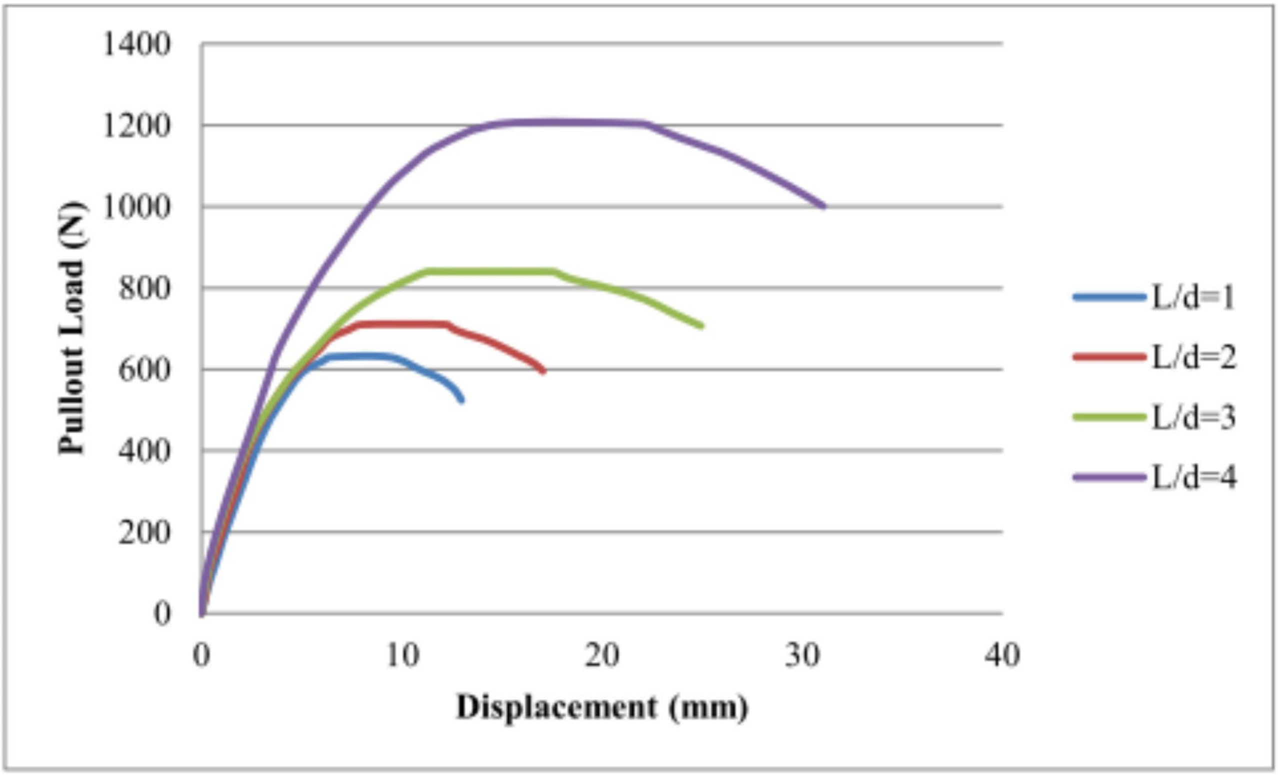

Fig. 4. Force-displacement diagram of steel plate anchor at the boundary of the loose layer (H= 400 mm).

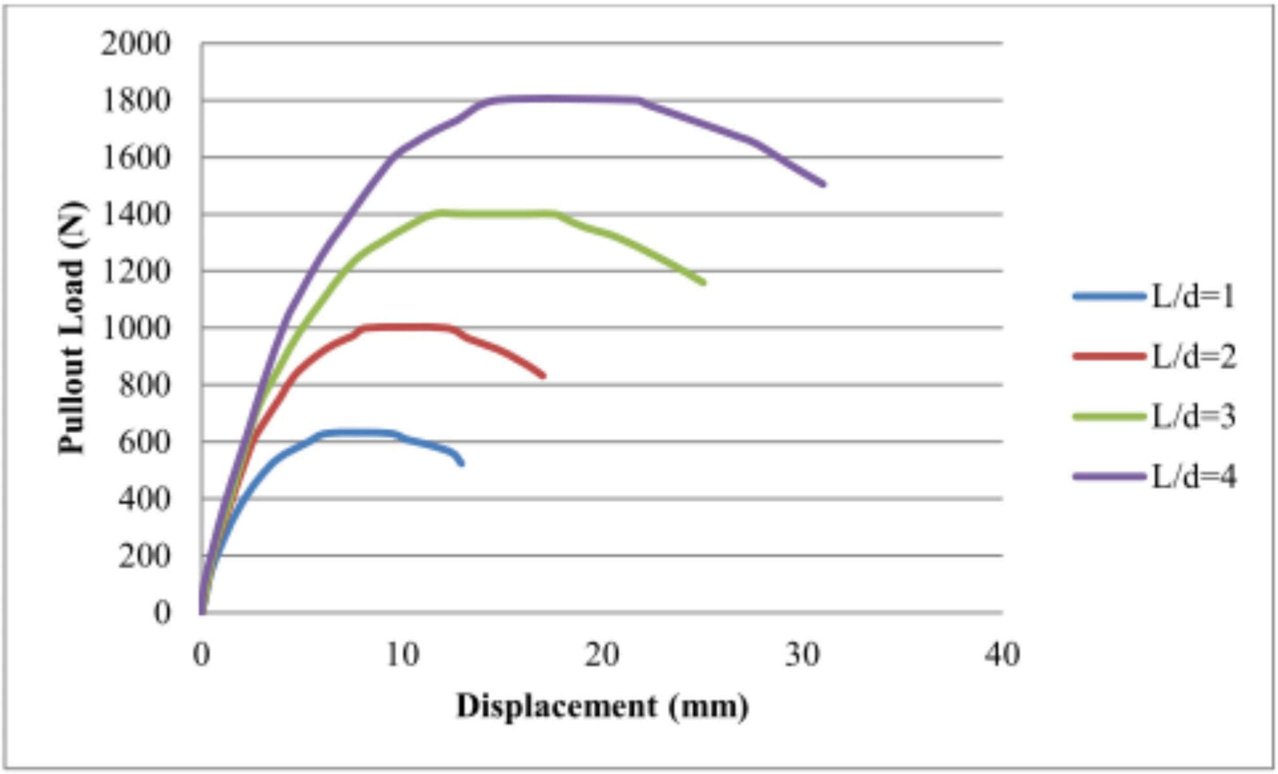

Fig. 5. Force-displacement diagram of steel plate anchor at the dense layer (H= 600 mm).

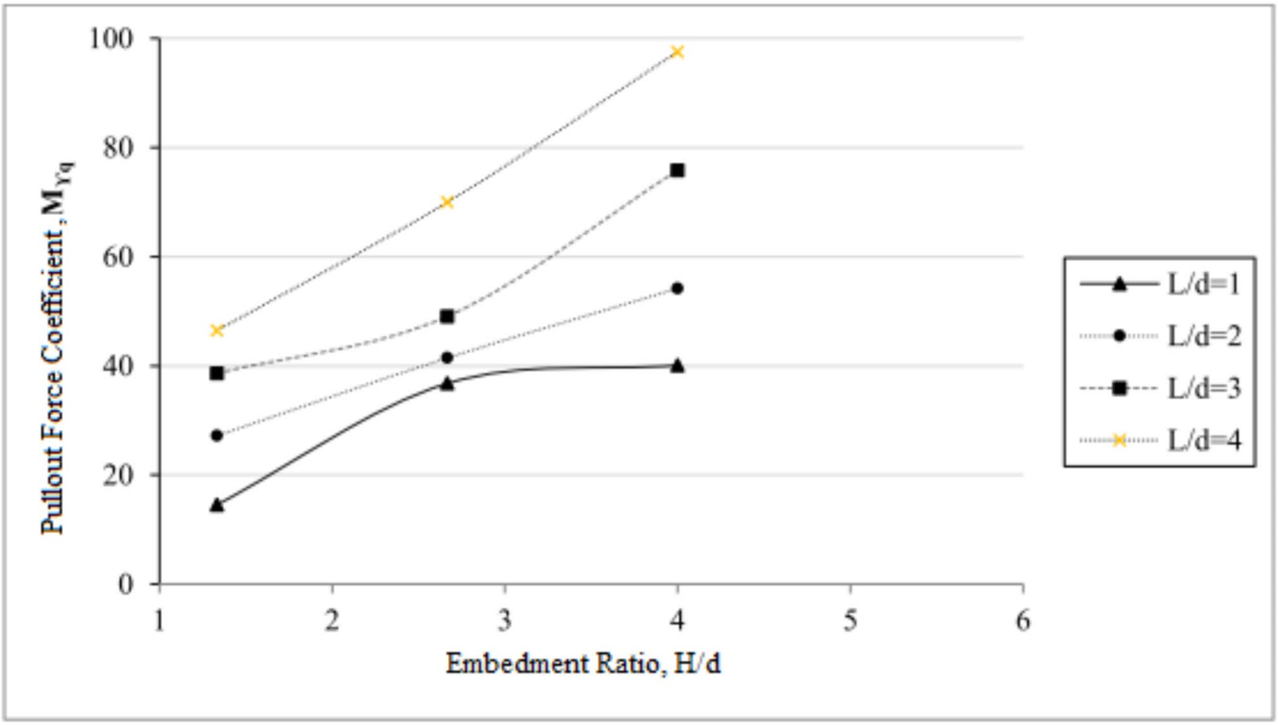

Fig. 6. Steel plate anchors' pullout force coefficient.

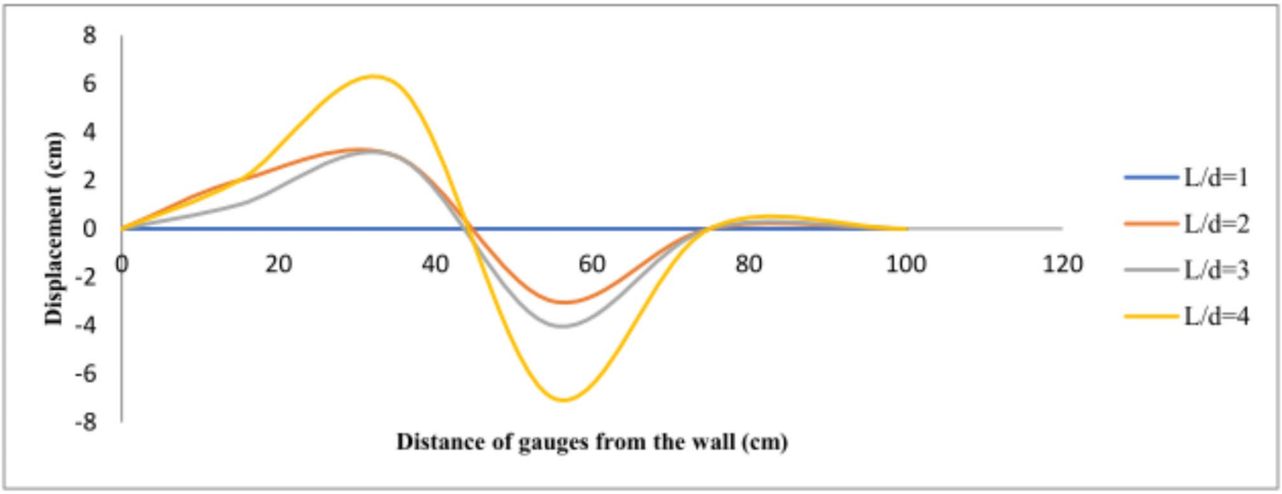

Fig. 7. Soil surface deformations caused by the pullout of the steel plate anchor at a depth of 200 mm.

and ultimately leads to an increase in the pullout force and the pullout force coefficient of the anchor. Ansari et al. (2021) also obtained similar results in their research[27].

The following presents the soil surface deformations caused by the pullout of different types of anchors. Figures 7, 8 and 9 show diagrams of the soil surface deformations caused by the pullout of steel plate anchors at different distances and depths. As seen, the soil surface deformations change with the increase in distance ratio (L/d). This is mainly due to the soil accumulation in front of the anchor during pullout, which first causes soil settlement and then uplifts the soil. The soil surface deformations also change with the embedment depth, such that increasing the embedment depth reduces the soil surface deformations. This is related to the decrease of the anchor force transition to higher levels with the increase in the anchor embedment depth. Moreover, the higher soil density and the increase in surcharge are other factors that reduce the soil surface deformations due to the increase in the embedment depth. Choudhary and Dash (2018) obtained similar results[4].

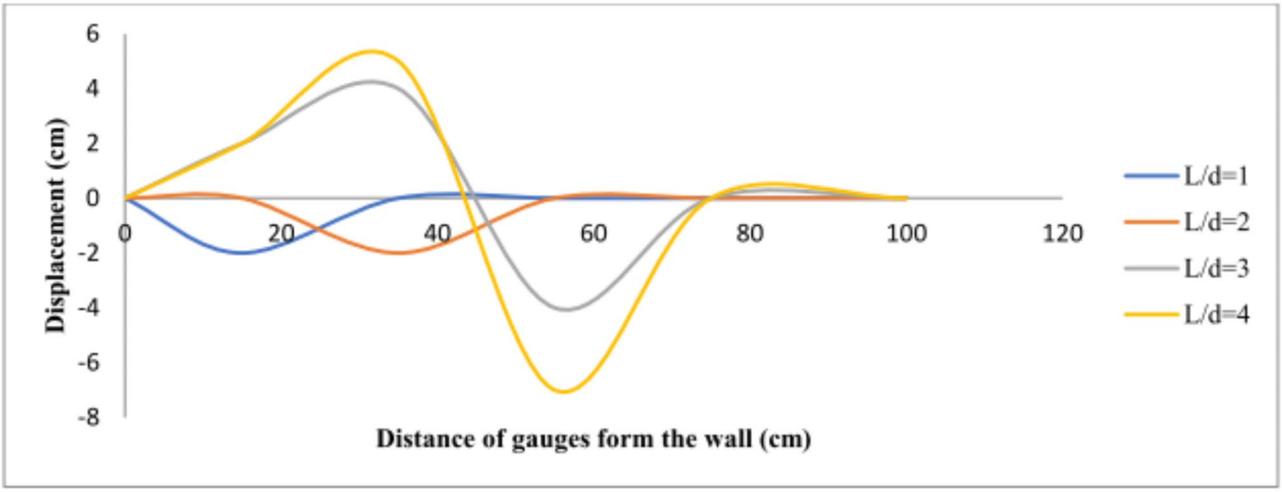

Fig. 8. Soil surface deformations caused by the pullout of the steel plate anchor at a depth of 400 mm.

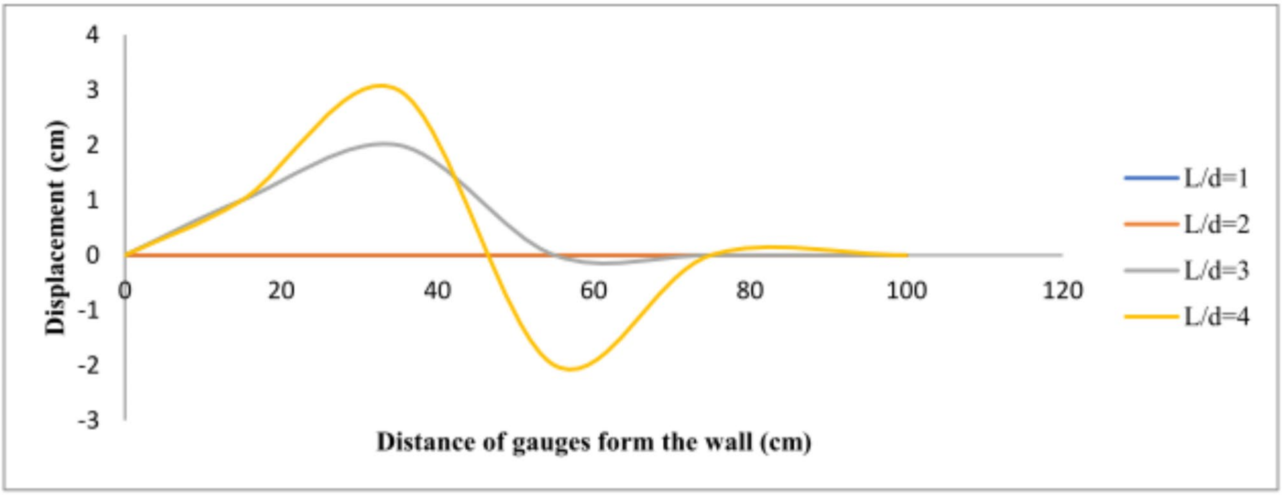

Fig. 9. Soil surface deformations caused by the pullout of the steel plate anchor at a depth of 600 mm.

Conclusions

Due to a significant gap in the performance data of anchor plates in multi-layered soils, this research investigates the behavior of vertical plate anchors under horizontal pullout force using physical modeling in a laboratory setting. This research evaluates steel plate anchors in two-layer sandy soils under specified conditions. The tests were conducted in a laboratory setting, and for field-scale applications, the field conditions and scale must be considered. The parameters specified in these tests have been assessed, and numerous other parameters could be explored in future studies to evaluate the performance of layered sandy soils and plate anchors. The goal of this research is to contribute to the limited body of research on anchors in multilayered soils and may pave the way for evaluating various parameters, factors, different conditions of multilayered soils and interface mechanics in future research. The anchor plates used in this research were made of steel. Considering the heterogeneous nature of the soil, the research aimed to evaluate the anchor behavior in two layers with different densities. The experiment showed that various soil parameters and anchor embedment geometry could significantly affect the pullout behavior of the anchor. Steel plate anchors with equal dimensions of 150 × 50 × 8 mm, with L/d ratios of 1–4 and H/d ratios of 1–4, were used. The main results obtained from this research are as follows:

- The pullout force changes with the number of soil layers, such that embedding the anchor in the lower layer increases the surcharge and soil density, leading to an increase in the pullout force of the anchor.
- The pullout force of the anchor increases with the distance of the anchors from the wall, mainly due to the increase of soil mass in front of the anchor during the application of pullout force.
- The pullout force of the steel plate anchor is 250 kN in the closest location to the soil surface and wall (L/d = 1). In this regard, the pullout force increases with the increase in the embedment depth and distance from the wall. At L/d = 4, when the anchor is located in the second layer with higher density and depth, the pullout

force of steel anchors is 7.2 times higher than that of the shallow state. This result is useful and necessary for the design of retaining walls.

- The location of the anchor embedment, as well as its shape and material, directly affect the amount and mechanism of the soil surface deformation during the pullout process. In this regard, the surface displacements increase with the distance of the anchor from the wall, while the surface displacements decrease with the increase in the embedment depth.
- When the anchor is placed between dense and loose layers at the start of the pullout, it can indeed cause rotation of the anchor plate. This is due to the differential resistance offered by the varying densities of the soil layers.
- The importance of the anchor plate's size impacts its performance. This result suggests that laboratory-scale samples, being much smaller than field-scale anchors, may not fully capture the performance of larger samples due to various factors such as plate size, boundary conditions, and the interaction between the soil and the anchor plate. Therefore, smaller-scale plates must be adjusted or interpreted with caution in field scale.
- A comprehensive examination of boundary condition effects on the pullout resistance of steel plate anchors in two sand layers is essential for accurate field predictions. Key factors include lateral and vertical boundary constraints, soil layer interactions, and soil compaction variations. Numerical modeling can aid in scaling results from laboratory tests to real-world scenarios. Understanding these effects ensures more reliable anchor performance predictions that they can evaluate in future research projects.

Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 27 December 2024; Accepted: 26 March 2025
Published online: 01 April 2025

References
1. Das, B. M. & Shukla, S. K. *Earth Anchors* (J. Ross Publishing, 2013).
2. Evans, T. M. & Zhang, N. Three-dimensional simulations of plate anchor pullout in granular materials. *Int. J. Geomech.* **19** (4), 04019004. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001367 (2019).
3. Niroumand, H. & Kassim, K. A. *Design and Construction of Soil Anchor Plates*. (Elsevier, USA, 2016).
4. Choudhary, A. K. & Dash, S. K. Pull-out behaviour of vertical plate anchor in granular soil. *Proc. Inst. Civil Eng. Geotech. Eng.* **171** (5), 379–390. https://doi.org/10.1680/jgeen.17.00174 (2018).
5. Das, B. M., Seeley, G. R. & DAs, S. C. Ultimate resistance of deep vertical anchor in sand. *Soils Found.* **17** (2), 52–56. https://doi.org/10.3208/sandf1972.17.2_52 (1977).
6. Dickin, E. A. & Leung, C. F. Evaluation of design methods for vertical anchor plates. *J. Geotech. Eng.* **111** (4), 500–520. https://doi.org/10.1061/(ASCE)0733- (1985).
7. Yue, H., Zhuang, P., Zhang, H. & Song, X. Failure and deformation mechanisms of vertical plate anchors subjected to lateral loading in sand. *Int. J. Geomech.* **20** (11), 04020210. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001859 (2020).
8. Al Hakeem, N. & Aubeny, C. Numerical investigation of uplift behavior of circular plate anchors in uniform sand. *J. Geotech. GeoEnviron. Eng.* **145** (9), 04019039. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002083 (2019).
9. Shahriar, A. R., Islam, M. S. & Jadid, R. Ultimate pullout capacity of vertical anchors in frictional soils. *Int. J. Geomech.* **20** (2). https://doi.org/10.1061/(ASCE)GM.1943-5622.0001576 (2020).
10. Yoshida, S., Xiong, X. & Matsumoto, T. Experimental and numerical study on reinforcement effect of plate anchors or flip anchors on model slopes. *Soils Found.* **63** (2), 101285. https://doi.org/10.1016/j.sandf.2023.101285 (2023).
11. Zhuang, P. et al. Ultimate pullout capacity of single vertical plate anchors in sand. *Mar. Georesour. Geotechnol.* **40** (8), 1004–1022. https://doi.org/10.1080/1064119X.2021.1950247 (2022).
12. Zhuang, P. Z. et al. Pullout behaviour of inclined shallow plate anchors in sand. *Can. Geotech. J.* **59** (2), 239–253. https://doi.org/10.1139/cgj-2020-0495 (2022).
13. Neely, W. J., Stuart, J. G. & Graham, J. Failure loads of vertical anchor plates in sand. *J. Soil. Mech. Found. Div.* **99** (9), 669–685 (1973).
14. Murray, E. J. & Geddes, J. D. Resistance of passive inclined anchors in cohesionless medium. *Geotechnique* **39** (3), 417–431 (1989).
15. Bhattacharya, P. & Kumar, J. Pullout capacity of inclined plate anchors embedded in sand. *Can. Geotech. J.* **51** (11), 1365–1370 (2014).
16. Stewart, W. Uplift capacity of circular plate anchors in layered soil. *Can. Geotech. J.* **22**, 589–592 (1985).
17. Kumar, J. Uplift resistance of strip and circular anchors in a two layered sand. *Soils Found.* **43** (1), 101–107 (2003).
18. Bhattacharya, P., Roy, A. & Bhattacharya, P. Variation of horizontal pullout capacity with width of vertical anchor plate. *Int. J. Geomech.* **16** (5), 06016002.
19. Roy, A., and 2020. Diameter effect on uplift capacity of horizontal circular anchor embedded in sand. *Int. J. Geotech. Eng.* **14** (7), 779–792 (2016).
20. Bhattacharya, P. & Kumar, J. Horizontal pullout capacity of a group of two vertical strip anchors plates embedded in sand. *Geotech. Geol. Eng.* **30**, 513–521 (2012).
21. ASTM (American Society for Testing and Materials). Standard test method for measuring geosynthetic pullout resistance in soil. ASTM standard D6706-01. ASTM International, West Conshohocken, PA, USA. (2013).
22. Chu, L. M. & Yin, J. H. Comparison of interface shear strength of soil nails measured by both direct shear box tests and pullout tests. *J. Geotech. Geoenviron. Eng.* **131** (9), 1097–1107. https://doi.org/10.1061/(ASCE)1090-0241(2005).
23. Mahmoudi-Mehrizi, M. E., Ghanbari, A. & Sabermahani, M. Investigating the effect of grout on improving the performance of helical anchors used in wall stabilization. *Transp. Infrastruct. Geotechnol.* **7**, 332–353. https://doi.org/10.1007/s40515-020-00125-8 (2020).
24. Su, L. J., Chan, T. C., Yin, J. H., Shiu, Y. K. & Chiu, S. L. Influence of overburden pressure on soil–nail pullout resistance in a compacted fill. *J. Geotech. GeoEnviron. Eng.* **134** (9), 1339–1347. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:9(1339) (2008).
25. ASTM (American Society for Testing and Materials). *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table. ASTM Standard D4253-00* (ASTM International, 2006).
26. Ilamparuthi, K., Dickin, E. A. & Muthukrisnaiah, K. Experimental investigation of the uplift behaviour of circular plate anchors embedded in sand. *Can. Geotech. J.* **39** (3), 648–664. https://doi.org/10.1139/t02-005 (2002).

27. Ansari, Y., Kouretzis, G. & Sloan, S. W. Physical modelling of lateral sand–pipe interaction. *Géotechnique* **71** (1), 60–75. https://doi.org/10.1680/jgeot.18.P.119 (2021).

Author contributions

A.P. and H.N. wrote the main manuscript text. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to H.N.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.