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Research Paper

Coupled analysis of dynamically penetrating anchors

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A R T I C L E I N F O

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A B S T R A C T

The development of a numerical procedure for the finite element analysis of anchors dynamically penetrating into saturated soils is outlined, highlighting its unique features and capabilities. The mechanical behaviour of saturated porous media is predicted using mixture theory. An algorithm is developed for frictional contact in terms of effective normal stress. The contact formulation is based on a mortar segment-to-segment scheme, which considers the interpolation functions of the contact elements to be of order N, thus overcoming a numerical deficiency of the so-called node-to-segment (NTS) contact algorithm. The nonlinear behaviour of the solid constituent is captured by the Modified Cam Clay soil model. The soil constitutive model is also adapted so as to incorporate the dependence of clay strength on strain rate. An appropriate energy-absorbing boundary is used to eliminate possible wave reflections from the artificial mesh boundaries. To illustrate the use of the proposed computational scheme, simulations of dynamically penetrating anchors are conducted. Results are presented and discussed for the installation phase followed by 'setup', i.e., pore pressure dissipation and soil consolidation. The results, in particular, reveal the effects of strain rate on the generation of excess pore pressure, bearing resistance and frictional forces. The setup analyses also illustrate the pattern in which pore pressures are dissipated within the soil domain after installation. Hole closure behind a dynamic projectile is also illustrated by an example.

1. Introduction

Dynamically penetrating anchors have proven to be promising systems for anchoring taut mooring lines of floating offshore oil and gas exploration and production units because of their relatively easy installation process. This system of dynamic anchors can be used in water depths well beyond where pile driving becomes impractical. The kinetic energy of a dynamic anchor attained by gravity free-fall through the water column provides the required dynamic penetration force, often making it more practical and cost-effective than other offshore foundations such as suction piles, driven piles, drilled and grouted piles, and drag embedment anchors.

The deep penetrating anchor [1,2], and the less sophisticated torpedo anchor [3], are two types of dynamically penetrating anchor that are conceptually similar. The deep penetrating anchor is a dart-shaped, thick-walled steel cylinder with a relatively blunt massive tip and flat plates or flukes attached to its upper section, which prevent rotation of the anchor during free-fall (Fig. 1a). A torpedo anchor usually consists of a pipe pile (typically 12–18 m in length and 0.76–1.07 m in diameter) filled with scrap metal and concrete, close-ended and fitted with a conical tip and sometimes including longitudinal fins (attached along the upper part of the anchor), which provide directional stability during free-fall (Fig. 1b). Torpedo anchors were first commercially employed in the Campos Basin, offshore Brazil [3]. The impact velocity of the torpedo anchors reported by Medeiros [3] varied between 10 and 22 m/s for hanging heights, from which free-fall commenced, between 30 and 150 m as measured from the seabed, and the penetration depth usually varied between 8 m and 22 m. As of 2009, more than 1000 torpedo anchors have been used for anchoring deep water flow-lines and floating facilities at the Campos Basin in water depths up to 1400 m [4].

Better understanding of the behaviour of dynamic projectiles in soil has been sought mainly by means of field and laboratory tests, but also by numerical simulations. Tests on small-scale and full-scale torpedo anchors have been carried out to study their installation characteristics and load capacities (e.g., Medeiros [3], Porto et al. [5], Brandão et al. [6], Zimmerman et al. [7], Lieng et al. [2,8]). Recently, O'Beirne et al. [9] conducted a series of field tests on a 1:20 reduced-scale anchor and studied the undrained capacity of the anchor under both vertical and inclined monotonic loadings. Geotechnical centrifuge tests on model dynamic anchors have

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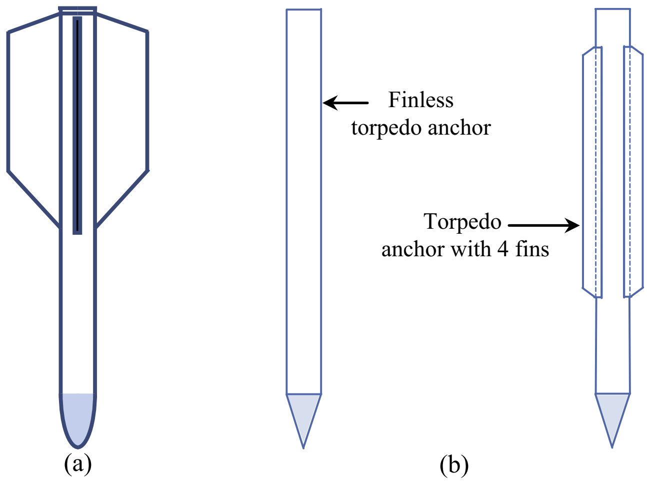

Fig. 1. (a) Deep penetrating anchor; (b) torpedo anchor with and without fins.

been conducted to simulate the stress conditions and soil response at the field scale (e.g., O'Loughlin et al. [10], Richardson et al. [11], and Hossain et al. [12]). Laboratory tests on 1:30 scale model finless torpedo anchors have been also conducted by Gilbert [13], which primarily aimed to understand the behaviour of the anchors during installation and pull-out in normally consolidated beds of kaolinite.

Despite the increasing relevance of dynamically penetrating anchors in offshore applications, the estimation of their embedment depth and pull-out capacity still remain a challenge. Current design procedures include an estimation of the penetration depth through a theoretical model developed by True [14], and predicting the pull-out capacity using either the Finite Element Method (FEM) or the American Petroleum Institute (API) [15] method. Simulation of the installation process is usually neglected in calculations of the pull-out capacity, even though the installation of a dynamic anchor may lead to considerable disturbance and remoulding of the soil in the vicinity of the anchor. It is notable that the prediction of the anchor embedment depth is complicated by the very high strain rate at the soil-anchor interface, resulting from high penetration velocities, and hydrodynamic aspects which may involve viscous and pressure drag forces.

Most current numerical models for simulating objects penetrating into soil are based upon a displacement formulation involving a single-phase soil, where the excess pore water pressures are not explicitly calculated, and they also use simplifying assumptions in the modelling (e.g., Sturm and Andresen [16], Sousa et al. [17], Kim et al. [18]). These methods, which assume saturated soil conditions, can only predict the total stresses developed in soil. In general, they cannot be used to find separately the excess pore water pressures and the effective stresses in the soil. Furthermore, most research devoted to the numerical analysis of dynamic anchors ignores the effects of installation on the pull-out and lateral capacity of the anchor. For these 'wished in place' anchors, perfect contact is usually assumed between the anchor system and the surrounding soil. A major limitation is, therefore, a lack of knowledge of the effective stress state and pore pressure around the penetrometer after installation. Indeed, laboratory tests have rarely been able to successfully measure excess pore pressures or effective stresses in the soil during or following the dynamic penetration of objects (for an exception see Chow et al. [19]).

Sabetamal et al. [20,21] presented rigorous coupled analyses for a few free falling torpedo anchors. These initial studies reported successful simulations of the installation process and reconsolidation stage of torpedo anchors, and revealed the pattern in which excess pore pressures are generated and dissipated. Recently, Liu et al. [22] also presented numerical simulation of torpedo anchor installation using the Coupled Eulerian–Lagrangian (CEL) approach. This particular study incorporated an undrained effective stress framework by specifying the components of the effective stress constitutive matrix and an equivalent bulk modulus of the pore fluid (e.g., see [23]). This approach enabled the effective stresses and the pore pressures to be calculated by assuming undrained conditions and the Mohr Coulomb soil model.

However, for analysis involving the time dependent dissipation of excess pore pressures, a coupled-flow FE analysis must be performed, incorporating the development of pore-fluid pressures along with deformations, velocities and accelerations (e.g., [24]). Moreover, subsequent dissipation can be investigated by providing the initial undrained or partially drained distributions of pore pressure. In addition, a robust algorithm is essential in order to model soil–structure interactions during the entire simulation process. Since the contact area may change or the contact behaviour may change as the structure penetrates deeper into the soil, the contact cannot be modelled by commonly-used interface elements. Instead, it has to be modelled by contact surfaces that gradually change position and shape.

In order to conduct a comprehensive analysis of dynamically penetrating anchors, a finite element (FE) procedure has been developed by Sabetamal [25]. In this paper, we provide an outline of the computational scheme followed by a study of predicted anchor behaviour. This involved simulation of the complete installation process and reconsolidation of the soil to assess the "set-up" of shear strength with time after installation. Estimation of the subsequent pull-out capacity under dynamic loading is not included here. The method adopted to incorporate strain rate effects in the Modified Cam Clay constitutive model is also described. The implications of a high strain rate, a frictional interface, and an inertial drag force for the behaviour of torpedo anchors are discussed. In addition, the need to use a strain rate-dependent coefficient of friction at the soil-anchor interface is explained, as this might be important for future computational modelling.

2. Governing equations

A saturated porous medium comprises solid and fluid constituents that interact with each other affecting the overall mechanical behaviour of the medium. Coupling the responses of each individual constituent complicates the mechanics of a porous medium in comparison with a single-phase material. Moreover, the incorporation of contact interfaces within these multiphase materials substantially increases the complexity of coupled problems, mainly because the contact formulation should generally conserve continuity of both the fluid flow and tractions across the contact interface. In particular, effective stresses have to be evaluated to account for tangential stresses due to frictional behaviour at these interfaces.

The response of saturated porous media can be described using the Biot theory [26–29], which provides a description of elastic wave propagation in a porous solid saturated with a viscous fluid. Alternatively, a continuum approach based on the theory of mixtures [30] can be employed to derive the governing equations of saturated porous media in light of the concept of volume fractions [31]. According to this approach, each phase is smeared over the entire domain of the porous medium with a reduced density in order to create a homogenised continuum assuming an immiscible mixture (i.e., no mass exchange between the solid and fluid constituents). The principles of continuum mechanics are then invoked to describe the behaviour of the equivalent medium at a macroscopic level. Accordingly, the local balance relations should