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Numerical implementation of the installation/mooring line and application to analyzing comprehensive anchor behaviors

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ABSTRACT

With the application of innovative anchor concepts and advanced technologies in deepwater moorings, anchor behaviors in the seabed are becoming more complicated and pose a great challenge to the analytical methods. In the present work, a large deformation finite element (FE) analysis employing the coupled Eulerian–Lagrangian technique is performed to simulate the installation/mooring line, and then is applied to analyzing comprehensive anchor behaviors in the seabed. By connecting cylindrical units with each other using connector elements, the installation/mooring line is constructed. With the constructed installation/mooring line, FE simulations are carried out to investigate comprehensive anchor behaviors in the seabed, including long-distance penetration of drag anchors, keying of suction embedded plate anchors and non-catastrophic behavior of gravity-installed anchors. Through comparative studies, the accuracy of the proposed method is well examined. A parametric study is also undertaken to quantify the effects of the frictional coefficient, initial embedment depth, and soil weight on the profile of the embedded anchor line and the shackle load. The present work demonstrates that the proposed FE model, which incorporates the installation/mooring line and the anchor, is effective in analyzing the comprehensive anchor behaviors in the seabed.

1. Introduction

The move of the oil and gas industry into deep and ultra-deep waters has resulted in innovative anchor concepts and advanced technologies being applied in deepwater moorings. Deepwater anchors are the core components of deepwater mooring systems, which have evolved from suction anchors, to vertically loaded plate anchors (VLAs), to suction embedded plate anchors (SEPLAs) and to gravity-installed anchors (GIAs), as illustrated in Fig. 1. Due to different installation methods and geometric features of the anchor during both installation and mooring, anchor behaviors in the seabed become more complicated and present different characteristics, such as long-distance penetration of drag anchors (including VLAs), keying of SEPLAs, and non-catastrophic behavior of OMNI-Max anchors (a new type of GIA) [1]. These comprehensive anchor behaviors have posed a great challenge to sound and accurate analytical methods.

Previous researchers proposed several theoretical and numerical methods to predict or simulate the comprehensive anchor behaviors in the seabed. An attractive theoretical method is the plastic limit approach supported by finite element (FE) analysis, which was first proposed by Bransby and O'Neill [2] and developed by O'Neill et al. [3] to analyze the trajectory of drag anchors. In the methodology of Bransby and O'Neill, a plastic limit interaction equation (or failure envelope) for the anchor should be derived from FE analysis. With the chain equation [4] and the failure envelope, the anchor trajectory can be obtained through successive iterations. Based on the anchor failure envelope proposed by Bransby and O'Neill [2], the installation of drag anchors [5,6] and keying of SEPLAs [7–9] were investigated to predict the trajectory and to calculate the embedment loss of the anchor, respectively. The OMNI-Max anchor is a recently developed GIA that features an omnidirectional arm placed toward the anchor tip. This design makes the anchor penetrate deeper and hence a higher capacity to reduce the risk of mooring failure during hurricane season, which was defined by Shelton as the non-catastrophic behavior [1]. The non-catastrophic behavior of OMNI-Max anchors was also investigated by Wei et al. [10] through the plastic limit analysis to evaluate the diving performance of the anchor. However, the shape of the anchor failure envelope was controlled by four power exponents, which should be fitted through FE analysis or experimental data. Note that the anchor behaviors were extremely sensitive to the exponents chosen [9]. Recently, a kinematic model for drag anchors was put forward [11,12], in which a closed-form drag equation is

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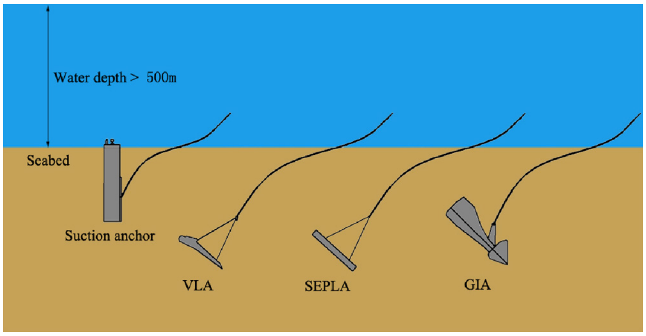

Fig. 1. Evolution of deepwater anchors.

developed and the anchor trajectory can be explicitly calculated. There are also other methods to predict the trajectory of drag anchors, such as empirical formulas and limit equilibrium methods, which were summarized by Murff et al. [13].

In the numerical analysis, the FE method is regarded as the main tool for simulating anchor behaviors in the seabed. The comprehensive anchor behaviors mentioned above always involve large deformations of the soil, requiring the large deformation finite element (LDFE) method that can deal with the convergent problem due to large mesh distortions and contact problems. The remeshing and interpolation technique with small stain (RITSS) method and the coupled Eulerian–Lagrangian (CEL) approach are two effective LDFE methods to analyze anchor behaviors in the seabed. The RITSS method was proposed by Hu and Randolph [14] and extended to three-dimensional conditions by Yu et al. [15] and Wang et al. [16]. It is essentially a form of arbitrary Lagrangian–Eulerian method with small strain Lagrangian calculations in each incremental step and "convection" of the stress and material properties from the old mesh to the new mesh. Tian et al. [17] presented an alternative development of the RITSS method, which avoids the effort of coding specialist meshing and mapping solution subroutines. With the RITSS method, the embedment loss of SEPLAs during keying was investigated [17–21]. For the vertical pullout of SEPLAs, the effect of the chain profile was not considered by all researchers; for the inclined pullout, the effect of the chain profile was quantified by Song et al. [18] and Wang et al. [20] through introducing a chain equation, while a small rigid bar element with high Young's modulus was used by Yu et al. [19] to simulate a segment of the chain. Recently, Liu et al. [22] investigated the diving performance of OMNI-Max anchors, in which the effect of the chain profile was still not considered.

As another LDFE method, the CEL approach overcomes the disadvantages of the pure Lagrangian and Eulerian methods and has been proved to be well suited to solve geotechnical problems with large deformations [23–26]. In recent years, the CEL method was utilized to simulate the installation process of drag anchors, in which the movement direction of the fluke, drag angle and drag force at the shackle, and anchor trajectory were investigated [27,28]. In the FE simulation of drag anchor installation, construction of the anchor line and allowing for its effects is necessary, which is also a work that should not be avoided in investigating the behaviors of SEPLAs and GIAs. Therefore, further validation and investigation of the numerically constructed anchor lines are required.

A survey of emerging methods for analyzing comprehensive anchor behaviors in the seabed reveals: (1) in the RITSS analysis, the effect of the chain profile on anchor behaviors was ignored [19,22] or considered by introducing a chain equation [18,20]. It is emphasized that the chain equation [4] involves some parameters (bearing capacity factor and frictional coefficient) and assumptions (ignoring the chain weight and a small angle assumption); (2) the FE simulation of drag anchor installation received limited attention; and (3) the investigation on the non-catastrophic behavior (or diving performance) of OMNI-Max anchors is very limited and preliminary by either theoretical or numerical methods.

In the present work, a large deformation FE analysis employing the coupled Eulerian–Lagrangian technique is performed to simulate the installation/mooring line, and then is applied to analyzing comprehensive anchor behaviors in the seabed. The installation/mooring line is constructed by connecting cylindrical units with each other using connector elements, with which the anchor-chain-soil interaction can be reasonably considered. Based on the constructed installation/mooring line, the FE analysis is carried out to predict the trajectory, calculate the embedment loss and evaluate the diving performance of the anchor by simulating the installation of drag anchors, keying of SEPLAs, and non-catastrophic behavior of OMNI-Max anchors, respectively. Comparative studies are performed to examine the accuracy of the proposed method. Parametric studies are also designed to quantify the effects of the frictional coefficient, initial embedment depth, and soil weight on the profile of the embedded anchor line and the shackle load.

2. Coupled Eulerian–Lagrangian method

The CEL technique is a LDFE method that overcomes the disadvantages of the pure Lagrangian and Eulerian methods, which uses an explicit time integration scheme [29]. The unknown solution in the next time step can be directly calculated by the solution of the previous time step without any iteration. Explicit integrations are conditionally stable. Numerical stability is guaranteed by introducing a critical time increment in every time step, i.e., $\Delta t_{\text{critical}} = \min(L_e/c_d)$, where L_e is the characteristic element dimension and c_d is the dilatational wave speed of the material.

The CEL technique supports multiple materials (including voids) in a single element. The flow of Eulerian material among different meshes is tracked by computing its Eulerian volume fraction (EVF). If a material completely fills an element, the EVF is 1; if no material is present in an element, the EVF is 0. Contact between Eulerian and Lagrangian materials is enforced by a general contact that is based on a penalty contact method. The contact force F enforced between the contact regions can be expressed in terms of the penetration distance p and the penalty stiffness, i.e., $F = kp$. The factor k is based on a representative stiffness of the underlying Eulerian elements and automatically maximized subjected to the stability limits.

3. Implementation of the installation/mooring line

Regarding that the installation/mooring line with zero bending stiffness can only transfer the axial force, it is reasonable to simulate the line with truss elements. However, the Eulerian–Lagrangian contact in Abaqus does not support truss elements [29]. In the present work, the installation/mooring line is constructed by connecting cylindrical units with each other using LINK connector elements. The construction procedure and merit of the constructed installation/mooring line are listed in Table 1. Before investigation of the comprehensive anchor behaviors, a numerical case is designed to verify the effectiveness of the FE simulation on the installation/mooring line. As illustrated in Fig. 2, the line is fixed at an attachment point and will cut through the soil as it is tensioned by enforcing a constant velocity at the drag point, so a reverse catenary shape of the line is formed in the soil.

3.1. Numerical modeling

According to the designed case (see Fig. 2), the FE model is established as illustrated in Fig. 3. The installation/mooring line is