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Experimental study on the uplift capacity of a new plate anchor embedded in cohesionless soil

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Research Paper

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Experimental study on the uplift capacity of a new plate anchor embedded in cohesionless soil

This study introduces a new type of cross-shaped anchor plate, resulting in a reduction in the plate surface area by over 92 % compared to a square plate, and more than 43% compared to a circular plate. In this study, experimental tests were conducted to assess the pullout force and resulting displacements of a cross-shaped anchor at various depths in sandy soil. A comparison of the results with existing studies demonstrates that this anchor exhibits a pullout performance very similar to that of traditional plate anchors (square or circular). These findings indicate that the proposed anchor is a promising alternative in terms of strength and stability. The reduced steel volume of the plate makes these anchors lighter and easier to install, providing economic and ecological benefits while maintaining a similar order of magnitude of maximum pullout load as that provided by traditional plate earth anchors. Further research is required to refine the design and assess the long-term performance of these anchors.

Key words:
anchor plate, pullout capacity, horizontal anchor plate tests, new type of earth anchor

Prethodno priopćenje

Hsaine Chabbi, Mohamed Meksaouine, Abdelmadjid Abdi, Latifa Louetri, Tarek Keffaf

Eksperimentalno istraživanje nosivosti uslijed uzgona nove sidrene ploče ugrađene u nekoherentno tlo

U ovome radu predstavljena je nova vrsta križne sidrene ploče, čime je površina ploče smanjena za više od 92 % u usporedbi s kvadratnom pločom i za više od 43 % u usporedbi s kružnom pločom. Također su provedena eksperimentalna ispitivanja procjene sile izvlačenja i rezultirajućih pomaka križnog sidra na različitim dubinama u pjeskovitu tlu. Usporedba rezultata s postojećim istraživanjima pokazuje da navedeno sidro pri izvlačenju pokazuje učinkovitost vrlo sličnu onoj tradicionalnih pločastih sidara (kvadratnih ili kružnih). Ti rezultati upućuju na to da je predloženo sidro obećavajuća alternativa u pogledu čvrstoće i stabilnosti. Smanjeni udio čelika ploče čini ta sidra lakšima i jednostavnijima za ugradnju, pružajući ekonomske i ekološke prednosti uz nosivost na izvlačenje sličnu onoj koju pružaju tradicionalne sidrene ploče za primjenu u tlu. Potrebna su daljnja istraživanja kako bi se poboljšao dizajn i procijenila dugoročna učinkovitost navedenih sidara.

Ključne riječi:
sidrena ploča, nosivost na izvlačenje, ispitivanja horizontalne sidrene ploče, nova vrsta sidra u tlu

1. Introduction

Geotechnics is an important field of study in civil engineering, aiming to ensure the stability and durability of structures built on or within the soil. Among the many challenges faced by geotechnical engineers, anchor plates play a crucial role in enhancing structural stability. Various types of anchors have been developed and deployed in the field to address the need for enhanced performance. Unfortunately, these solutions encounter difficulties and drawbacks, such as the high cost of rods, which is a primary concern for this type of reinforcement. Over the past few decades, improving and determining the maximum load capacity of anchor plates through experimental and numerical studies has become a key area of research, attracting considerable attention from researchers. The central issue of this study revolves around innovations in the field of plate anchoring and the search for an improved solution that offers both optimal performance and ease of use. An experimental approach is used to address this issue. In this paper, we present a new approach in the field of earth anchoring, highlighting a type of anchor plate characterised by a reduced plate surface, which offers significant advantages over traditional systems. These anchor plates are designed to provide increased strength, reduced ecological footprint, and economic benefits compared with conventional anchors. This study continues previous research by incorporating on-site experimental work, primarily aimed at measuring the maximum horizontal pullout stress and corresponding displacements of the newly proposed anchor. A comparative analysis with conventional plate anchors is presented, followed by a discussion of the results and the technological choices involved.

2. Objective of the study

The objective of this experimental study was to analyse and assess the impact of reducing the steel surface area of anchor plates by adopting a new cross-shaped form, compared to existing circular or square forms, on the pullout resistance and associated displacements. We aimed to determine whether this new configuration can offer improved performance in terms of pullout resistance capacity and anchoring system stability. By conducting tests and comparing the results with those of existing anchors, we evaluated the potential advantages of this new form of anchor plate and provided recommendations for its use in the field of geotechnical engineering.

3. Theoretical analysis

Recent studies have focused on anchor plates with geometries and mechanisms comparable to those of the proposed system, which serve as benchmarks for performance evaluation. Several analytical approaches for predicting the uplift capacity of sandy soils have been summarised by Jung et al. [9]. The seminal work of Meyerhof and Adams [14] laid the foundation for the design criteria based on soil conditions and loading, which was later refined by Roy et al. [10], who provided guidance on the embedment depth, plate shape, and safety margins. Complementary investigations by Yünkül and Gürbüz [13] and Niroumand and Kassim [16] further highlighted the effects of geometry and reinforcement on the uplift behaviour in cohesionless soils [13, 16].
Numerous studies have employed dimensionless coefficients to normalise the ultimate uplift capacity of horizontal plate anchors. Among these, coefficient F_q is the most commonly used. This allows for the assessment of the uplift capacity of an anchor based on its dimensions and the properties of the surrounding soil [6], as expressed in Equation (1), according to [7, 11]:

$$F_q = \frac{Q_u}{\gamma \cdot B \cdot h \cdot H} \tag{1}$$

Several analytical formulations were proposed to enhance the accuracy of this coefficient. These incorporate the effects of the anchor plate geometry, soil mechanical properties, and soil–structure interaction mechanisms. One such formulation, proposed in [14], is presented in Equation (2), according to [3, 5]:

$$F_q = 1 + \left\{ \left[1 + 2m \left(\frac{H}{h} \right) \right] \left(\frac{h}{B} \right) + 1 \right\} \left(\frac{H}{h} \right) K_U \tan\varphi \tag{2}$$

where:
- F_q – Breakout factor
- B – Anchor width [m]
- h – Anchor length [m]
- H – Anchor depth [m]
- Q_u – Ultimate pullout capacity [kN]
- K_U – Nominal pullout coefficient
- φ – Soil friction angle [°]
- γ – Soil unit weight [kN/m³]
- *m* – coefficient dependent on the values of *m* are indicated in Table 1
- φ – as determined through experimental observations [15].

This expression provides a comprehensive assessment of the combined influence of the geometric parameters and soil properties on the uplift behaviour of the anchor plates. This served as a solid theoretical basis for the design and verification of plate anchors in cohesionless soil. The nominal pullout coefficient K_U is deduced from Figure 1.

Table 1. Values of m provided by the experimental observation [5]

φ [°]	20	25	30	35	40	45	48
m	0.05	0.1	0.15	0.25	0.35	0.5	0.6

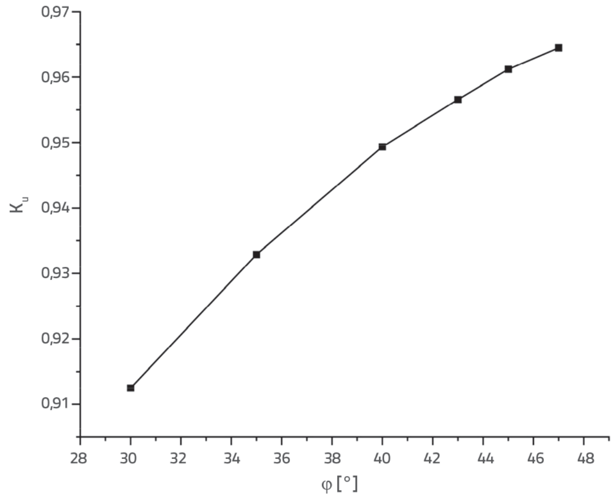

Figure 1. Variation of K_u with soil friction angle [3]

4. Study materials

4.1. Nature of the backfill

In this study, nearly uniformly graded sand was utilised and its characteristics were determined in a laboratory. The soil is characterised by a bulk unit weight of γ_h = 20.9 kN/m³ and a dry unit weight of γ_d = 19.7 kN/m³. The internal friction angle ϕ was determined through standard direct shear tests and found to be approximately 45°.

4.2. Construction of the embankment

The embankment was built by compacting layers of the material, each 20 cm thick. To avoid the influence of the tank walls on the test results, these experiments were conducted on an embankment compacted in the form of a cone, with slopes having a ratio of 3/2 and a summit with a diameter of 2.5 m (see Figure 2).
Figure 2 Illustrate the geometry of the embankment implementation. Compaction was ensured using a jumping jack compactor to guarantee proper compaction across the entire material surface.

Figure 2. Geometry of the embankment used

4.3. Steel type used

Ordinary steel with a diameter of 2 cm was used in the form of a round bar constituting the anchor rod connected at its end to articulated parts made of an ordinary steel T-profile (20 x 20 x 3 mm) with a thickness of 0.3 cm.

5. Model description

This anchoring model is a device inspired by the shape of an umbrella, practical and foldable, allowing for the permanent or temporary stabilisation of structures in geotechnics. The CMA (Chabbi-Meksaouine Anchor) is a 20 mm diameter steel round bar connected at its end by four T-profiles in a symmetrical manner, these profiles can open from 0° to 90° relative to the symmetry axis of the anchor through joints (see Figure 3). Length h of the anchor plate after its opening was 0.5 m.

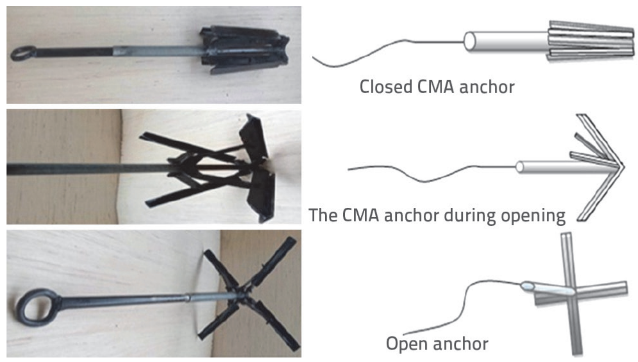

Figure 3. Various states of the CMA

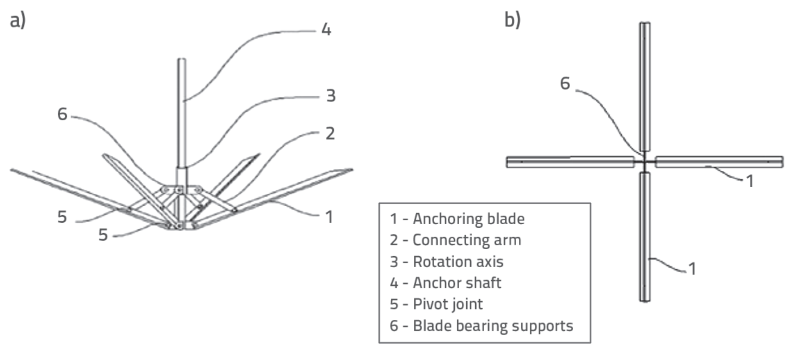

Figure 4. Sketches of the cross-shaped anchor at different stages

The mechanism allowing this model to close is designed to provide several advantages, such as the ability to fold the CMA; facilitate its implementation, transport, and storage; and conduct additional tests in the future. Sketches of the cross-shaped anchors are shown in Figure 4.

6. Experimental procedure

6.1. Test setup

The test involved applying a step of pullout force provided by a pneumatic crane and transmitting it through a cable to a CMA-type anchor in the middle of a compacted sand volume. The cable was connected to a dynamometer to measure the applied forces. A displacement comparison device (water level and millimetre rule) was attached to the upper end of the anchor rod to measure the vertical displacements. The details of the device are shown in Figure 4.

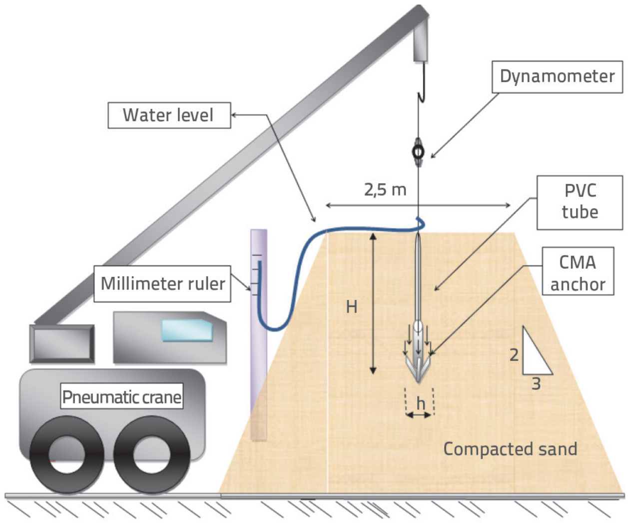

Figure 5. Diagram of the test setup

6.2. Conduct of the test

The following section outlines the procedure used to conduct the experiment on the newly proposed horizontal anchor plates. The embedment ratio (H/h), where H represents the vertical distance from the ground surface to the anchor plate, and h denotes the height (or diameter for circular anchors) of the anchor. This ratio is a critical dimensionless parameter that standardises the relative embedment depth and plays a decisive role in assessing anchor uplift performance. In this study the anchor length was kept constant at h = 50 cm and the depth H was varied to achieve the desired H/h ratio. Five cases were investigated: H/h = {0.3, 0.5, 1, 2, and 3}. The sand was placed at the test site, and the layers and dimensions were created according to the process presented in Section 4.2. This involves placing the sand layer by layer, compacting to a height of 0.2 m, and levelling the surface of the volume in the form of uniform layers, with excess sand moving towards the ends. The horizontal anchor plate is then placed in the center of the embankment at a height of 0.4 m on a leveled and compacted section to avoid possible settling under the anchor. The cable that ensures transmission of the pullout force between the crane and anchor must be taut and perpendicular to the anchor. The dynamometer, equipped with a remote display (to move away from the risk zone), was placed between the anchor and cable, allowing the pullout force levels to be recorded. This deposition of compacted soil layers is continued above the anchor until the depth of the sand equals the desired depth H deduced from the H/h ratio. These operations are monitored by topographic equipment to achieve better precision.

A tool for measuring the displacement of the anchor head consisting of a transparent tube containing coloured water was connected at its first end to the anchor head and its second end to a millimetre ruler. The next step was to verify the verticality of the cable and reset the dynamometer and displacement measurement tool to zero (see Figure 5). To eliminate any doubt regarding the potential influence of the embankment boundaries on the results, an additional test was conducted for H/h = 3 using a larger embankment volume with a surface diameter exceeding 3 m.

Figure 6. CMA anchor embedded in the sand

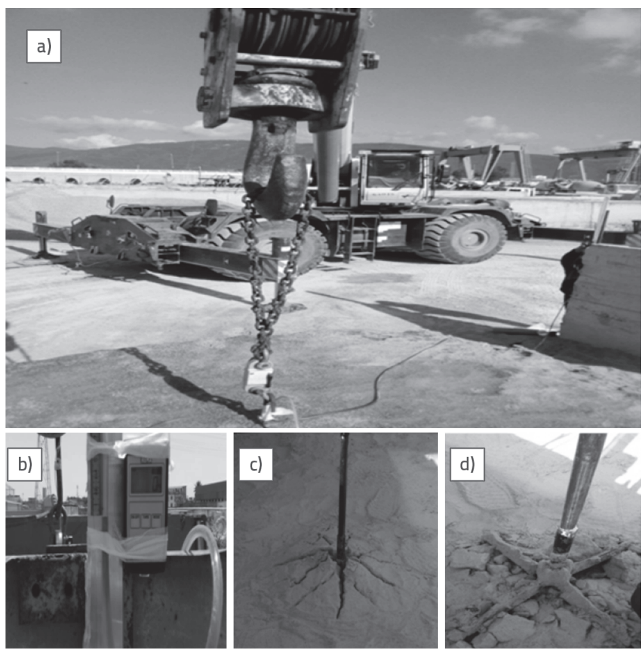

Figure 7. Overview of the test components

After anchoring the open CMA in the compacted sand over multiple layers, we applied successive and increasing axial pullout load increments of approximately 100 N provided by a crane through a metal cable. These loads were immediately recorded using the remote display of the dynamometer, whereas the anchor displacements were measured using a water level

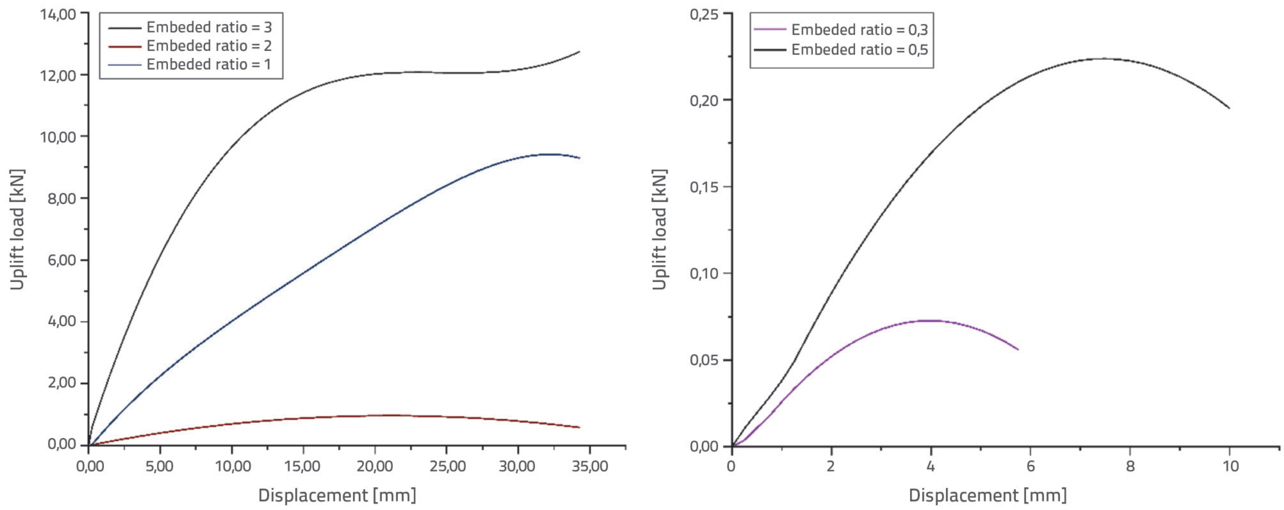

Figure 8. Uplift capacity of the CMA at various depths as a function of resulting displacements

Table 2. Details of some existing experiments on commonly shaped anchor plates [1, 2, 4]

Experimentation	Year of implementation	Shape	φ [°]	Dimension [mm]
Dickin [1]	1988	Square and rectangular	48	50
Patel and Parmar [2]	2022	Square	45.65	300
Bouazza and Finlay [4]	1990	Circular	39	37.5

and a millimetre ruler. The pullout test was performed until soil failure occurred and the entire test procedure was filmed using a digital camera throughout the experimental period.
Figure 7 illustrates the main stages of the experimental procedure: a) initial load application, b) measurement of the pull-out forces and associated displacements using a remote-reading dynamometer and water level for displacement tracking, c) onset of soil failure, and (d) extraction of the anchor at the conclusion of the test.

7. Test results

7.1. Results of the experiments

To visualise the evolution of soil resistance during the experimental investigations conducted in sand at various depths, these are presented in the form of curves (Figure 8). This figure highlights the behaviour of the CMA anchor plates from the application of force until the soil ruptures.
We observed a rapid increase in the pullout resistance of the CMA, accompanied by a minimal displacement of the anchor from the beginning of the applied efforts until soil failure was observed. In the vicinity of soil failure, the increase in resistance diminished, indicating a well-defined peak. This is crucial, because it represents the maximum pullout load that the soil can withstand. After soil failure, the resistance decreased and was accompanied by significant displacement. With the exception of the effort–displacement curve for the depth H/h = 1, it is characterised by a very rapid reduction in resistance after soil failure, and the curves for H/h = 0.5 and 0.3, where displacements increase rapidly from the onset of pullout loading up to failure.
In the case of shallow anchor embedment, the low pullout resistance can be attributed to the reduced volume of the anchorage block mobilised against the uplift. This behaviour is further explained by the fact that the soil located between the anchor blades does not significantly contribute to the overall pullout resistance.

7.2. Reference experiments for comparison

To ensure a reliable comparison, experiments conducted under conditions similar to the current investigation were selected; these will form the basis of this comparison.
Three benchmark experimental studies were selected for comparative analysis. The first study [2] involved pull-out tests on square anchor plates with h = 0,15, and 0.30 m embedded in sand with φ = 45.65°, at depths reaching 0.8 m. The second study [1] examined rectangular anchors with a thickness B = 50 mm and varying aspect ratios (h/B = 1, 2, 5, and 8) embedded in sand with φ = 48 °, for embedment ratios (H/h) up to 8.
The third study [18] focused on circular anchor plates with diameters of 37.5 mm, subjected to vertical loading in dry sand with φ = 39° and embedment ratios between 1 and 12 [1, 2, 4]. The selected experiments are grouped in the table 2.
We were primarily interested in the shape of the curve representing the relationship between the pullout force and the resulting displacements. To this end, we refer to the results obtained by [1], who studied the anchors of square (h = B = 50 mm) and rectangular shapes anchored in sand at various depths.

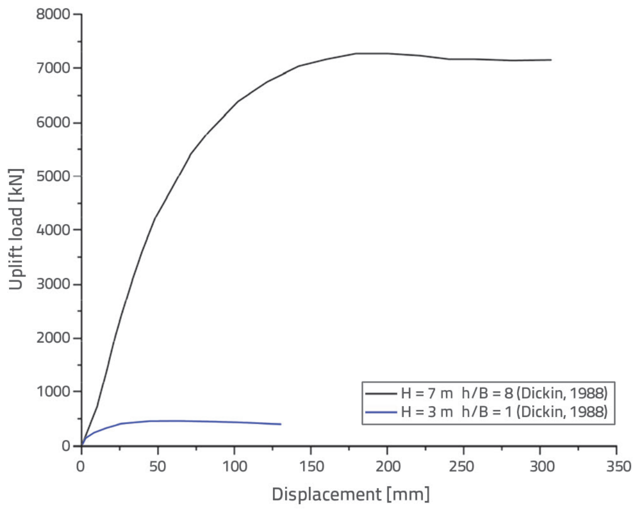

Figure 9. Several results from Dickin's experiments [1, 8]

By comparing the shapes of the curves obtained with those from reference [1] presented in Figure 9 and the following reference [12], which observed a clear difference in the load-displacement relationship for shallow and deep anchors, we noted the following: The soil supporting a CMA anchor subjected to a pullout force reacted with a behaviour similar to that of the soil supporting a square or circular anchor. Except for the soil resistances constituting a CMA anchor with a ratio H/h ≤ 1, which is identical to that of a shallow traditional anchor, all anchors with ratios H/h > 1 behave like deep a square or circular anchor.

7.3. Breakout factor F_q

In each experiment conducted at a certain anchor depth, the ultimate pullout force was deduced, which was then introduced into Eq. (1). The objective is to calculate the corresponding pullout factors. The pullout factors corresponding to each test are grouped together in the form of a curve (Figure 9).

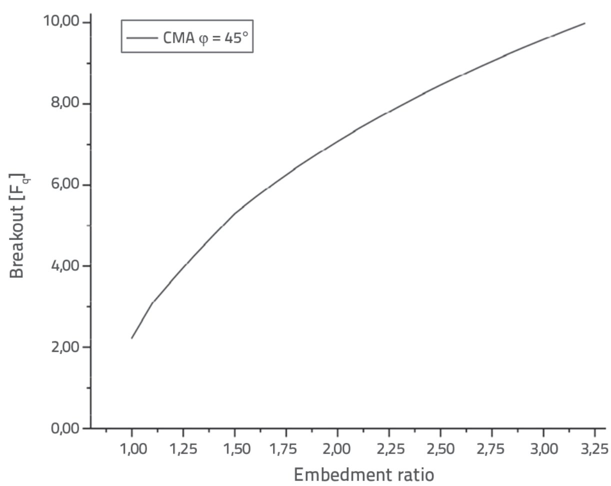

Figure 10. Variation of breakout factor of the CMA with embedment ratio (H/h)

The significance of F_q increased continuously with increasing H/h ratios. However, this growth in the breakout factor diminished with an increase in H/B for higher values, especially for H/B ratios greater than 2.2. The results of the current analysis were compared with the experimental results of [1], conducted in a centrifuge at the Department of Civil Engineering, University of Liverpool (United Kingdom), as well as with the results of [17]. A comparison is presented in Figure 10.

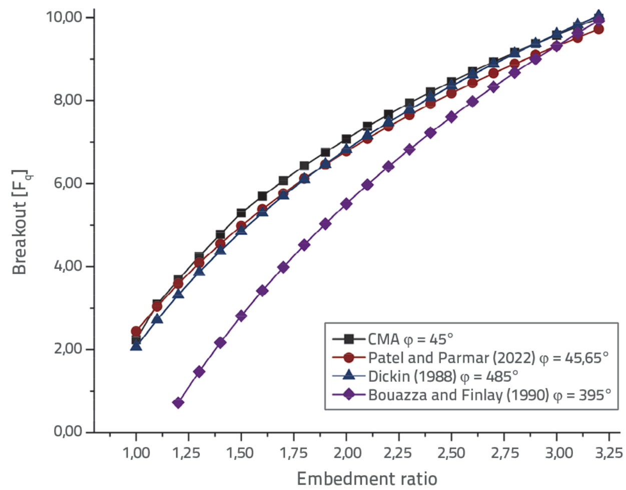

Figure 11. Comparison between the pull-out factor of the CMA and the laboratory experimental results for plate anchorage [1, 2, 4]

The illustration shows that for H/h ratios greater than or equal to 1.4, the CMA provides pullout factors that are very close and sometimes identical to the common anchor rods used in references [1, 2]. We recorded an average deviation of $|\Delta F_q|$ equal to 0.19 for very shallow depths with an H/h ratio less than 1.4, indicating a significant difference between the compared anchors, with an average deviation of $|\Delta F_q|$ being 0.26. These conclusions instill confidence in the reliability of the results obtained in the current investigation because they demonstrate that boundary effects do not impact the overall outcomes. The anchoring block of the CMA was identical to that of the anchor plate with identical dimensions. Notably, the deviation in the pullout factor values between the conventional anchor plate and the CMA is confined to an H/h ratio in the range of [0;1.4]. The interpretation of this difference is that the blockage occurring just above the anchor, precisely between the bars of the CMA, is less significant.

8. Conclusion

The results indicated that the evolution of the pullout force of the new CMA anchor shape in a layer of sand during loading was identical to that of a conventional anchor plate. It was distributed in two phases, an initial linear elastic phase and a plastic phase which were imposed until the rupture of the soil. This observation was noted in all the tests. The maximum uplift force was related to an increase in the H/h anchor ratio. Indeed, the pullout force is greater when the anchoring depth is larger because the soil that restrains the anchor becomes more substantial. The results obtained from the CMA are encouraging and favourable, and this new plate anchor rod has proven its effectiveness in pullout tests with critical tensions equivalent to those of conventional plate anchors (the same anchor block involved in pullout resistance) after comparing them with the experimental results of previous studies [1, 2].

After removing a significant percentage of the surface area of the conventional anchor plate (square by 92 % or circular by 43 %) to obtain the cross-shaped CMA, we achieved the same results regarding the pullout resistance. This reduction in steel volume has several economic and ecological advantages. This anchor minimises the quantity (volume and weight) of steel constituting the anchor plate, resulting in a decrease in manufacturing costs, transportation costs (reduced weight and more arrangement possibilities), and energy consumption during manufacturing, ultimately reducing the equipment required for its installation.

In this study, we investigate the effect of installing a closed CMA before applying a brief lifting force until the anchor is completely open. Subsequently, we conducted the necessary pullout tests and studied the recovery conditions. The influence of different soil types on the breakout factor will be addressed in future studies planned as part of subsequent publications.

This new earth anchor plate introduces new possibilities for the geotechnical industry, paving the way for more efficient and cost-effective solutions. The insights gained from this research will contribute to enhancing design and construction practices in the field of geotechnics, while reinforcing the stability and durability of structures in various applications. In conclusion, this new cross-shaped anchoring represents a promising advancement in the field of geotechnics. The results suggest that these anchors can be effectively used to reinforce geotechnical structures and resist lateral loads, thereby providing more economical and efficient solutions for various geotechnical applications. Further research is required to refine the design and assess the long-term performance of these cross-shaped plate-earth anchors.

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