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Uplift response of multi-plate helical anchors in cohesive soil

Ahmet Demir [*1] and Bahadir Ok [2a]

[1] *Department of Civil Engineering, Osmaniye Korkut Ata University, Karacaoğlan Campus 80000 Merkez / Osmaniye, TURKEY*
[2] *Department of Civil Engineering, Adana Science and Technology University, 01180 Seyhan / Adana, TURKEY*

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Abstract. The use of helical anchors has been extensively beyond their traditional use in the electrical power industry in recent years. They are commonly used in more traditional civil engineering infrastructure applications so that the advantages of rapid installation and immediate loading capability. The majority of the research has been directed toward the tensile uplift behaviour of single anchors (only one plate) by far. However, anchors commonly have more than one plate. Moreover, no thorough numerical and experimental analyses have been performed to determine the ultimate pullout loads of multi-plate anchors. The understanding of behavior of these anchors is unsatisfactory and the existing design methods have shown to be largely inappropriate and inadequate for a framework adopted by engineers. So, a better understanding of helical anchor behavior will lead to increased confidence in design, a wider acceptance as a foundation alternative, and more economic and safer designs. The main aim of this research is to use numerical modeling techniques to better understand multi-plate helical anchor foundation behavior in soft clay soils. Experimental and numerical investigations into the uplift capacity of helical anchor in soft clay have been conducted in this study. A total of 6 laboratory tests were carried out using helical anchor plate with a diameter of 0.05 m. The results of physical and computational studies investigating the uplift response of helical anchors in soft clay show that maximum resistances depend on anchor embedment ratio and anchor spacing ratio S/D. Agreement between uplift capacities from laboratory tests and finite element modelling using PLAXIS is excellent for anchors up to embedment ratios of 6.

Keywords: uplift capacity; helical anchors; soft clay; breakout factor; finite element analysis

1. Introduction

Soil anchors create an important component of many civil engineering structures. The primary function of these anchors is to transmit upward forces to the soil at certain depth below the ground. In some structures, they are also designed to resist compressive forces, moments and combinations of these forces. Different types of anchors are being used in the field depending upon the magnitude and type of loading, type of structure and sub-soil conditions. Especially, helical anchors which are one of the soil anchor types have been used to resist tension loading for a

*Corresponding author, Assistant Professor, Dr., E-mail: ahmetdemir@osmaniye.edu.tr
[a] Research Assistant, E-mail: bahadirok@adanabtu.edu.tr

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variety of structures such as transmission towers and cell phone towers, and resist uplift loading from buoyancy effects, such as in buried pipelines. Both single-plate and multi-plate helical anchors are in common use, and the selection for a particular design problem depends on a number of factors, including soil type, loading, availability, and installation equipment. The behavior of multi-plate helical anchors may also be dependent on the geometry used; (i.e., the number, diameter and spacing of the helices).

Most of studies have been performed model tests on single helix anchors in an attempt to develop semiempirical theories that can be used to estimate the capacity of anchors in soil. For anchors in clay, results can be found in the works of Vesic (1971), Meyerhof and Adams (1968), Meyerhof (1973), and Das (1978, 1980). All the aforementioned studies are limited to anchors with a single helix.

Some studies of helical anchor systems have been performed both in the laboratory and in the field to study the behavior of multi-helix screw anchors in a variety of soils (Mitsch and Clemence 1985, Ghaly *et al*. 1991). However, most existing theoretical and experimental studies have been focused on predicting the anchor behaviour and capacity more in cohesionless soil than in cohesive soil (Singh and Ramaswamy 2008). Moreover, there have been few detailed studies performed on the behavior of multi-helix anchors in clays and no systematic investigation of their behavior in soil deposits (Weikart and Clemence 1987, Mitsch and Clemence 1985, Mooney *et al*. 1985, Lutenegger *et al*. 1988, Hoyt and Clemence 1991, Narasimha Rao *et al*. 1991, 1993, Merifield 2011).

The research reported herein compares computations using the finite element package PLAXIS 2D V2011, specially developed for the analysis of deformation and stability in geotechnical engineering problems (Brinkgreve and Vermeer 1998), with results from the laboratory model study. Comparisons are also drawn with predictions from a number of previous theoretical design methods based on either limit state or finite element analyses. The findings will help in a better understanding of the helical anchor plates design with a different embedment depth and with a different footing geometry. It is expected that the information presented in this study will provide a contribution to the literature results and will be an alternative source for the design and applications for geotechnical engineers. This will result in a decrease in the cost of construction and save simplicity and time for the engineer, the contractor and the owner of the construction.

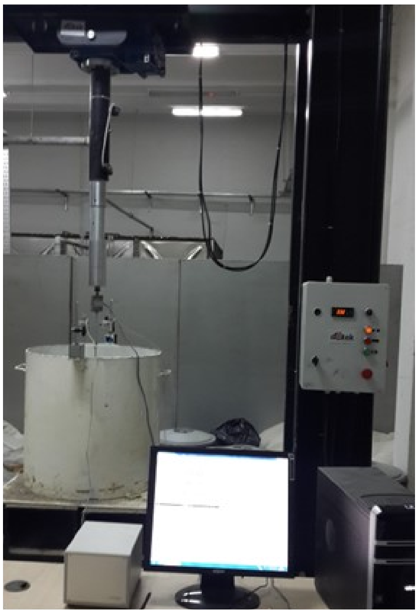
2. Experimental investigations

2.1 General

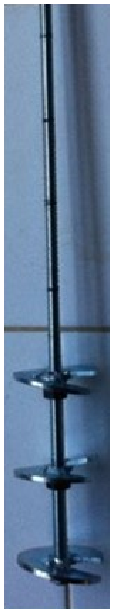
The experimental program, which consists of a total of 6 laboratory model tests conducted for different embedment ratios H/D from 1 to 6 in soft clay, was carried out using the facility in the Geotechnical Laboratory of the Civil Engineering Department at the University of Osmaniye Korkut Ata. The facility and a typical model are given in Fig. 1.

2.2 Test setup and loading arrangements

Loading tests were performed using a rigid model helical anchor plate fabricated from mild steel, with a thickness of 6 mm. The helical anchor plate had a diameter of 5 cm and it was fixed to the anchor bolt to give extra rigidity to the plates. Stainless steel rod of 6 mm diameter were used as anchor rod and was connected to model helical anchor by threaded nuts fixed to the anchor



(a)



(b)

Fig. 1 Test set-up: (a) overview; (b) helical anchor plate

plate.

Tests were conducted in a circular steel tank with dimensions of 0.6 m (diameter) and 0.6 m (depth). The bottom and vertical edges of the tank were made up using steel plates with a thickness of 12 mm to avoid lateral yielding during the soil placement and loading of the model helical anchor plate.

The model helical anchor was pulled out by a motorized gearbox arrangement attached to loading frame located above the tank. A 7.5 horsepower DC motor with a speed control unit was used to supply the necessary power to pull out the anchors. In the present work the speed of the motor was adjusted by the speed control unit so as to give an anchor displacement rate of 2.33 mm/min. The pullout displacement was transmitted to the model anchor through the anchor rod, connected to the loading arrangement. While uplift load was taken using a load cell installed between the jack and the model helical anchor, the displacement of the helical anchor was measured with the help of two LVTDs of 0.01 mm sensitivity suitably connected to the anchor rod. A schematic diagram of the pullout test setup is given in Fig. 2.

2.3 The soil properties

The soft clay used in this research was obtained from locally available soil, which two test pit excavations were performed, in the Adana Metropolitan Municipality's (AMM) Water Treatment Facility Center (WTFC) located in west part of Adana, Turkey. After conducting required conventional laboratory tests (sieve and hydrometer analysis, moisture content analysis, unit weight analysis, liquid and plastic limit analyses, unconfined compression test) the soil was prepared for model tests. The particle size distribution of the clay soil is shown in Fig. 3. The soil

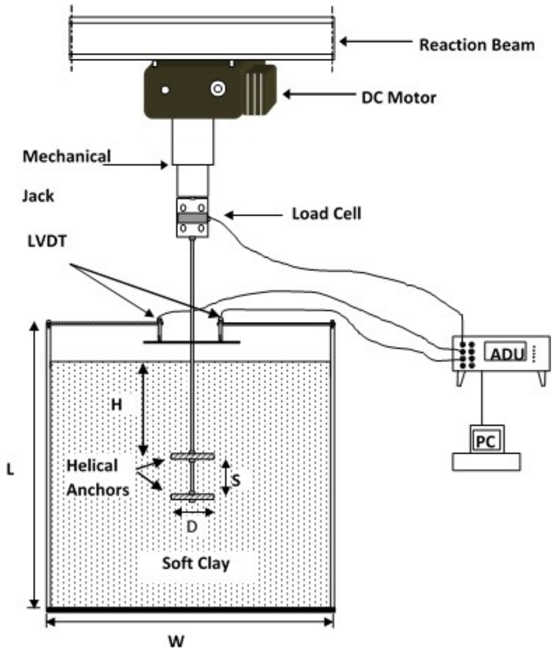


Fig. 2 General layout of apparatus for the model test

was identified as high plasticity inorganic clay, CH according to the unified soil classification system. The values of liquid limit, plastic limit and plasticity index of soft soil were obtained as 53%, 22% and 31%, respectively. The values of specific gravity and the undrained shear strength of clay soil were obtained as 26.0 kN/m^3 and 20 kPa, respectively. The characteristics of the soft soil determined through an extensive testing program that consisted of a combination of laboratory and in situ tests were given in detail by Demir *et al*. (2013).

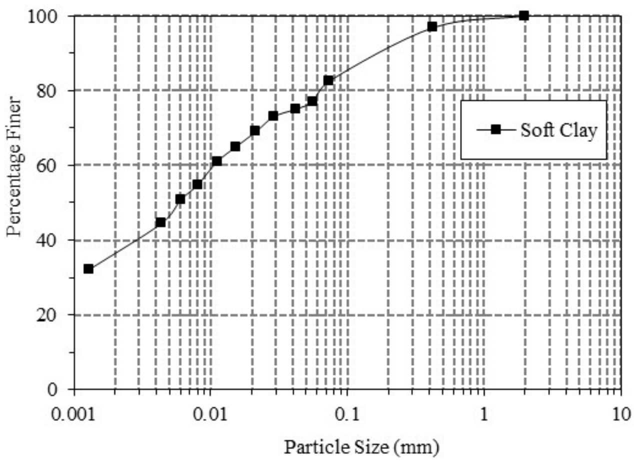


Fig. 3 Particle size distribution for soft clay

2.4 Experimental procedure

The soft clay pulverized was thoroughly mixed with required amount of water (ω_n = %35). To achieve uniform moisture distribution, the wet soil was placed in air tight plastic containers and stored for 2 to 3 days before being used in experimental study. The soft soil was placed in the test tank in layers with small quantities which were tapped gently with a special hammer and spread uniformly. After filling the tank to the base level of the anchor, the anchor with the connecting rod was placed and the filling operation continued until the required embedment depth was achieved. The anchors were pulled out at the prescribed rates and the resistance to pullout was recorded by tension load cell at regular displacements until there is a drop in anchor capacity or the displacement becomes equal to half of the anchor diameter. For each test, the load-displacement readings were recorded with a twenty-nine-channel data-logger unit (ALMEMO 5690 series Autonomous Data Acquisition System) and converted to produce values of the displacement at ground level and load using The AMR WinControl software package, which has been specially developed for data acquisition and measured data processing with ALMEMO equipment, on a PC. The degree of saturation was also calculated by taking undisturbed samples from the tank in tests. The average degree of saturation by this placement method was achieved as about 93.0%.

3. Finite element modeling

The FE analyses have been primarily performed to obtain the load–displacement curves in relation to different embedment ratios (H/D = 1-6) for rigid helical anchor plate (single helical anchor plate) in soft clay with the same model geometries as in the tests. FE modeling has the advantages that parameters may be easily varied, and details of stresses and deformations throughout the system may be studied. FE analysis is a powerful mathematical tool that makes it possible to solve complex engineering problems. The finite-element method is a well-established numerical analysis technique used widely in many civil-engineering applications, both for research and the solution of real engineering problems. The constitutive behavior of the soils can be successfully modelled with numerical analyses. The finite-element method is one of the mathematical methods in which continuous media is divided into finite elements with different geometries. It provides the advantage of idealizing the material behaviour of the soil, which is non-linear with plastic deformations and is stress-path dependent, in a more rational manner. The finite-element method can also be particularly useful for identifying the patterns of deformations and stress distribution during deformation and at the ultimate state. Because of these capabilities of the finite-element method, it is possible to model the construction method and investigate the behaviour of uplift of helical anchor plates and the surrounding soil throughout the construction process, not just for the limit equilibrium conditions (Laman and Yildiz 2007). The FE analyses were conducted using the program Plaxis 2D-V2011. It is a finite-element package that is specially developed for the analysis of deformation and stability in geotechnical engineering problems (Brinkgreve and Vermeer 1998). In order to simplify the geometry of this problem, The FE analyses were carried out using an axisymmetric model for helical anchor plates in soft clay soil with the aim of better understanding the fundamental mechanics of the problem. This effectively eliminates the difficulties in modeling the anchor's helical pitch and the anchors are, therefore, idealized as embedded circular plates (Merifield 2011). During the generation of the mesh, 15-node triangular elements were selected in preference to the alternative 6-noded versions in order to provide greater accuracy in the determination of stresses. The Plaxis software used in this study incorporates a fully automatic mesh-generation procedure, in which the geometry is divided into elements of the basic element type, and compatible structural elements. Five different mesh densities are available in Plaxis, ranging from very coarse to very fine. In order to obtain the most suitable mesh for the present study, preliminary analysis using the five available levels of global mesh coarseness were performed. It was decided to use the medium mesh with a refinement line around the helical anchor plates in all the analyses, since there is not too much difference in the results for different mesh configurations. A typical finite element mesh composed of the soil and multi-plate circular anchors, together with the boundary conditions and the geometry of the soil system used, is shown in Fig. 4. Although it is likely that shaft friction contributes to the capacity, the term is generally ignored in anchor design because of the uncertainties involved (Merifield 2011). So, the shaft was not considered in the FE analyses.

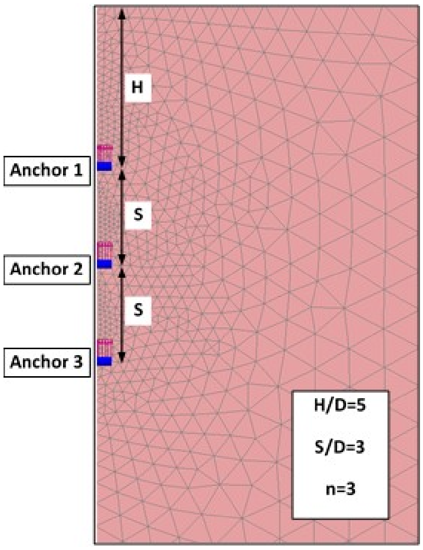


Fig. 4 Typical mesh configurations in the FE Analyses

Table 1 Values of Soft Soil parameters used in PLAXIS analyses

Parameter	Soft clay
	Value
Unit weight, γ_n (kN/m^3)	18
Modified compression index, λ^*	0.085
Modified swelling index, κ^*	0.035
Cohesion, c' (kN/m^2)	12.5
Friction angle, ϕ' (degrees)	25.0
Dilatancy angle, ψ (degrees) ($\phi' - 30°$)	0
Poisson's ratio for unloading/reloading, v_{ur}	0.15
Coefficient of lateral stress in normal consolidation, K_o^{nc}	0.5774
Tangent of CSL, M	1.242

An elasto-plastic model described as the Soft Soil Model (SSM) was selected from those available in PLAXIS to describe the non-linear soft clay soil behaviour in this study. The Soft Soil model is capable to simulate to soil behaviour under general states of stress. For general states of stress, the plastic behaviour of soft soil model is defined by a total of six yield functions; three compression yield functions and three Mohr-Coulomb yield functions (Plaxis 2011). The soil parameters used in the main investigation, which were obtained from conventional laboratory tests, are shown in Table 1 (ASTM D 2435-96 1998).

4. Comparison between results from PLAXIS analyses and physical modelling

Experimental and numerical studies were performed to investigate the effect of embedment ratio of helical anchor plate (single plate) buried in soft clay soil. A total of 6 tests and analyses were carried out using six different embedment ratio changing from H/D = 1 to 6 and including the uplift loading. The uplift resistance (Q_u)-displacement ratio (s/D) curves of the single helical plate case for different H/D ratios including uplift loading are given in Fig. 5.

The uplift displacement changes presented in Fig. 5 are non-dimensional. The displacement ratio (s/D) is defined as the ratio of anchor plate displacement (s) to the diameter of anchor plate (D). Comparisons for anchors with embedment ratios, H/D = 1-3 and 4-6, considered as typical examples of shallow and fairly deep anchors, are included in the figure, respectively. As seen from the figure that the variation of uplift load with displacement from the FE analyses shows generally good agreement in the pre-peak region with the physical modelling obtained from the laboratory tests for all anchor depths.

In accordance with the trends shown on Fig. 5, a two-phase load-displacement behavior is observed for shallow and deep anchors, respectively. In the case of shallow anchors in soft clay, it shows an initial rapid increase of pullout load with displacement followed by a non-linear increase of pullout load, and finally almost asymptotic to the displacement axis. Whereas, it presents an initial rapid increase of uplift load with displacement followed by nonlinear behaviour in the case of deep anchors.

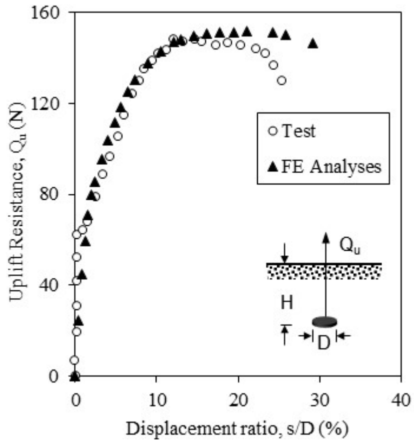
Uplift capacities are often expressed in dimensionless form as breakout factors which are given below (Singh and Ramaswamy 2008)

$$Q_u = A \times \left(c_u \times F_c + \gamma \times H\right) \tag{1}$$

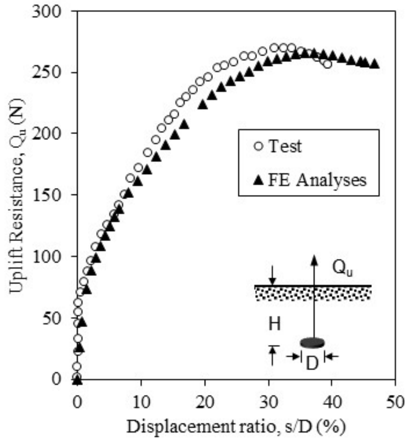
Where F_c is the breakout factor, Q_u is the maximum uplift resistance, γ is the soil unit weight, c_u is the soil undrained shear strength and H and A are the anchor embedment depth and area, respectively. The anchors can also be classified as shallow or deep, depending on their mode of failure that is shown in Fig. 6 (Merifield 2011). An anchor is classified as shallow when the observed failure mechanism reaches the surface at ultimate collapse (Figs. 6(a) and (b)). In contrast, a deep anchor is one whose failure mode is characterized by localized shear around the anchor(s) and is not affected by the location of the soil surface (Figs. 6(c) and (d)).

4.1 Single-plate anchors

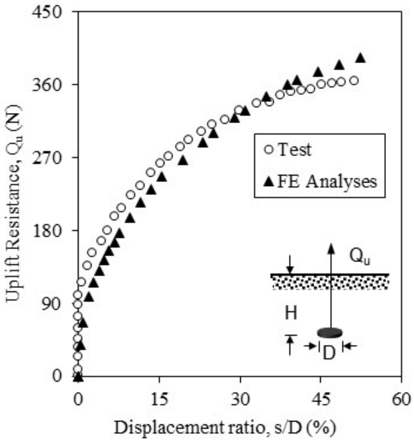
The comparison of breakout factors obtained from the PLAXIS (FE) analyses with lower bound limit analysis solutions of Merifield *et al*. (2003), finite- element analyses of Merifield



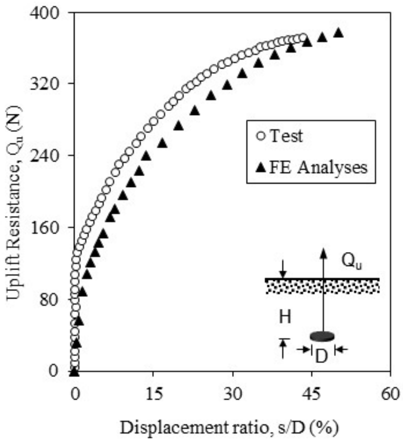
(a) $H/D = 1$



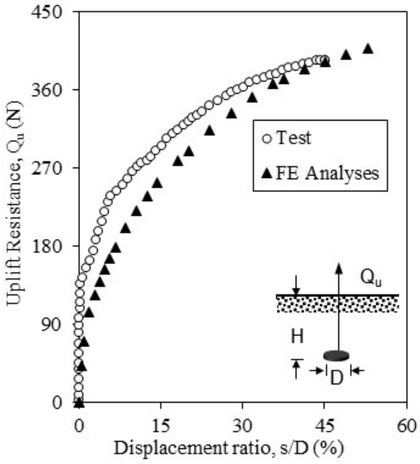
(b) $H/D = 2$



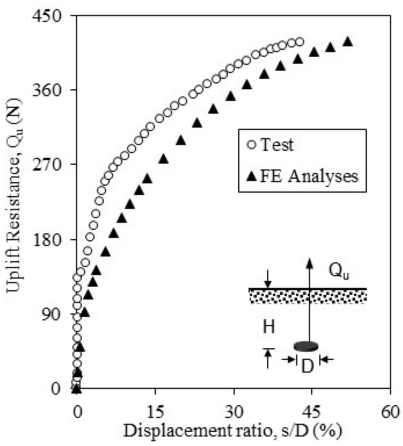
(c) $H/D = 3$



(d) $H/D = 4$



(e) $H/D = 5$



(f) $H/D = 6$

Fig. 5 Comparison between FE Analyses and test data for different H/D

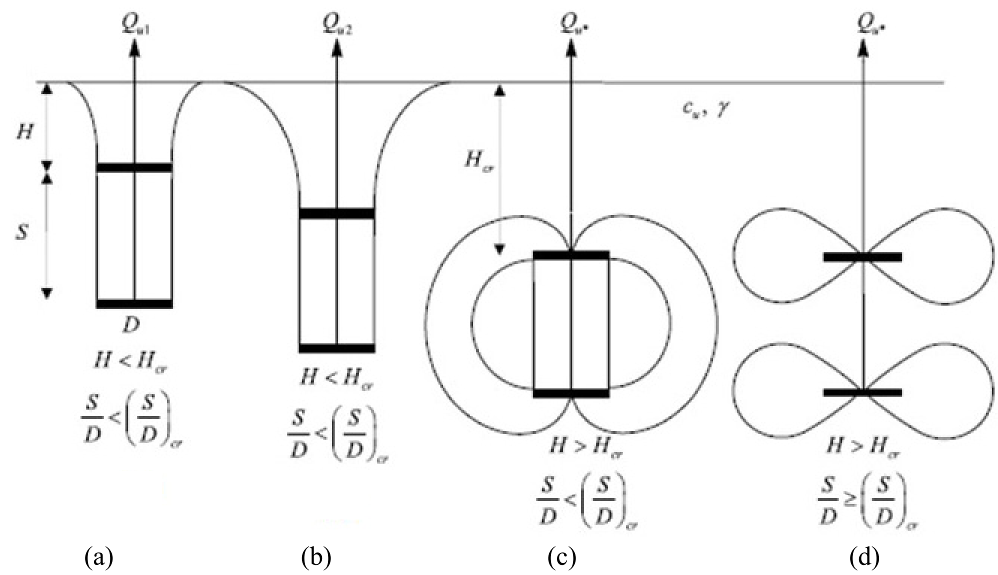


Fig. 6 Shallow and deep anchor behavior: (a) and (b) shallow failure mechanism; (c) global deep failure mechanism; (d) local deep failure mechanism (Merifield 2011)

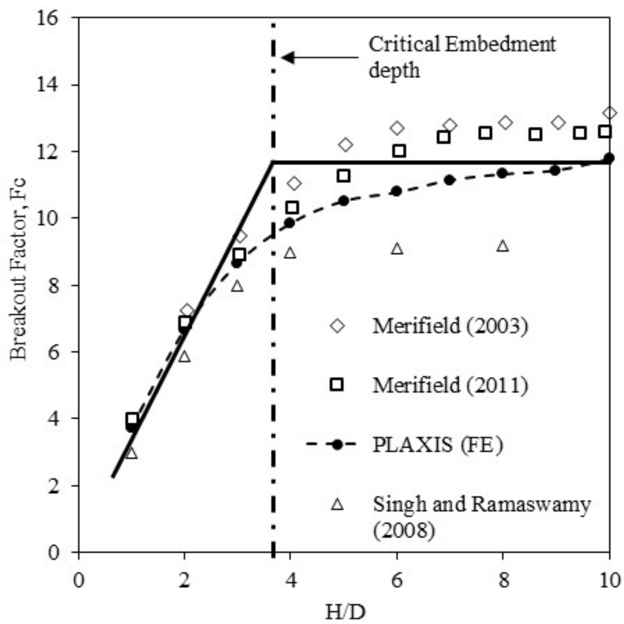
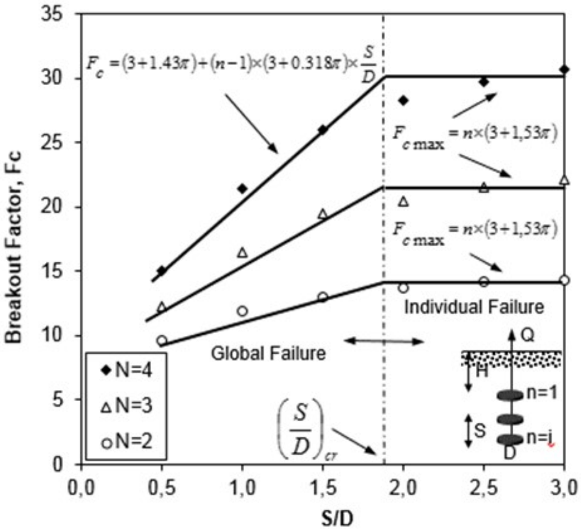
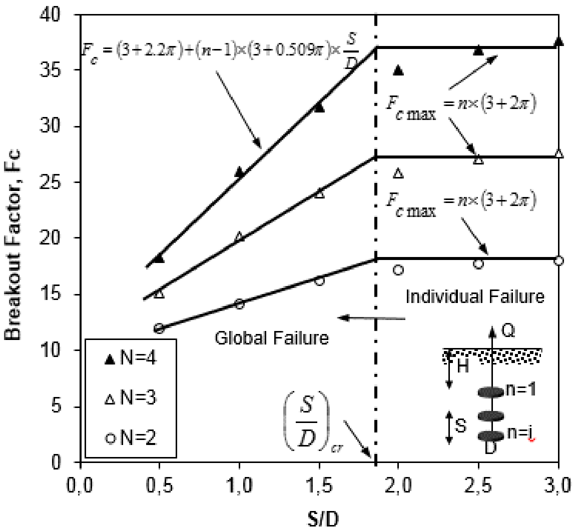


Fig. 7 Comparison of breakout factors for circular anchors in clay

(2011) and model test results of Singh and Ramaswamy (2008) is shown in Fig. 7 for single circular plate anchors. The present numerical results compare well with the numerical and analytical results of Merifield and laboratory test results of Singh and Ramaswamy (2008) for shallow anchor conditions. However, the breakout factor values proposed by Merifield



(a) Shallow conditions



(b) Deep conditions

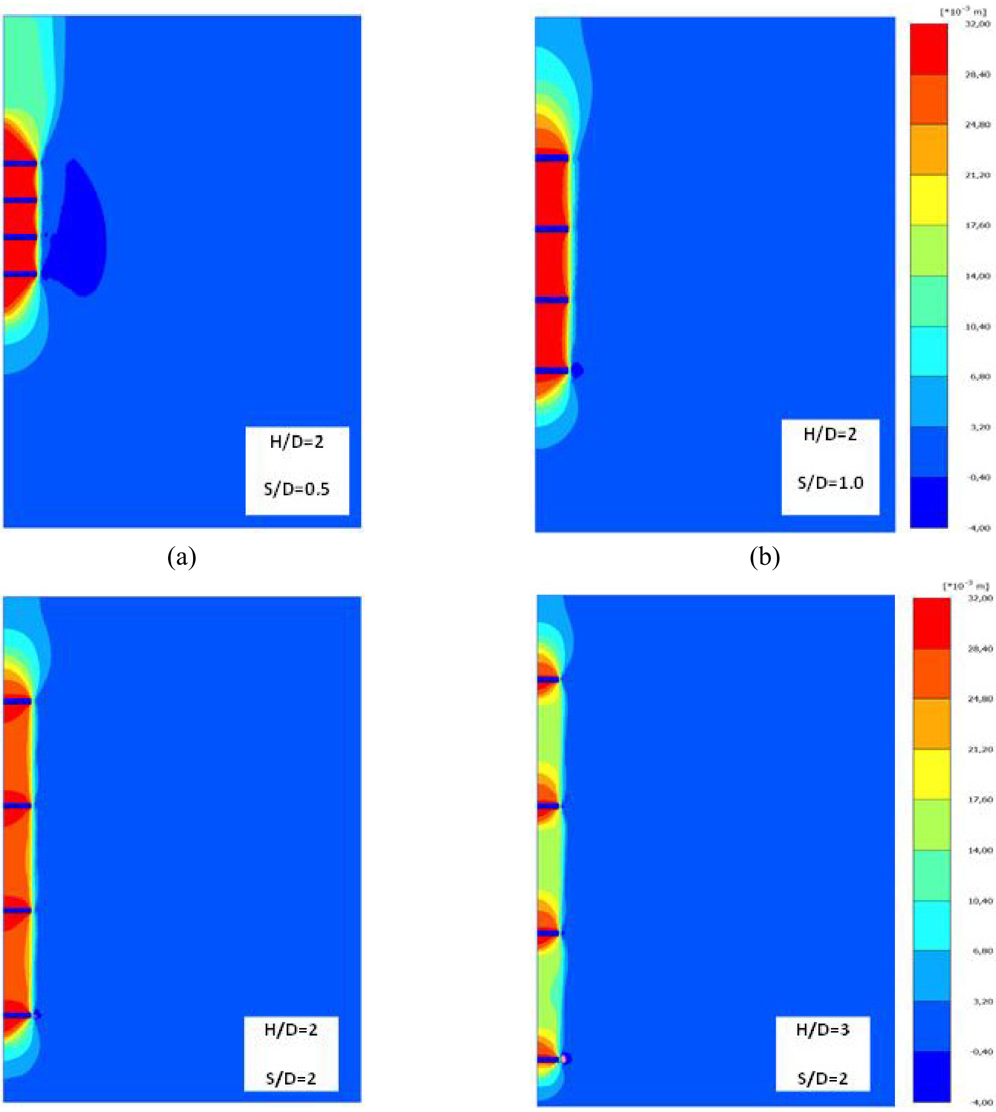
Fig. 8 Comparison of analytical and PLAXIS (FE) results for breakout factors of multi-plate anchor system

overestimate the breakout factors for deep anchor conditions. Also, the breakout factors obtained using the model test results of Singh and Ramaswamy (2008) are clearly over-conservative and as much as 10% below the PLAXIS (FE) values for deep anchor conditions.

4.2 Shallow and deep multi-plate anchors

The breakout factors computed from PLAXIS (FE) analyses for a range of anchor spacing, S from 0.5 to 3.0 are included in Figs. 8(a) and (b) for shallow (H/D = 2) and deep (H/D = 8) anchor conditions, respectively. Results are shown graphically in this figures for anchors with two, three and four plates (n = 2, 3 and 4). As seen from the Fig. 8 that it shows the transition from a global deep failure mechanism, surrounding all anchor plates, to an individual deep failure mechanism, in which a local failure mechanism exists around each anchor plate. The transition between the two cases occurs when the anchor spacing ratio reaches a critical value, when $S/D \geq (S/D)_{cr}$.

The change in response in the soil above the multiplate anchors, which is dependent on anchor embedment, was also reflected in the displacement contours obtained from PLAXIS (FE) analyses shown in Figs. 9 and 10. As seen from the Fig. 9 that, for an anchor at relatively shallow depth



(a) (b) (c) (d)

Fig. 9 Displacement contours illustrating transition from shallow global to shallow individual plate failure mode (n = 4)

($H \leq H_{cr}$), the soil displacements, and hence increased shear stresses, extend to the soil surface. The displacement contours for a number of problems in which the overburden and/or anchor spacing are sufficient to lead to a deep failure mode are shown in Fig. 10. These figures illustrate the transition between the two types of deep anchor failure mechanism previously shown in Figs. 6(c) and (d).

For a shallow and deep global failure mode that encloses all the anchor plates in Fig. 6, the expressions in Table 2 for anchors with a total of n individual plates is proposed, respectively

The expressions shown in Fig. 8 appear to provide a reasonable estimate for the cases of a global shallow and deep failure mechanism.

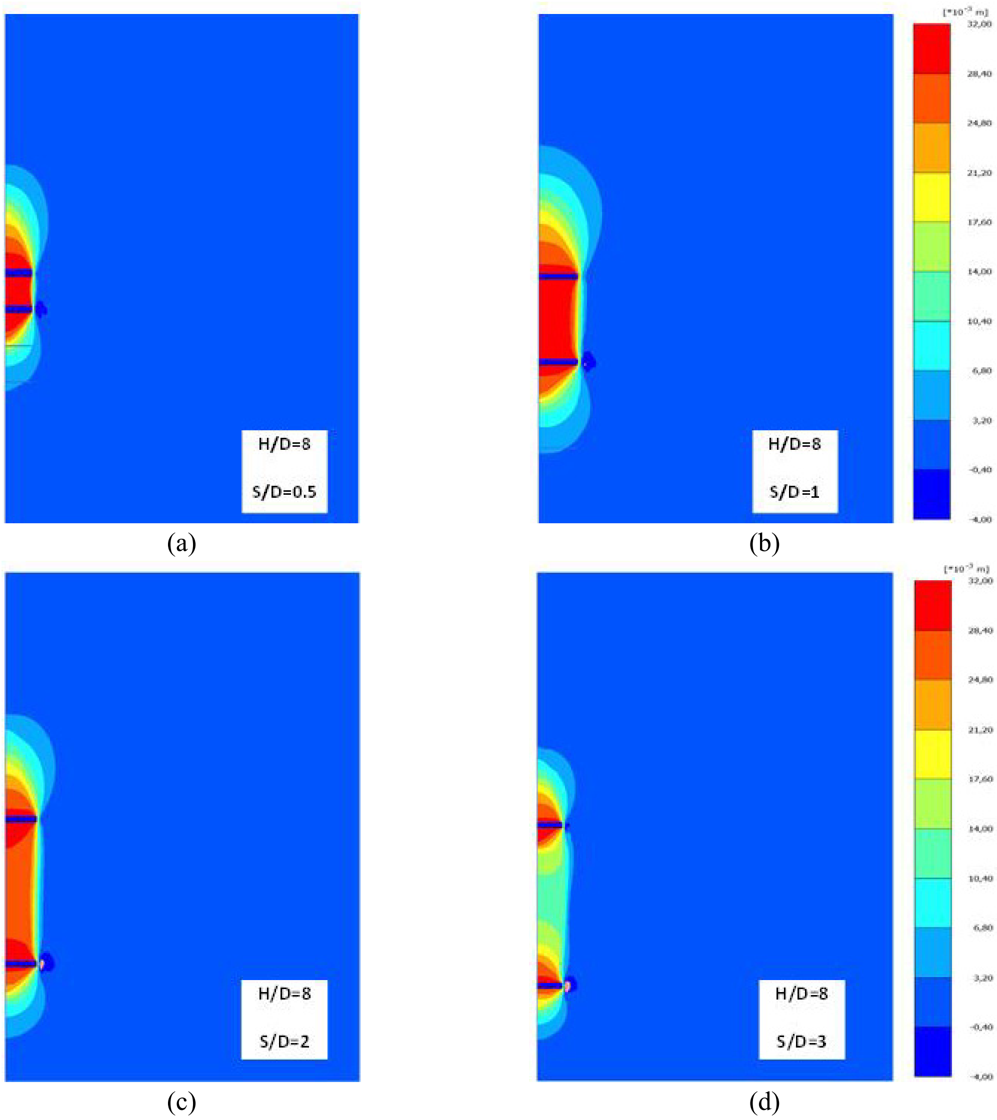


Fig. 10 Displacement contours illustrating transition from deep global to deep individual plate failure mode (n = 2)

Table 2 Expressions of breakout factor for different cases

For shallow conditions	
$F_c = (3+1.43\pi)+(n-1)\times(3+0.318\pi)\times\dfrac{S}{D}$	$H/D < (H/D)_{cr}$ and $S/D < (S/D)_{cr}$
$F_{c\max} = n\times(3+1.53\pi)$	$H/D > (H/D)_{cr}$ and $S/D < (S/D)_{cr}$
For deep conditions	
$F_c = (3+2.2\pi)+(n-1)\times(3+0.509\pi)\times\dfrac{S}{D}$	$H/D < (H/D)_{cr}$ and $S/D > (S/D)_{\mathrm{cr}}$
$F_{c\max} = n\times(3+2.2\pi)$	$H/D > (H/D)_{cr}$ and $S/D > (S/D)_{cr}$

Table 3 Comparison of test results (Narasimha Rao *et al*. 1991) and PLAXIS (FE) results

				Narasimha Rao *et al*. (1991)		This study	
Test No.	n	S/D	H/D	$Q_{u\text{-}exp}$ (kN)	$Q_{u\text{-}calc}$ / $Q_{u\text{-}exp}$	$Q_{u\text{-}calc}$ (kN)	$Q_{u\text{-}calc}$ / $Q_{u\text{-}exp}$
1	1	4.58	4.58	0.84	1.72	0.70	0.83
2	2	2.29	2.29	0.97	1.49	1.07	1.10
3	3	1.53	1.53	1.34	1.09	1.35	1.01
4	1	4.58	4.58	0.67	1.64	0.54	0.81
5	2	2.29	2.29	0.91	1.2	1.07	1.17
6	3	1.53	1.53	0.97	1.12	1.35	1.39
7	1	4.58	4.58	0.55	1.37	0.37	0.68
8	2	2.29	2.29	0.63	1.19	0.60	0.95
9	3	1.53	1.53	0.73	1.03	0.73	1.00
10	1	3.05	3.05	1.48	1.1	0.98	0.66
11	2	1.53	1.53	1.67	0.97	1.33	0.79
12	3	1.02	1.02	1.72	0.94	1.33	0.77
13	2	4.00	6.13	0.69	1.43	0.52	0.75
14	3	2.00	6.13	0.83	1.19	0.77	0.93
15	4	1.33	6.13	0.9	1.10	0.69	0.76
16	2	1.67	6.13	0.65	1.19	0.45	0.69
17	3	0.83	6.13	0.71	1.09	0.67	0.94
18	2	4.00	6.13	1.52	1.43	1.26	0.83
19	3	2.00	6.13	1.86	1.16	1.89	1.02
20	4	1.33	6.13	2.13	1.01	1.86	0.87
21	2	1.67	6.13	1.19	1.41	0.96	0.80
22	3	0.83	6.13	1.48	1.12	1.44	0.97

5. Comparison between results from PLAXIS analyses and established physical modelling

The results from experimental programs conducted by Narasimha Rao *et al*. (1991) in relation to the behavior of multiplate anchors in clay are summarized in Table 3. Small scale anchors

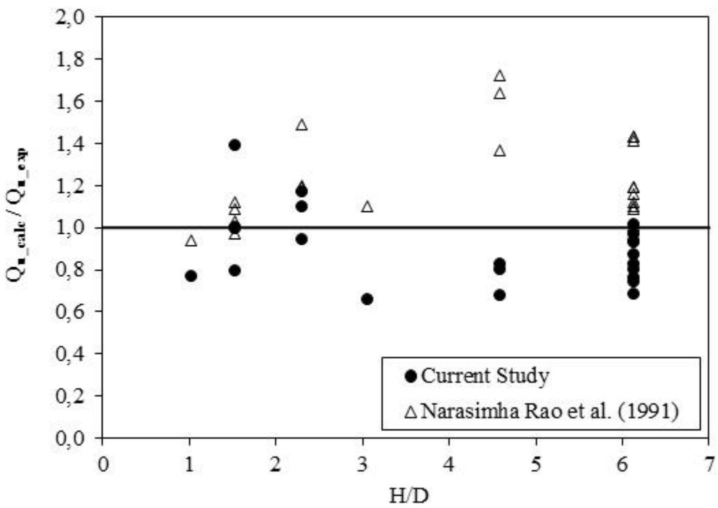


Fig. 11 Comparison between numerical and laboratory results for multihelical plate anchors

ranging in diameters from 100 mm to 150 mm were tested under uplift loading in soft to firm clays in a number of different size clay test chambers. Full details of the experimental procedures and apparatus can be found in Narasimha Rao *et al*. (1991). The variables in Table 3 include the number of plates on each anchor tested n, the embedment ratio H/D, the anchor spacing ratio S/D, and the measured experimental uplift-capacity Q_u-$_{exp}$.

As seen from the Table 3 that it shows a close agreement between the experimentally and using the proposed method obtained capacities. It is also, as seen from Fig. 11 that it is indicated a close agreement between the experimentally obtained capacities and the capacities calculated using the proposed method. For the majority of cases, the calculated capacities are about within 15% of the measured values, which is adequate for design purposes.

6. Limitations

There are several limitations that should be mentioned. The models created in this research were based on data obtained from helical anchor pullout tests in cohesive soils, with a plate diameter of roughly 0.05 m. The further testing and verification is recommended for the use of these models in other soils or with significantly larger plate diameters. It is well known that full-scale loading test results are valid, especially for in-situ conditions and for soil properties in which the test was performed. However, a full-scale loading test is not economic, due to the expensive cost in terms of time and money that is required for the construction, instrumentation and testing. Therefore, small-scale model test studies are widely used as an alternative to full-scale loading tests, despite of their scale-errors (Kaya and Ornek 2013, Dickin and Nazir 1999).

7. Conclusions

The understanding of the behavior of helical anchors is current unsatisfactory and has essentially remained unchanged for 20 years. In this paper, the uplift capacity of multi-plate helical anchor embedded in soft clay was investigated using 2D FE program PLAXIS and by physical laboratory modeling. Based on this investigation, the following main conclusions can be drawn:

- In general the results obtained from PLAXIS (FE) analyses produce good agreement with a number of established methods of predicting the uplift capacity of multi-plate helical anchors.
- The breakout factor, F_c for a multi-plate helical anchor embedded in a clayey soil has been computed under undrained condition by using the results of PLAXIS (FE) analyses. The magnitude of F_c is found to increase continuously with an increase in H/D up to a certain critical embedment ratio (H_{cr}/D) beyond which F_c becomes almost constant.
- The displacement contours obtained from PLAXIS (FE) analyses show the transition from a global deep failure mechanism, surrounding all anchor plates, to an individual deep failure mechanism, in which a local failure mechanism exists around each anchor plate. The transition between the two cases occurs when the anchor spacing ratio reaches a critical value, when $S/D \geq (S/D)_{cr}$.
- A practical design framework for multiplate helical anchor foundations has been presented to replace existing semiempirical design methods.

Nevertheless, the investigation is considered to have provided a useful basis for further research leading to an increased understanding of the application of multi-plate helical anchors to the ultimate uplift capacity and displacement problems.

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