Computers and Geotechnics 81 (2017) 39–48

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Numerical prediction of undrained response of plate anchors under combined translation and torsion

Hamidreza Nouri [a], Giovanna Biscontin [b], Charles P. Aubeny M. ASCE [c,*]

[a] Golder Associates, Inc., 18300 NE Union Hill Road, Suite 200, Redmond, WA 98052, USA
[b] Department of Engineering, University of Cambridge, Schofield Centre, High Cross, Madingley Road, Cambridge CB3 0EL, UK
[c] Texas A&M University, 3136 TAMU, College Station, TX 77843-3136, USA

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 13 July 2016
Accepted 17 July 2016

Keywords:
Plate anchor
Torsional capacity
Translational (shear) resistance
Plastic limit analysis
Finite element analysis
Failure envelope

ABSTRACT

The undrained pure translational and torsional capacity of anchors and the plate response under eccentric translational loading is investigated in this paper using three-dimensional finite element (3D-FE) analysis. Plastic limit analysis is adopted to establish a benchmark solution for ultimate translational resistance with satisfactory agreement with the FE values which confirms the developed numerical model. Although plate thickness has a marked impact on the maximum shear and torsion resistance, the shape of failure envelope is minimally affected by thickness. A simple three-degree-of-freedom interaction equation is curve-fitted to FE failure datapoints. Representative interaction relationships are introduced for square and rectangular plates.

1. Introduction

The offshore industry is expanding farther into very deep water, leading to a number of economical and technical challenges. Floating structures anchored to the seabed using catenary and taut-wire mooring systems are generally more technically feasible and cost effective than gravity based platforms in these deep water environments. Anchorage for floating systems can include piles, caissons and various types of plate anchors. This paper addresses performance of the latter alternative. Under normal operating conditions, plate anchors are mainly subjected to pull-out loading in an intended plane of loading, for example, the X-Z plane in Fig. 1(a). However, extreme storm events may cause partial failure with the loss of one or several mooring lines resulting in substantial changes in the orientation of the intact lines, as well as to the applied resultant force (Fig. 1(b)). Under these conditions the anchor must resist a general system of loads, with some components of load acting outside the plane of intended loading.

A full description of behavior of an anchor plate in a partially failed mooring system requires adequate understanding of undrained response of anchor plates subjected to general loading conditions involving six degrees of freedom. This entails characterizing anchor behavior for six components of uniaxial loading (3 translational and 3 rotational) as well as the interaction effects amongst all possible load combinations. Much of the research in this area to date has focused on in-plane loading conditions involving forces in the X and Z directions and moments about the Y-axis (Fig. 1) [8,5]. This paper investigates anchor behavior for loading in the X-Y plane in Fig. 1, which will be termed 'shear-torsional' loading. The loading comprises 'shear' forces H_x and H_y and a torsion T; i.e., a moment acting about the Z-axis. All loads act within the plane of the plate. The study presented herein does not attempt to fully characterize anchor behavior for general 6 degree of freedom loading conditions. Rather, it investigates a critical component for a more general model to be developed in the future.

The plate anchors considered in this paper are idealized as rectangular plates with specified aspect ratios (*W*/*L*) and thickness t (Fig. 1). Some plate anchors, such as suction embedded plate anchors (SEPLAs) match this idealized geometry to a reasonable degree. By contrast, drag embedded plate anchors usually have relatively complex geometric configurations to facilitate embedment. The findings of this paper can provide useful insights into the behavior of drag anchors, but the inherent limitations of the analyses arising from the simplified geometry must be carefully considered.

* Corresponding author.
E-mail addresses: Nouri.hreza@gmail.com (H. Nouri), gb479@eng.cam.ac.uk (G. Biscontin), caubeny@civil.tamu.edu (C.P. Aubeny).

http://dx.doi.org/10.1016/j.compgeo.2016.07.008
0266-352X/

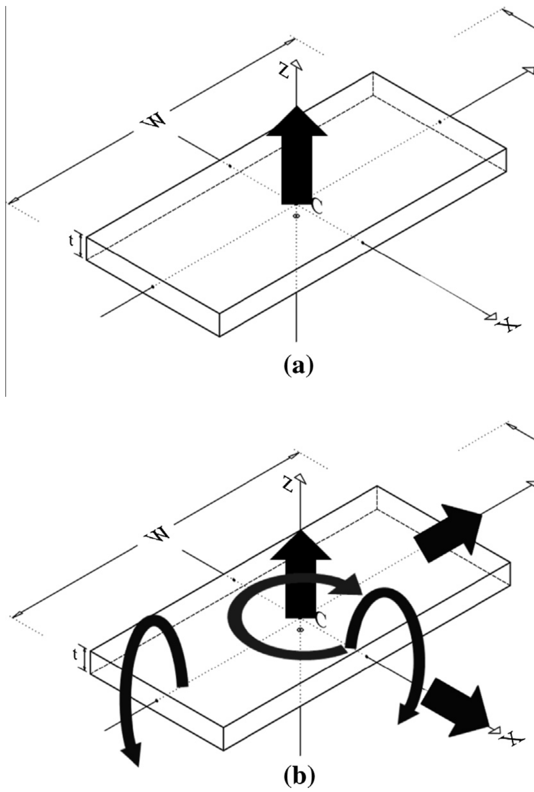

Fig. 1. Applied loads to idealized plate anchor: (a) pull-out force in normal operating condition and (b) general six degrees of freedom loading after extreme loading condition.

O'Neill et al. [8] used plane strain finite element (2D-FE) analysis to investigate the behavior of rectangular and wedge-shaped strip anchors subjected to combined in-plane translational, vertical, and rotational loading. They also developed plastic upper bound solutions to evaluate pure parallel, normal, and rotational capacity factors for strip plates to validate the FE results. Using two-dimensional finite element (2D-FE) analysis, they produced failure loci and plastic potentials from considerations of fluke-soil interaction and then developed a design method to predict drag anchor trajectory during embedment. Murff et al. [5] used 2D-FE to develop a failure locus for the ratio of plate length to thickness (L/t) of 7 and 20 with different plate roughness. Yang et al. [14] employed 3D-FE, to study the behavior of infinitely thin plate anchors subjected to loading in all six degrees of freedom. They also introduced a plasticity solution for failure envelope of a plate under combined translation-torsion and developed formulas to estimate pure sliding and torsional bearing capacity. This plasticity solution predicts the behavior of an infinitely thin plate, but provided only an approximate solution for a plate with finite thickness. Nouri [7] modified the plastic limit solution originally developed by Yang et al. [14] to predict more accurately the torsional collapse load and failure envelopes of a plate anchor with finite thickness. Researchers have also conducted 3D-FE analysis on other types of offshore foundations under general loading condition, such as for mudmats [3] or OMNI-max anchor [13].

In the current study, we use 3D-FE analysis to evaluate the translational (parallel to plate) and torsional ultimate bearing capacity of plates, as well as the interaction of these two modes of loading. Results of the FE analysis are also used to validate analytical solutions to predict bearing capacities and to confirm whether the postulated failure mechanism for the analytical solution is correct.

2. Material properties for numerical model

The commercial software *ABAQUS* [4] is used in this study. The plate is assumed to be deeply embedded, with localized plastic flow forming around the plate anchor and not extending to the surface, resulting in capacity factors that are not affected by overburden and soil weight [10,12]. Thus, the soil is assumed to be a weightless material without loss of accuracy. Since the size of the plastic zone around the plate anchor at failure is smaller for shear and torsion than for uplift and rotation, the assumption of deep embedment is valid even for shallower embedment depths. This assumption also implies that the soil and plate are fully bonded. Thus, "no separation" is assumed as the normal (i.e. perpendicular to interface) contact behavior for the plate-soil interface in conjunction with "rough" for the tangential contact property to realistically simulate a fully bonded condition. The interaction between soil and plate is modeled using surface to surface contact pairs in which the plate outer surface is chosen as a "master surface" and the soil surface in contact with the plate as a "slave surface". The active degrees of freedom of the nodes on the slave surface are constrained to the master surface nodes through relationships which define the tangential and normal interaction at the nodes of these two surfaces.

Clay under undrained conditions is modeled as a linear elastic perfectly plastic material, with yielding determined by the Von Mises failure criterion with undrained shear strength, s_u. The Young's modulus of the soil, E, is given by a modulus ratio of $E/s_u = 500$, and Poisson's ratio is taken as 0.49 to simulate no volume change for undrained clay in total stress analysis. The ultimate capacity of the plate is not affected by the pre-failure elastic behavior of the soil [2]. In addition, in studies on plate uplift bearing capacity it was observed that as the soil rigidity (E/s_u) increases, the anchor displacement required to mobilize the maximum capacity reduces, while the maximum capacity does not change [10,12]. Therefore, the Young's modulus of the soil is assumed constant in these studies. Since the analysis of the structural behavior of the anchor is not within the scope of this work, the plate is modeled as a rigid body with Young's modulus 10^{10} times that of the soil, and Poisson's ratio of 0.30. The analysis is conducted using small strain displacement control, since the ultimate translational and torsional capacities are developed within an anchor movement of 0.1 times the anchor length. A reference node is defined in the center of the plate and prescribed displacements are applied at the reference point to perform displacement controlled analysis. Standard boundary conditions are also applied to the model: the base is fixed in all directions, while the vertical boundaries are fixed in the lateral direction and free to move vertically. In all the models with a plane of symmetry, the nodes on the plane of symmetry are only allowed to move in the plane.

3. Challenges of the numerical modeling

Unrealistic stress distributions arise from the displacement discontinuities that take place at the edges of a rigid structure penetrating a softer material [11] resulting in higher overall resistance. The unfavorable effect on the numerical results is more severe for buried structures and materials with no volume change. There are mainly two approaches to overcome such loss of numerical accuracy:

1. Mesh refinement.
2. Contact pairs along the corners of the plate.

As plane strain 2D analyses take much less time and fewer memory resources, they are a reliable and fast way to evaluate pos-