PREDICTING THE UPLIFT CAPACITY OF VERTICALLY LOCATED TWO-PLATE ANCHORS

NAPOVEDOVANJE IZVLEČNE NOSILNOSTI NAVPIČNIH SIDER Z DVEMA PLOŠČAMA

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Keywords

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Ključne besede

izvlečna nosilnost; Plaxis 2D; sidra z dvema ploščama; pristop oblikovanja; regresijska analiza

Abstract

Soil anchors are generally used for structures that are subjected to pullout forces, such as offshore floating bodies, transmission towers, structures requiring lateral resistance or submerged platforms etc. Multi-plate anchors are used as a foundation that apply either large compression or tension forces using a number of plates welded along a central shaft. These anchors that have more than one plate have a complex interaction between the adjacent plates due to over applying stress zones. Therefore, this interaction affects the failure mechanism and the uplift capacity of the system. However, no thorough numerical analyses have been performed to determine the ultimate pullout loads of multi-plate anchors. By far the majority of the research has been directed towards the tensile uplift behavior of one-plate single anchor. Estimating the uplift capacity by using a practical design method that is obtained from a numerical analysis of two-plate anchors in sand is described in this paper. This method can be used more confidently by design engineers to estimate the pullout capacity of two-plate anchors under tension loading. The theoretical results are compared with the numerical data and acceptable values are obtained.

Izvleček

Sidra v zemljinah se običajno uporabljajo za konstrukcije, ki so obremenjene z izvlečnimi silami, kot so plavajoča telesa na odprtem morju, stolpi električnih vodov, konstrukcije z bočnim odporom ali potopljene ploščadi itd. Sidra z več ploščami se uporabljajo kot temelj, ki lahko prenese velike tlačne ali natezne sile z uporabo več plošč varjenih vzdolž osrednje gredi. Sidra, ki imajo več kot eno ploščo, imajo kompleksno interakcijo med sosednjimi ploščami zaradi medsebojnega prekrivanja napetostnih vplivnih območij. Zato ta interakcija vpliva na porušitveni mehanizem in izvlečna nosilnost sistema. Natančna numerična analiza, s katero bi ugotovili mejno nosilnost sider z več ploščami, ni bila opravljena. Večji del raziskav je bil usmerjen v ugotovitev obnašanja natezno obremenjenega samostojnega sidra z eno ploščo glede na izvlek. V tem prispevku je opisan način ocenitve izvlečna nosilnosti z uporabo praktične metode načrtovanja, ki jo dobimo iz numerične analize sider z dvema ploščama v pesku. To metodo lahko inženirji bolj zanesljivo uporabljajo za načrtovanje ocenitve izvlečne nosilnosti sider z dvema ploščama pri natezni obremenitvi. Rezultati teoretičnih izračunov se sprejemljivo ujemajo z rezultati numeričnih analiz.

1 INTRODUCTION

Many structures experience overturning moments due to lateral loads, which result in a combination of tension and compression responses at the foundation level. The design of such structures needs various systems to resist the uplift forces. Under such conditions, effective and safe design methods can be achieved through the use of tension elements. These elements are referred to as ground anchors. The elements are typically fixed to the structure and embedded into the soil to effective depths, so that they can resist the uplift loads. Soil anchors are typically used for retaining walls, transmission towers, foundations, sea walls, pipelines, etc. The soil anchors involved are of different types, such as screw anchors, grout-injected anchors, anchor plates and anchor piles. The use of different types of anchors is dependent on the magnitude and type of loading, the type of structure and the sub-soil conditions. Multi-plate anchors are also geotechnical foundations that can be used as either tension or compression members to resist the forces listed above, composed of a number of plates welded along a central steel shaft. The anchors can have more than one plate located at an appropriate spacing on the shaft. The uplift capacity of the multi-plate anchor system is dependent on the number of plates. The central shaft is used to transfer axial loads to the anchor plates. Unfortunately, the current understanding regarding the behavior of buried foundations, and multi-plate anchors in particular, is unsatisfactory and has remained essentially unchanged for about 20 years. There have been numerous theoretical/experimental studies that address the uplift of single horizontal anchors. In contrast, there are very few publications that deal with the theoretical problem of multi-plate anchor foundations.

In the literature, the uplift capacities of horizontal (plate/helical) anchors have been investigated by many researchers (Mitsch and Clemence [1], Ghaly et al. [2], Meyerhof and Adams [3], Das [4,5], Ilamparuthi et al. [6], Dickin and Laman [7], Rowe and Davis [8], Bildik and Laman [9], Zhang et al. [10], Tang and Phoon [11], Demir and Ok [12], Nazir et al. [13], Mittal and Mukherjee [14], Mokhbi et al. [15], Papadopoulou et al. [16], Schiavon et al. [17], Tsuha et al. [18]). The failure mechanisms and pullout resistances have also been examined theoretically or experimentally. Hanna et al. [19] investigated the pullout resistance of single vertical shallow helical and plate anchors. The analytical results were compared with the experimental results of Ilamparuthi et al. [6] and Ghaly et al. [20], and they observed higher breakout factor values in the helical type of anchor compared with the circular plate anchor. But in contrast, there are very few publications that deal with the uplift behavior of multi-plate anchor systems. Merifield [21] developed a numerical modeling technique to understand the uplift behavior of the multi-plate circular anchor in clay soil. The established design framework for multi-plate anchor foundations was compared with Narashime and Rao's [22, 23] experimental results, and it was shown that the existing semi-empirical design methods have been excessively under- or over-conservative. Merifield and Smith [24] presented a study about the behavior of the multi-plate plain-strain anchor based on numerical modelling techniques. They used the finite-element software Abaqus. A practical and straightforward design framework was presented to predict the ultimate uplift capacity of the plane-strain multi-plate anchor foundations buried in undrained soils.

This paper presents an empirical method that was developed from a numerical analysis to predict the uplift capacity of a two-plate anchor system with different embedment depths and spacing ratios in the sand. The numerical analyses were performed by using the finite-element package PLAXIS 2D, which was developed for an analysis of deformation and stability problems in geotechnical engineering. The results of the numerical analyses were modified with regression analyses and a practical design method was developed to determine the uplift capacity of the two-plate anchor system, because the desired vertical movement provides realistic results for the parameters considered in this study. It is expected that the developed approach presented in this study will provide an alternative solution for the design and applications of geotechnical engineers, together with an increase in the simplicity and a gain in time.

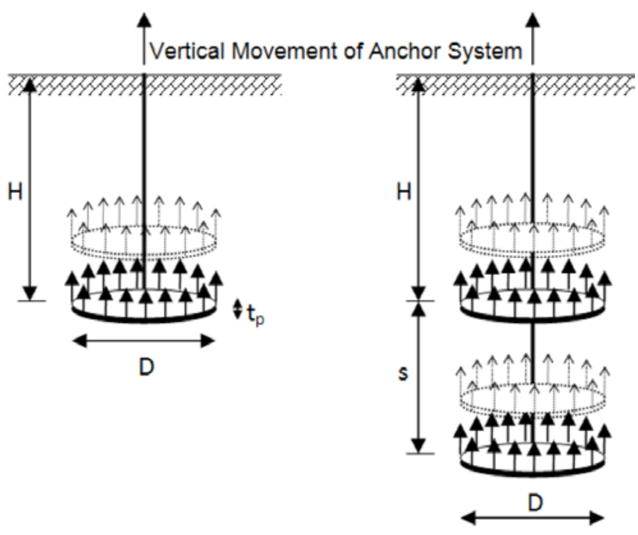
2 FINITE-ELEMENT MODELLING

The numerical analyses were performed by using the finite-element software PLAXIS 2D-V8.2 as an axi-symmetric problem. This software is especially useful for the analysis of deformation and the stability of complex geotechnical engineering problems (Brinkgreve and Vermeer [25]). Additionally, this numerical analysis technique is well established and widely used in many researches and case studies of geotechnical applications by modelling the realistic constitutive behavior of the soils. The finite-element method can also be generally used for identifying the patterns of deformations and stress distributions at the ultimate state or allowable service load. Because of these capabilities of the finite-element method, it is possible to model the construction method and investigate the behavior of the uplift of anchor plates and the surrounding soil throughout the construction process, not just for the limit equilibrium conditions (Laman and Yildiz [26]).

Single and multi-plate anchors are generally designed with a central shaft to transfer the axial loads from the anchor plates to the structure. In this study, single and double circular rigid plates were used to obtain the uplift forces in relation to different embedment and spacing ratios. The layout of the model geometry is shown in Figure 1. The anchor system has a total of 1 or 2 individual plates of the same diameter D and the same plate thickness (t_p). The depth of the upper-plate embedment is shown as "H", while the distance between the plates is shown as "s" in the two-plate anchor system. Therefore, the anchor spacing ratio is defined as s/D and the anchor embedment ratio is defined as H/D.

Table 1. Sand parameters used in the numerical analysis.

Parameters	Value
Unit weight, γ_n (kN/m^3)	17.00
Saturated Unit weight, γ_d (kN/m^3)	18.00
Cohesion, c' (kN/m^2)	0.01
Friction angle, ϕ' (degrees)	30.0
Dilatancy angle, ψ (degrees) (ϕ' – 30°)	0.00
Poisson's Ratio	0.25
Elasticity Modulus, E (kN/m^2)	30.000
R_{inter}	0.10



(a) (b)

Figure 1. Mesh grid of topographic model.
(a) Single-plate anchor; (b) Two-plate anchors

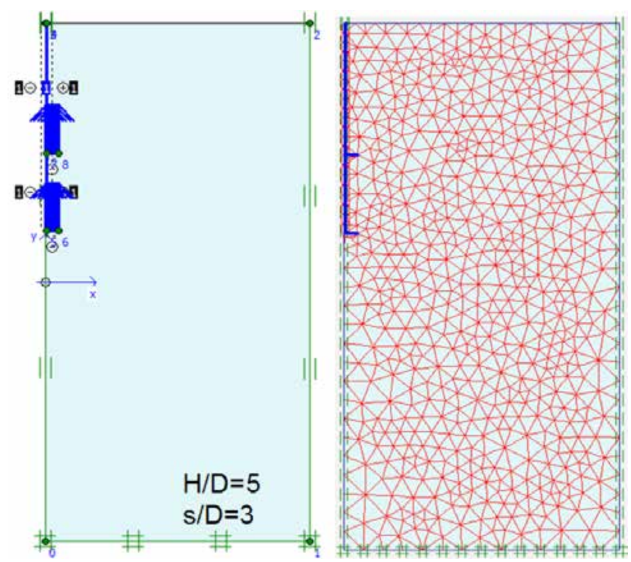


Figure 2. Typical finite-element mesh.

The one-plate anchor system was modelled to obtain the reference bearing capacities. In the analyses, the upper-plate depth (H/D) was changed from 1 to 7 and the spacing between the two plates (s/D) for each different H/D value was changed from 0.5 to 7. Consequently, 84 analyses were performed for this study. In the finite-element analysis the axi-symmetric model was used since the geometry and the loading conditions of the problem provide axi-symmetry. Only half of the geometry is considered in the PLAXIS 2D analysis of axi-symmetric problems. The thickness (t) and the diameter (D) of the plate were 1 cm and 20 cm, respectively. The soil was modelled as an isotropic elasto-plastic continuum with failure described by the Mohr-Coulomb yield criterion. The parameters of the sandy soil were listed in Table 1. The anchor was modelled as being much stiffer than the soil as a discrete plate element.

Although it is likely that, shaft friction contributes to the capacity, the term is generally ignored in the anchor design because of the uncertainties involved (Merifield [21]). So, the interface element was defined around the shaft and the interaction between the shaft and the surrounding soil was neglected. Also, the interaction was neglected between the plate bases and the soil under the plates (Fig 2).

The rationale of the finite-element method is one in which continuous media is divided into finite elements with different geometries. The mesh configuration can be generated automatically for the desired refinement and each element is compatible with the structural and interface elements. During the generation of the mesh, 15-node triangular elements were selected in preference, to provide greater accuracy in the determination of the stresses. In this study, in order to select the suitable mesh refinement, preliminary analyses were conducted at five different mesh coarseness. The fine-mesh coarseness was used in all analyses, since there is a remarkable difference observed for the coarser mesh sizes. A typical finite-element mesh that is composed of the soil, multi-plate circular anchors, boundary conditions and the geometry of the model used, is shown in Fig. 2.

The uplift behavior of the plate anchor was analyzed by using the displacement-definition approach. The common opinion about the failure criteria is in the range of 10% of the plate's diameter. However, the determination of the failure criteria was based on the comparisons of the experimental and theoretical results, as indicated in the literature (Sakr [27], Elsherbiny and Hesam El Naggar [28], Sakr [29]). The 5% displacement criterion has been recommended as a failure criterion to satisfy the serviceability requirements. For this purpose, the failure criterion was selected as 5% of the plate diameter (20 cm). Therefore, the vertical stresses above the horizontal plates were used to calculate the total ultimate load F_y, which was obtained against the 1-cm movement of the two-plate anchor system in the analyses.

3 NUMERICAL ANALYSIS

3.1 Single-Plate Anchor

The uplift capacity of the single-plate anchor at seven different embedment ratios (*H/D*) from 1 to 7 was analyzed using PLAXIS 2D. The results of the single-plate anchor analysis were only used to compare the results with the literature and to assess the performance change that would occur in a two-plate case. The analyses were performed until the collapse of the soil was observed. The criterion of the displacement-defined analysis was increased up to the collapse of the soil to obtain the same ultimate situation as in the literature. Uplift capacities are often expressed in dimensionless form as breakout factor (*BF*), as given below:

$$BF = \frac{F_u}{\gamma A_{pl} H} \tag{1}$$

where *BF* is the breakout factor, F_u is the maximum uplift resistance, γ is the soil unit weight, *H* and A_{pl} are the anchor embedment depth and plate area, respectively.

The graph in Figure 3 presents the variation of the relationship between the breakout factor and the embedment ratio (*H/D*) at a 30° constant angle of the shearing resistance of the soil, for a single-plate anchor in sand.

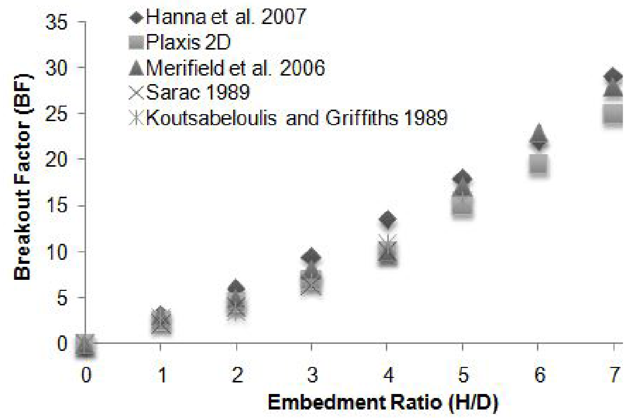


Figure 3. Comparison of the breakout factor for a single plate.

According to the graph, the breakout factor that was obtained from PLAXIS 2D are in accordance with the literature (Hanna et al. [19], Merifield et al. [30], Sarac [31], Koutsabeloulis and Griffiths [32]). The breakout factors obtained from the PLAXIS 2D are slightly below the results of the literature, especially at the large embedment depths. Consequently, the validation of the model and the parameters that are used in the analysis have been approved in the literature by dimensionless values.

3.2 Two-Plate Anchors

A total of 77 different analyses were performed. The analysis program is listed in Table 2. Evaluations were made at the maximum vertical stresses caused by a 1-cm plate's movement. The stress distributions were presented together with the upper and lower plates, and they were compared with the single-plate condition for each embedment ratio, as seen in Figure 4.

Table 2. Analysis program.

Plate Diameter	Constant Value	Variable Value
(*D*) cm	Embedment Ratio, *H/D*	Spacing Ratio, *s/D*
20	1	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0
20	2	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0
20	3	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0
20	4	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0
20	5	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0
20	6	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0
20	7	0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0

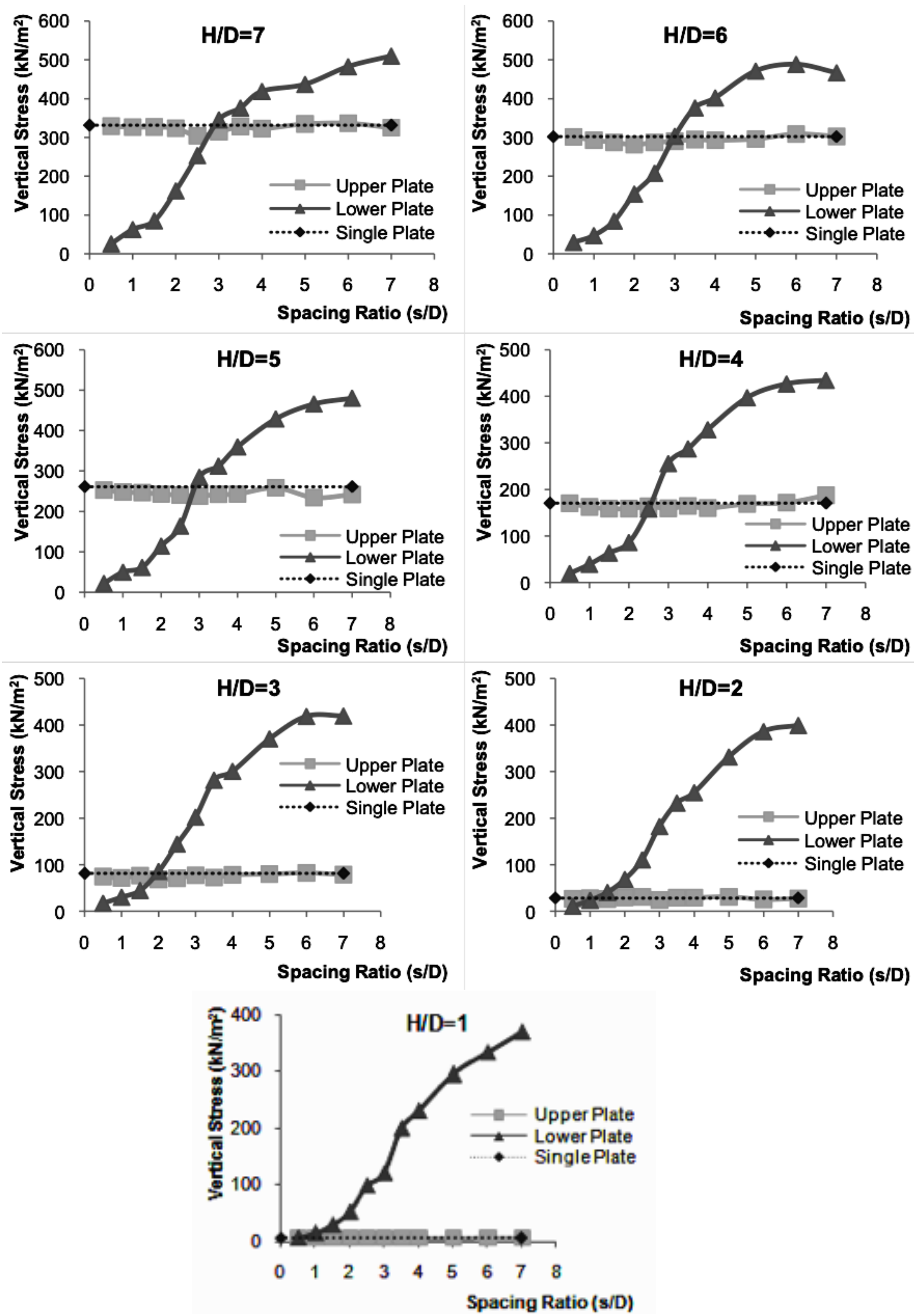


Figure 4. Vertical stress versus spacing ratio for the constant embedment ratios.

According to Figure 4, the maximum vertical stress (with a 5% vertical movement) on the single plate was obtained as being similar to the upper plate of the two-plate anchor system at the same embedment depth ratio. An average absolute error of 3% was obtained for all the 7 embedment depth ratios.

While the upper-plate stresses were obtained about a constant value, independent of the spacing ratio, the lower-plate stresses were in a trend of increasing with an increase of the spacing ratio.

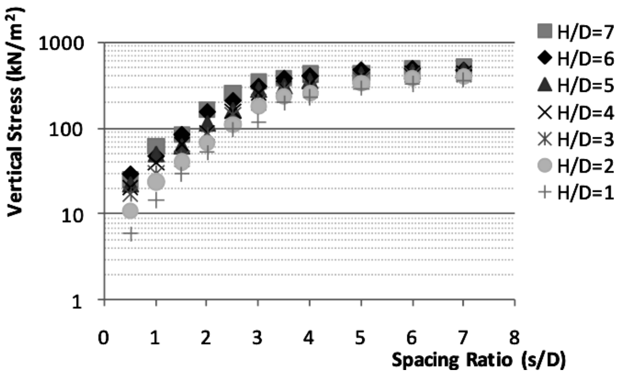
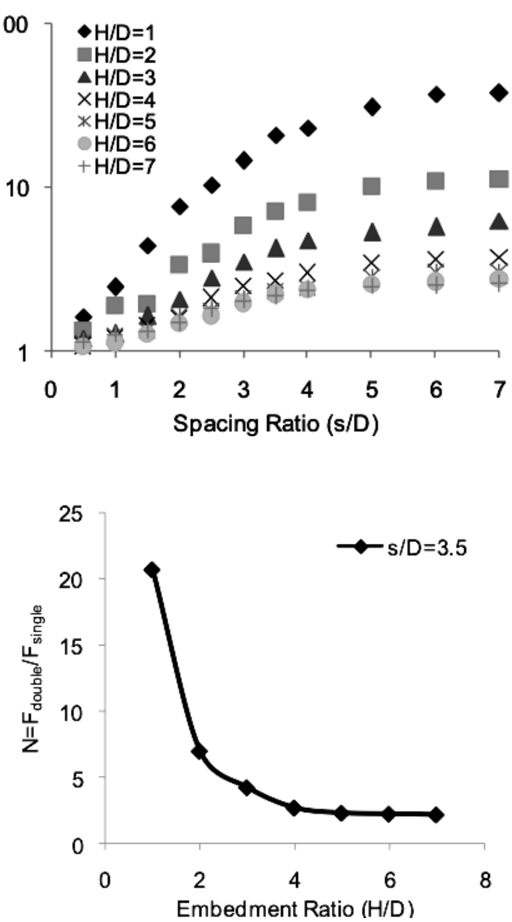


Figure 5. Vertical stress distribution at the bottom plate.



(a)

(b)

Figure 6. Performance variation.
(a) Two-plate case; (b) Optimum value (s/D=3.5%)

The stress distribution in a logarithmic form on the lower plate was in a trend of increasing until a 3.5 spacing ratio and the trend of the stress was transformed into an asymptote for the larger values of the spacing ratios (Figure 5). It can be concluded that using a spacing value between the plates wider than 3.5D has no significant effect on the vertical stress on the lower plate. Therefore, the uplift capacity of the two-plate anchor system has become constant for a constant value of H/D and for any values of the spacing ratios s/D>3.5.

The performance variation of the two-plate anchors according to the single-plate anchor system (N) was described as $N=F_{double}/F_{single}$.

In Figure 6, the N values increase when the spacing ratio (s/D) increases in a non-linear form. According to the graph, the maximum performance in a two-plate anchor system was obtained as 20 times, compared with the single-plate case, for the lowest embedment depth ratio, H/D=1 (Figure 6.a). As described earlier, the optimum spacing ratio was obtained as 3.5D for the performance increments. The graph of the performance variation against the embedment depth ratio was given in Figure 6.b for the specific spacing ratio of 3.5D.

From the graph it can be concluded that, the N values decrease when the embedment ratio increases significantly until H/D=4, but it is more or less constant for the values of H/D>4.

4 STATISTICAL ANALYSIS

For predicting the performance of the systems, empirical estimation methods are generally used in civil-engineering applications, including geotechnical engineering (Rao and Prasad [33], Niroumand and Kassim [34]). Regression analysis is one of the most commonly used empirical methods to examine the relationship between a dependent variable and a set of independent variables. Correlation and regression analysis are related in the sense that both deal with the relationships among variables. Neither regression nor correlation analyses can be interpreted as establishing cause and effect relationships. The correlation coefficient (R) measures only the degree of linear association between two variables and also the coefficient of determination (R^2) is used as a measure of the quality of the regression. The method that is used in this study is preferred as a similarity model and can be adopted for pullout capacities of double-plate anchor systems because the independent variables used are explicit and the dimensionless variables are physically bounded (Misir and Laman [35]).

The formulation was derived from 84 numerical analysis results with different embedment and spacing ratios. The developed formulation contains the dimensionless parameters of the embedment ratio (*H/D*) with a range of 1 to 7 and a spacing ratio (*s/D*) with a range of 0.5 to 7 for a double-plate anchor. After the studies in the literature were examined, it was decided that the curve type controlling of the plate stress ratio is a function of the exponential behavior, as seen in Eq. 2.

$$y = a * e^{b/x} \tag{2}$$

$$\frac{\sigma_{yy\ bottom}}{\sigma_{yy\ single}} = \left(-7.11 + \left(0.98 * \frac{H}{D} \right) + \frac{127.19}{\left(H/D \right)^2} \right) * e^{\left(\frac{\left(0.424 * \frac{H}{D} \right) - 5.4}{s/D} \right)} \tag{3}$$

Regression analysis is a technique used to estimate values that are unknown using known values. It is important to know the shape and the degree of the functional relationship between the variables. The value of the correlation coefficient indicates the degree of reliability for the estimated values (Misir and Laman [35]). The comparison of the vertical stresses on the bottom plate of the two-plate anchors and the single-plate anchor $\sigma_{yy\ bottom}/\sigma_{yy\ single}$ in dimensionless form obtained from PLAXIS and the formulation results is shown in Figure 7. The relationship between the PLAXIS and the formulation (Eq. 3) results are very comparable, with the line of $y=x$ having a high coefficient of determination equal to 0.995 (Figure 7).

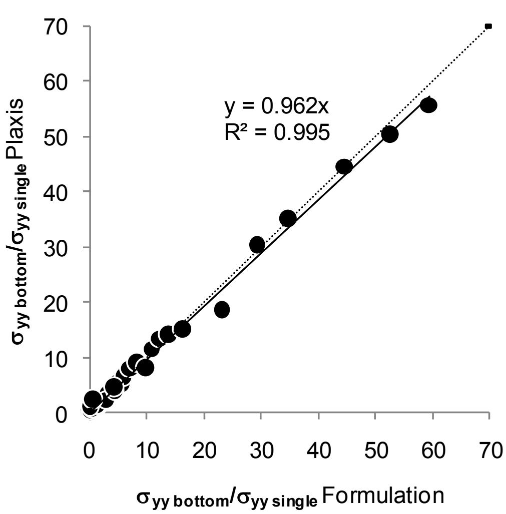


Figure 7. Correlation of the predicted results from the formulation data and PLAXIS.

5 RESULTS AND DISCUSSION

5.1 Analytical Determination of the Uplift Capacity

There have been numerous theoretical studies that address the uplift capacity of a single horizontal anchor. The majority of these studies, however, assume a condition of plane strain for the case of a continuous strip anchor or axi-symmetric for the case of circular anchors. In recent years the failure mechanisms and the pullout capacities of multi-plate anchor systems have been investigated and current approaches are now being developed. The most common approach is to categorize the multi-plate anchor system according to their failure mechanisms. For this purpose, the pullout capacities of the multiple anchor systems can be calculated based on the failure mechanisms in two groups as individual bearing or cylindrical shear. The important point in this approach is that the designer should know the critical embedded ratio and the spacing ratios to distinguish the behavior of the failure between the shallow and deep anchors.

However, in this study the double-plate anchor system and failure mechanisms have not been categorized as either a shallow or deep individual bearing versus cylindrical shear. All of the models that have been analyzed comprise a combination of both the deep and shallow anchor systems. Unlike the general approaches in the literature, in this study the pullout capacity was calculated from the vertical stress variation over the plate surface during the vertical movement caused by the pulling force. A similar semi-empirical approach was used by Meyerhof and Adams [3] to include the circular anchors by extending the strip anchor results by modifying the passive earth pressures with a shape factor.

To obtain the pullout capacity, the maximum vertical stresses corresponding to the defined vertical displacement over the plates were collected and the effective stresses at the plate depth levels were subtracted from this value (Eq. 4)

$$F = \left[\left(\sigma_{yy_{bottom}} + \sigma_{yy_{upper}} \right) * A_{pl} \right] - \left[\gamma * D * A_{pl} * \left(2\frac{H}{D} + \frac{s}{D} \right) \right] \tag{4}$$

5.2 Comparison of the PLAXIS results with those obtained from Eq. (4)

The pullout capacities can be obtained from the conventional formulation given in Eq. (4) with the known vertical stresses, from the upper (single-plate analysis results from PLAXIS 2D) and the lower plate (statistical approach). The graph in Figure 8 shows the comparison of the uplift capacities obtained from the PLAXIS 2D analysis and the developed approach that are given in Equation 4 for the double-plate anchor system. The linear 1:1 line was also plotted in this figure in order to discuss the performance of the statistical models. It can be seen from the figure that by using Eq. (4) the location points of the numerical and the predicted pullout capacity values are scattered around the 1:1 line with a high coefficient of determination equal to 0.982.

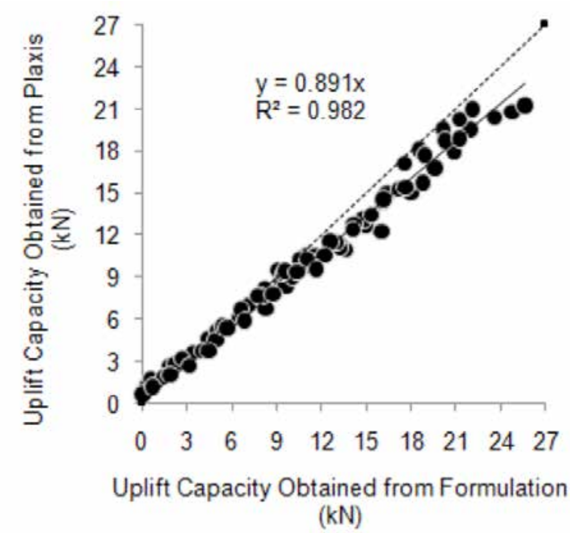


Figure 8. Comparison of the uplift capacities obtained from PLAXIS and formulation (Eq. 4).

As seen from Table 3, the pullout capacities between the results of the numerical analysis and the proposed approach were obtained in a close fit. The variables in Table 3 include the embedment ratio *H/D* and the anchor spacing ratio *s/D*. The comparisons between the numerical and proposed methods were given as the rate of the pullout capacities ($F_{Developed}/F_{Plaxis}$). For the majority of cases, the calculated capacities are approximately within +3% of the measured values, which is adequate for design purposes as an average. As seen in Table 3, the developed $F_{Developed}/F_{Plaxis}$ parameters, especially for *H/D*=1, 2 and *s/D*=0.5, 1.0, 1.5, are well below the prescribed limit value of 1. Especially for these six values, the difference is caused from the exponential part of the formulation for the shallow embedded depths and the close spacing ratios.

In summary, the implementation steps of the proposed approach are as follows:

1. The single-plate anchor model is generated at the desired embedment ratio (*H/D*) in the numerical analysis. But the most important thing is that the *H/D* value must be the same with the upper plate depth in the two-plate anchor model.
2. The single-plate model should be analyzed at a 5% vertical displacement ratio with PLAXIS 2D.
3. The maximum vertical stress value on the circular plate can be obtained from this analysis.
4. This vertical stress value corresponds to the upper plate in the case of two plates because of the same effective stress and the same vertical movement.
5. The stress value on the bottom plate can be calculated from the statistical formulation as given in Eq. (3) by using the embedded and spacing ratios.
6. After the two last steps, the vertical stresses are the known parameters to obtain the pullout resistance for the desired vertical displacement.
7. Finally, the uplift capacity of the two-plate anchor system can be calculated using Eq. (4).

Limitations

The results reported in the present study are only valid for the embedment and spacing ratios referred to herein. The breakout factors and the failure mechanisms and also the size and scale effects of the plate anchors have not been investigated. Therefore, the results obtained from this study should not be used in practice without a verification based on experimental studies.

6 CONCLUSIONS

On the basis of the analysis of the results obtained from the present investigation, the following main conclusions can be drawn:

– The aim of the single-plate anchor modelling was to understand the effect of the embedment depth of the anchor. The results of this group of analyses were used as a reference analysis to make a transition to the two-plate anchor model. The breakout factors' variation of the single-plate anchor according to the versus embedment ratios from 1 to 7 (*H/D*) at a constant 30° angle of the shearing resistance of sandy soil were in good agreement with the literature.
– The vertical stress distribution at a predetermined vertical displacement (1 cm) on the upper plate was obtained as similar to the single-plate anchor model at a constant embedment ratio. Also, the maximum vertical stress on the upper plate increased with the increment of the embedment ratios, but it was independent of the spacing ratios (*s/D*) for a 1cm movement of the anchor system.
– In the two-plate anchoring case, the maximum

Table 3. Comparison of the results of the Plaxis analysis and the developed formulation.

H/D	s/D	F (kN) Developed	F (kN) Plaxis	$F_{Developed}/F_{Plaxis}$	H/D	s/D	F (kN) Developed	F (kN) Plaxis	$F_{Developed}/F_{Plaxis}$
7	0.5	9.063	9.494	0.95	3	0.5	1.880	2.626	0.72
7	1	10.990	10.462	1.05	3	1	2.233	2.771	0.81
7	1.5	13.651	10.914	1.25	3	1.5	3.401	3.575	0.95
7	2	16.041	12.277	1.31	3	2	4.965	4.518	1.10
7	2.5	18.006	15.023	1.20	3	2.5	6.573	6.076	1.08
7	3	19.598	16.776	1.17	3	3	8.076	7.615	1.06
7	3.5	20.895	17.838	1.17	3	3.5	9.428	9.243	1.02
7	4	21.962	19.528	1.12	3	4	10.626	10.304	1.03
7	5	23.597	20.370	1.16	3	5	12.611	11.517	1.09
7	6	24.775	20.735	1.19	3	6	14.159	12.390	1.14
7	7	25.651	21.237	1.21	3	7	15.381	13.459	1.14
6	0.5	8.229	8.149	1.01	2	0.5	0.421	1.257	0.33
6	1	9.371	8.677	1.08	2	1	0.617	1.766	0.35
6	1.5	11.338	9.764	1.16	2	1.5	1.464	1.828	0.80
6	2	13.290	11.247	1.18	2	2	2.719	3.154	0.86
6	2.5	14.987	12.686	1.18	2	2.5	4.084	3.707	1.10
6	3	16.411	15.011	1.09	2	3	5.406	5.473	0.99
6	3.5	17.600	17.103	1.03	2	3.5	6.624	6.648	1.00
6	4	18.595	18.083	1.03	2	4	7.722	7.622	1.01
6	5	20.149	19.528	1.03	2	5	9.578	9.431	1.02
6	6	21.288	20.251	1.05	2	6	11.050	10.267	1.08
6	7	22.147	20.954	1.06	2	7	12.227	10.568	1.16
5	0.5	7.125	7.025	1.01	1	0.5	0.057	0.415	0.14
5	1	7.933	7.678	1.03	1	1	0.063	0.622	0.10
5	1.5	9.657	8.363	1.15	1	1.5	0.750	1.131	0.66
5	2	11.547	10.122	1.14	1	2	1.880	1.960	0.96
5	2.5	13.286	11.014	1.21	1	2.5	3.179	2.645	1.20
5	3	14.799	13.107	1.13	1	3	4.483	3.682	1.22
5	3.5	16.093	14.382	1.12	1	3.5	5.715	5.334	1.07
5	4	17.199	15.293	1.12	1	4	6.846	5.862	1.17
5	5	18.960	17.668	1.07	1	5	8.795	7.779	1.13
5	6	20.280	18.730	1.08	1	6	10.372	9.337	1.11
5	7	21.292	18.856	1.13	1	7	11.651	9.550	1.22
4	0.5	4.463	4.574	0.98					
4	1	5.024	5.133	0.98					
4	1.5	6.505	6.063	1.07					
4	2	8.300	6.729	1.23					
4	2.5	10.046	8.972	1.12					
4	3	11.620	10.487	1.11					
4	3.5	13.002	11.448	1.14					
4	4	14.204	12.717	1.12					
4	5	16.158	14.527	1.11					
4	6	17.654	15.400	1.15					
4	7	18.818	15.714	1.20					

vertical stress distribution on the bottom plate was in a trend of increasing, depending on the increasing spacing ratio.

- The vertical stress on the bottom plate remained unchanged at the larger spacing ratios from 3.5*D*. At the smaller values from 3.5*D*, the vertical stresses increased with the spacing ratios. Therefore, the maximum performance of the bottom plate was obtained at a spacing ratio of 3.5.
- When the performance increment on the two-plate anchor system was plotted on the graph for the optimum 3.5*D* plate spacing, the effect of the second plate increased the system performance to 20 times for the embedment depth of *H/D*=1. This increase was continued in a trend of decreasing up to *H/D*=4 and resulted in an average 2.3 times increase in the system performance with values of greater than *H/D*=4.
- Based on the analysis, the vertical stresses on the lower plate were formulated using a statistical analysis based on dimensionless parameters such as the *H/D* and *s/D* ratios. When compared with the values obtained from this formula and the values obtained from PLAXIS, the vertical stress value on the lower plate was estimated with a high correlation coefficient of 0.995.
- When a proportional relationship between PLAXIS and the developed approach is established, the $F_{y\ developed}$ / $F_{y\ plaxis}$ ratio, which should be 1 in the ideal solution, was obtained in average as 1.03 for all the analyses.
- It can be concluded that, the perspective of the developed approach is quite promising for the prediction of the ultimate pullout capacity of two-plate anchor system as a preliminary design work.

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