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Numerical investigations of the effects of different design angles on the motion behaviour of drag anchors

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ABSTRACT

The factors that may influence the motion behaviour of drag anchors include drag velocity, shape and density of the drag anchor, length of the anchor line, etc. This paper presents a coupled Eulerian-Lagrangian (CEL) model of both an anchor and its chains to simulate the installing processes of drag anchors. The comprehensive anchor behaviours including the variations of anchor trajectory, movement direction, drag angle and drag force at the shackle of drag anchors with various design angles are presented. The numerical results agree well with both existing FE results and theoretical solutions. Fitting equations describing the anchor motion behaviours are proposed. The effects of the values of the bearing capacity factor and the ratio between tangential and normal soil resistances of the anchor chains, when deriving theoretical solution of drag forces, are discussed. The influence of the friction coefficient of the chains is also analysed.

1. Introduction

With the offshore oil and gas development into deep and ultra-deep waters, there is a large demand for new anchors that can withstand large uplift mooring forces. In addition, low cost and easy installation are equally important. Thus, the new drag anchors are used increasingly widely. The new drag anchors, also called vertically loaded plate anchors (VLAs), can bear both horizontal and vertical loads and can withstand uplift mooring forces of more than 100 times the weight of the anchor body [1]. When a drag anchor is lowered to the seabed and sufficient installation line has been paid out, an anchor handling vessel (AHV) starts moving along a certain direction. The anchor plate will penetrate into the soil with the towing of the AHV. In addition, because of the soil resistance and the friction, the embedded line will gradually form a reverse catenary shape. As the embedded depth increases, the anchor plate is gradually lifted to form a stable azimuth angle. Moreover, the chain can be divided into three parts: the catenary line, the horizontal line and the embedded line [2]. A schematic diagram of the installation chain is shown in Fig. 1.

However, compared with the suction anchor, it is still not possible to determine the exact location of the drag anchor (including embedding depth and azimuth). The study of drag anchors not only is of its trajectory but also includes the drag force at the attachment point, the drag angle and the movement direction of the anchor plate [3].

There have been many studies on the force of a drag anchor and the reverse catenary shape of the chain. Reese [4] built the equilibrium equation of the drag chain based on the limit equilibrium theory, neglecting the influences of tangential soil resistance and unit weight, in order to analyse the tension distribution on the anchor chain unit. In 1974, Gault and William [5] considered the effects of the tangential earth pressure and the weight of cable and calculated the shape and tension distribution of the whole cable. This study showed that the principal effect on the reverse catenary is the normal soil resistance and that the tension distribution of the embedded cable is mainly affected by the tangential force of soil. Additionally, the dead-weight of the cable has relatively little influence on the shape and tension distribution of the reverse catenary. To make the model more universal, Bang and Taylor [6] extended the mechanical control equations of the embedded cable to sand. The biggest difference between the mechanical governing equations of embedded cables in sandy soil and those in saturated clay is the mechanical description of soil resistance. Vivatrat et al. [7] proposed a straight rod element model with discrete zero bending stiffness, taking into account the normal earth pressure Q, the tangential earth pressure F and the weight of the cable W, and established the normal and tangential equilibrium equations. Based on the research of Vivatrat et al. [7], Dutta [8] and Degenkamp and Dutta [9] used curved bar elements instead of the straight pole elements to establish the normal and tangential equilibrium equations. In 1995, Neubecker and Randolph [10] established the equations to solve the analytical solution of the reverse catenary line and the tension distribution of the embedded line based on the mechanical differential control equation of Vivatrat et al. [7], ignoring the chain weight and

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Nomenclature

B	Width of fluke
B_s	Width of shank
D	Dive depth
d	Diameter of chain
E	Young's modulus
E_n	Effective bearing factor
L, W, and H	Length, width and depth of the soil, respectively
L_c	Total length of the chain
L_f	Length of fluke
L_s	Length of shank
L_u	Length of the discrete cylinder
N_c	Bearing capacity coefficient of chain
s_u	Soil undrained shear strength
T_a	Drag force at the shackle
t_f	Thickness of fluke
t_s	Thickness of shank
z_a	Depth of the attachment point
γ'_{anchor}	Submerged unit weight of the anchor
γ'_{soil}	Submerged unit weight of the soil
γ'_{line}	Submerged unit weight of the anchor line
θ	Angle between the chain and the horizontal plane at the depth of z
θ_a	Angle between the drag force at attachment point and horizontal plane
θ_e	Angle between the chain and the horizontal surface of the seabed
θ_s	Angle between the shank and fluke (design angle)
θ_t	Angle between drag force at the attachment point and upper surface of drag anchor
θ_y	Angle between the movement direction of the drag anchor and the upper surface of drag anchor
μ	Friction coefficient between the chain and soil
μ_c	Coulomb friction coefficient in FE model

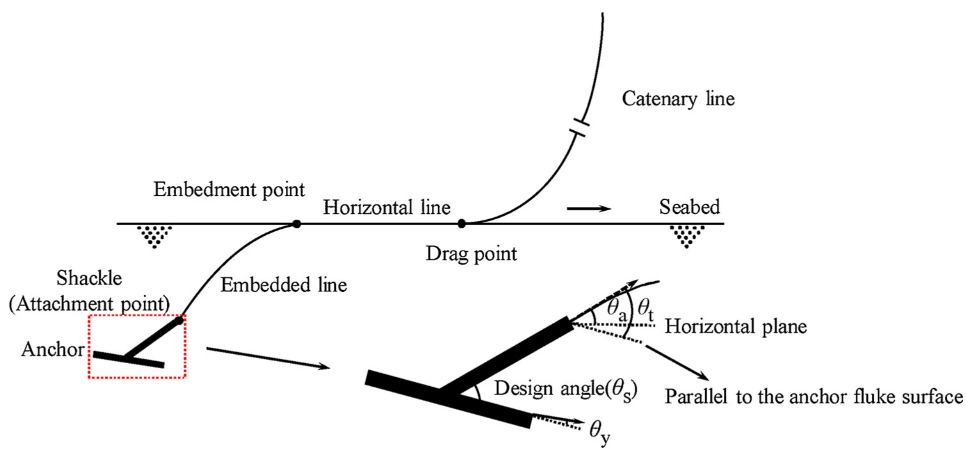

Fig. 1. Schematic diagram of the installation chain.

small angle assumption. Zhao and Liu [11] took a CEL approach in which the LINK element was used to simulate the chain in order to simulate the installation process of drag anchors based on large deformation finite element analysis.

Starting from physical reality, Liu et al. [12,13] deduced the reverse catenary equations for both saturated clay ($s_u = s_{u0} + kz$) and sand and gave an analytical solution of the shape of the reverse catenary. The concepts of embedded point, effective cable length, equivalent cable length and critical cable length were put forward, which have an effective theoretical support for the engineering application of deep-sea anchors, especially for the installation of a drag anchor. Han and Liu [14] put forward a modified method, based on physical modelling, to estimate the chain inverse catenary profile embedded in seabed sediments based on the chain equations and the chain-soil interacting envelopes. To provide a more accurate prediction of the behaviour of an embedded chain, Wang et al. [15] established a novel quasi-static model that considers the three-dimensional (3D) characteristics of soil resistance and chain elastic elongation. Based on this model, the chain profiles and tension distributions under different pretension levels are first calculated.

The study of the motion of a drag anchor in the seabed is mainly reflected in the prediction of its motion trajectory. Many researchers have predicted the trajectory of a drag anchor by the empirical method, the limit equilibrium method and the plastic limit method. An empirical formula for predicting the trajectories of drag anchor was proposed by NCEL [16] and Vryhof [17,18]. In addition, the limit equilibrium method is based on the bearing capacity theories, and the formula of friction resistance is used to calculate the soil resistance acting on the anchor. Then, the diving position of the drag anchor is derived from the position of the anchor chain on the seabed surface, the anchor chain tension and the anchor chain equation. Stewart [19], Neubecker and Randolph [20], Thorne [21], Dahlberg [22], DNV [23] and Ruinen [24] all used the limit equilibrium method to study the trajectories of drag anchors. Similarly, the plastic limit method is also applied to predict the trajectory prediction of a drag anchor. It involves obtaining the plastic yield function that represents the embedding behaviour of a drag anchor in advance by the FE method, and that yield function includes the influences of anchor translation and rotation. Bransby et al. [25] were the first to apply this method to predict the trajectory of a drag anchor. Aubeny et al. [26], Aubeny and Chi [27,28] and Wang et al. [29] also studied the trajectories of drag anchors based on plastic limit methods. Wang et al. [29] discussed the trajectory of a drag anchor in different installation methods (towing installation and coiling anchor line by a winch). The differences in the line profiles and tension distributions for these two installation methods were also analysed. Murff et al. [30] carried out a comparative study of trajectories of drag anchors. The study compared five prediction methods, in which methods 1, 2, 4 and 5 were limit equilibrium methods and method 3 was a plastic limit method. Shen et al. [31] proposed a numerical model for the dynamic response of the mooring chain, considering the dynamic interaction between the mooring chain and the clay and sand sediment, which included the monotonic motion of the fairlead and the cyclic horizontal drift and vertical heave of the floating facility.

This paper simulates the installation processes of drag anchors with