Ocean Engineering 150 (2018) 167–175

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Short communication

Vertical uplift resistance of rectangular plate anchors in two layered sand

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ARTICLE INFO

Keywords:
Anchors
Layered sand
Limit analysis
Upper bound
Uplift resistance

ABSTRACT

Based on rigid block collapse mechanism and employing the upper bound theorem of limit analysis, the ultimate vertical uplift resistance of rectangular plate anchors embedded horizontally in two layered sand has been determined. Closed form analytical expressions were derived for computing the vertical uplift resistance in terms of dimensionless uplift factors F_γ and F_q, due to the components of soil unit weight (γ) and surcharge pressure (q) acting on the ground surface, respectively. For given embedment ratios of the anchor, the effect of relative position and thickness of sand layer with higher angle of internal friction (φ_h) and unit weight (γ_h), and sand layer with lower angle of internal friction (φ_l) and unit weight (γ_l), on the magnitude of F_γ and F_q was studied for different length to width ratio of anchor varying from unity to infinity (square to strip). The solutions obtained from the present theory compare reasonably well with the available data from literature.

1. Introduction

Horizontal plate anchors are often used for providing the uplift resistance to various structures such as transmission towers, dry docks and pipelines under water, etc. The uplift resistance must be greater than the anticipated uplift load acting on these structures; which can be achieved with a great flexibility on the selection of shape, size and embedment depth of plate anchors depending upon type of structure, sub-soil conditions, construction feasibility and space availability for the installation of anchors. In this regard, different shapes and sizes of anchors are being employed to meet the requirements of various design needs. In order to compute the vertical uplift capacity of different shapes of plate anchors placed in homogeneous soil, a number of investigations have been reported (Meyerhof and Adams, 1968; Das and Seeley, 1975; Rowe and Davis, 1982; Murray and Geddes, 1987; Dickin, 1988; Ilamparuthi and Muthukrishnaiah, 1999; Merifield et al., 2006; Kumar and Kouzer, 2008; Liu et al., 2011; Rokonuzzaman and Sakai, 2012; Sahoo and Kumar, 2013; O'Loughlin et al., 2014; Liu et al., 2016). The applications of the above discussed studies are limited only to homogeneous soil deposits. In practice, however, soil deposits are rarely homogenous. The determination of uplift resistance of anchors placed in the non-homogeneous soil has been addressed by a few researchers (Stewart, 1985; Bouazza and Finlay, 1990; Manjunath, 1997; Kumar 2003; Sakai and Tanaka, 2007; Bhattacharya and Kumar, 2015, 2016). By conducting small scale model tests, Stewart (1985) has made an attempt to increase the uplift capacity of a shallow anchor buried in clay seabed by placing a cohesionless layer over the clay bed. It was reported that the displacement of anchor required to obtain substantial improvement in uplift capacity would almost be equal to the depth at which anchors are embedded in the clay layer. By performing a limited number of model tests on shallow plate anchors buried in two-layered sand, Bouazza and Finlay (1990) have reported that the uplift capacity of anchors is greatly dependent on the relative strength and thickness of two layers, and the embedment depth of anchor. With the help of simple rigid wedge collapse mechanism and by using the upper bound theorem of limit analysis, Kumar (2003) has obtained expressions for estimating the uplift capacity of strip and circular anchors buried in two-layered sand. Sakai and Tanaka (2007) have evaluated the uplift resistance, direction of the shear band propagation and the scale effect of a shallow circular anchor in two layered sand by carrying out 1 g model test and elasto-plastic finite element analysis. By employing finite element lower bound limit analysis, numerical solutions have been produced for determining the uplift capacity of strip and circular anchors embedded (i) in clay under undrained condition overlain by sand layer (Bhattacharya and Kumar, 2015), and (ii) in two layered sand medium (Bhattacharya and Kumar, 2016). However, it seems hardly any work has been reported for determining the ultimate uplift resistance of rectangular anchors placed horizontally in a non-homogeneous soil, particularly, in layered sand. In this note, theoretical expressions have been developed to compute the uplift resistance of shallow rectangular anchor plates buried horizontally in two layered sand by employing the upper bound theorem of limit analysis and with the assumptions of translational failure mechanism similar

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https://doi.org/10.1016/j.oceaneng.2017.12.056
Received 3 August 2017; Received in revised form 20 October 2017; Accepted 24 December 2017
Available online 5 January 2018

to that considered earlier by Murray and Geddes (1987). In the analysis, it has been considered that both the unit weight and internal friction angle of top soil layer is different from that of bottom soil layer. Recently, Ganesh and Sahoo (2017) have obtained solutions for examining the influence of groundwater table fluctuations on the uplift resistance of rectangular plate anchors using similar concept as that of present study; however, the internal friction angles of both top and bottom soil layers are set to be equal. Furthermore, to the best of the authors' knowledge, no studies seem to have been reported for computing the vertical uplift resistance of rectangular plate anchors buried in layered soil by considering the influence of surcharge pressure on the ground surface. Therefore, the effect of relative position of sand layers on the uplift resistance of rectangular plate anchors owing to the components of soil unit weight and surcharge pressure has been examined in the present study.

2. Problem statement

A rigid plate rectangular anchor with length L and width B is placed horizontally at a depth H below the ground surface in a two layered sand with (i) H_1 and H_2, (ii) φ_1 and φ_2, and (iii) γ_1 and $\gamma_2$are the thickness, angle of internal friction, and unit weight of upper and lower layer of sand, as illustrated in Fig. 1. The ground surface is horizontal and is subjected to uniform surcharge pressure (q). The thickness of anchor plate is assumed to be negligible as compared to its length and width. The magnitude of the uplift resistance is not affected by the roughness of the horizontal plate anchors (Rowe and Davis, 1982). Therefore, the angle of interface friction between the anchor plate and the surrounding soil mass is taken equal to angle of internal friction of sand; it is the internal friction angle of lower layer sand (φ_2) for the present problem. Depending on the position of both the soil layers, φ_1 and φ_2 become φ_h or φ_l and γ_1 and γ_2 become γ_h or γ_l. Here, higher internal friction angle (φ_h) and unit weight (γ_h) and lower internal friction angle (φ_l) and unit weight (γ_l) are used for differentiating the sand layers in the two layered system considering relative resistance of sand layers for different combinations, that is, loose and medium-dense sand layers, loose and dense sand layers, medium-dense and dense sand layers. The soil mass in both the layers are assumed to be perfectly plastic satisfying Mohr-Coulomb failure criterion with an associated flow rule. The principle of superposition is assumed to be valid for determining the total uplift resistance; that is, the factors F_γ and F_q are determined separately (i) $\gamma \neq 0$, $q = 0$ for computing F_γ; and (ii) $\gamma = 0$, $q \neq 0$ for computing F_q. It needs to be mentioned that the failure load obtained with the usage of the principle of superposition remains always smaller than the true failure load, that is, the solution obtained with this assumption remains always on the safer side. It is intended to determine the magnitude of the ultimate uplift load P_u per unit length of anchor plate which will lead to ultimate shear failure.

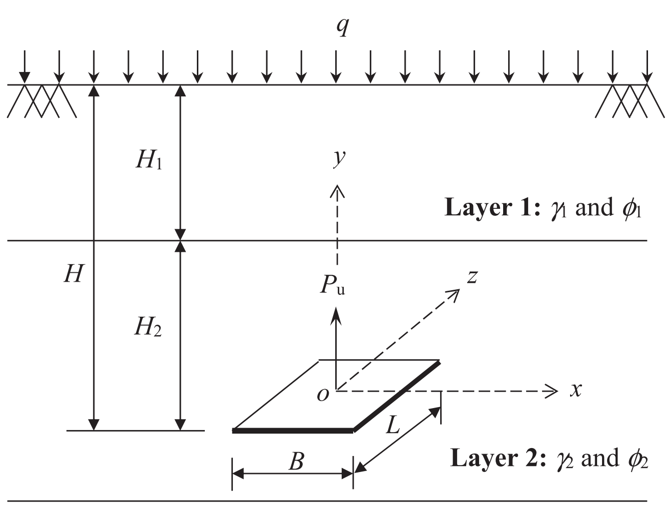

Fig. 1. Definition of problem.

3. Analysis

3.1. Collapse mechanism

Following Kumar (2003), the rigid wedge collapse mechanisms for rectangular anchors buried in two layered sand with (i) sand layer of higher internal friction angle underlying sand with lower internal friction angle ($\varphi_1 < \varphi_2$), and (ii) sand layer having higher angle of internal friction overlying sand layer with lower internal friction angle ($\varphi_1 > \varphi_2$), as shown in Fig. 2a and (b), respectively, has been assumed in the present analysis. Similar to Murray and Geddes (1987), the improvement in the upper bound solution is obtained by introducing the portions of right circular arcs in the collapse mechanism at each corner of the section normal to the anchor central axis. From both laboratory experiments and elasto-plastic three dimensional finite element analysis performed by Rokonuzzaman and Sakai (2012) for square and rectangular plate anchors embedded in homogeneous dense sand, the same type of collapse mechanism consisting of circular arcs at each corners and straight boundaries along the edges of the anchor plate have been identified. Taking into account the symmetric nature of problem about the vertical planes *yox* and *yoz* as illustrated in Fig. 1, only one fourth of the collapse

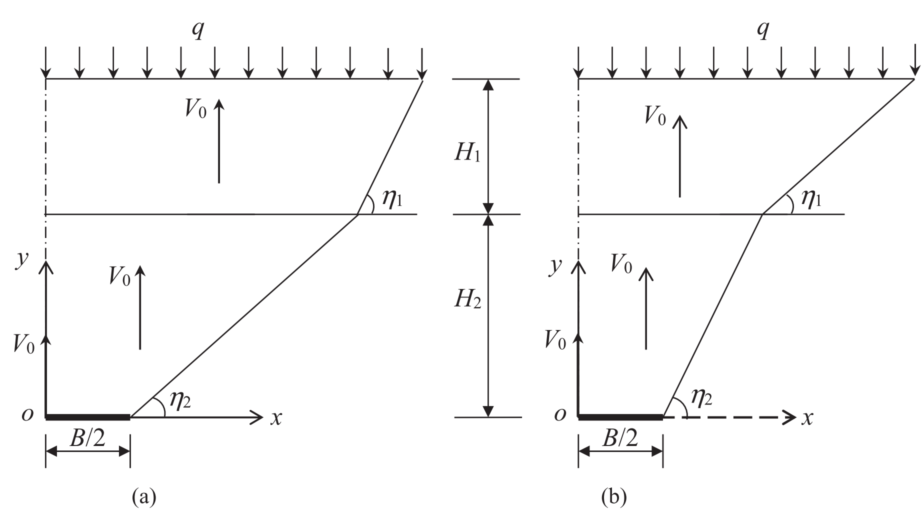

Fig. 2. Collapse mechanism associated with (a) sand layer of higher internal friction angle underlying sand layer of lower internal friction angle ($\phi_1<\phi_2$); and (b) sand layer of higher internal friction angle overlying sand layer of lower internal friction angle ($\phi_1>\phi_2$).