Applied Ocean Research 59 (2016) 201–215

Contents lists available at ScienceDirect

Applied Ocean Research

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

An efficient approach to incorporate anchor line effects into the coupled Eulerian–Lagrangian analysis of comprehensive anchor behaviors

Yanbing Zhao[a], Haixiao Liu[a,b,*], Peidong Li[a]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 17 January 2016
Received in revised form 9 June 2016
Accepted 9 June 2016

Keywords:
Anchor line
Drag anchor
Suction embedded plate anchor
Gravity installed anchor
Anchor behavior
Coupled Eulerian–Lagrangian
Numerical

ABSTRACT

With the application of innovative anchor concepts and advanced technologies in deepwater moorings, anchor behaviors in the seabed are becoming more complicated and significantly affected by the anchor line. Based on the coupled Eulerian–Lagrangian (CEL) method, a numerical approach incorporating anchor line effects is developed to investigate comprehensive anchor behaviors in the soil, including penetration of drag anchors, keying of suction embedded plate anchors and diving of gravity installed anchors. Compared to the method directly incorporating the anchor line into the CEL analysis, the proposed method is computationally efficient. To examine the robustness and accuracy of the proposed method, numerical probe tests and then comparative studies are carried out. It is found that the penetration (or diving) and keying behaviors of anchors can be well simulated. A parametric study is also undertaken to quantify the effects of various factors on the behavior of OMNI-Max anchors, whose mechanisms are not yet fully understood. The maximum embedment loss of OMNI-Max anchors during keying is not influenced by the initial anchor embedment depth, whereas significantly increases with increasing drag angle at the embedment point. With decreasing initial anchor embedment depth or increasing soil strength gradient, drag angle at the embedment point and diameter of the anchor line, the behavior of OMNI-Max anchors could change from diving to pullout, which is undesirable in offshore engineering practice. If the drag angle increases over a certain limit, the anchor will fail similar to a suction anchor.

1. Introduction

The move of offshore oil and gas development into deep and ultra-deep waters has resulted in a need for low cost deepwater anchors that can withstand large uplift mooring force and be easily installed to the designed penetration depth, such as suction anchors, vertically loaded plate anchors (VLAs), suction embedded plate anchors (SEPLAs) and 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 diving of OMNI-Max anchors (a new type of GIA) [1].

Anchor line is a very important component of the installation or mooring system, which connects the anchor and the anchor handling vessel (AHV) or mobile offshore drilling unit (MODU). With the moving of the AHV or MODU, the anchor presents complicated behaviors in the seabed. As illustrated in Fig. 2, the anchor line can be split into two parts, i.e., the line in the water column and the line embedded in the soil, which are called water line and embedded line, respectively. The embedded line forms a reverse catenary shape and hence a drag angle (θ_{ah}) at the shackle owing to soil resistances. The effect of the embedded line on anchor behaviors can be quantified by the drag force (T_a) and drag angle θ_{ah} at the shackle. The water line and the embedded line interact with each other at the embedment point, which can be evaluated by the drag force (T_e) and drag angle (θ_e) at the embedment point. When $\theta_e = 0°$, the bottom segment of the water line will lie on the seabed, which is common in the installation of drag anchors [2].

In the theoretical methods, including the limit equilibrium method [3–6], macroelement plasticity modelling [7–18] and kinematic model [2,19], the effect of the anchor line on anchor behaviors

---

[*] Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China.
E-mail address: liuhx@tju.edu.cn (H. Liu).

http://dx.doi.org/10.1016/j.apor.2016.06.005

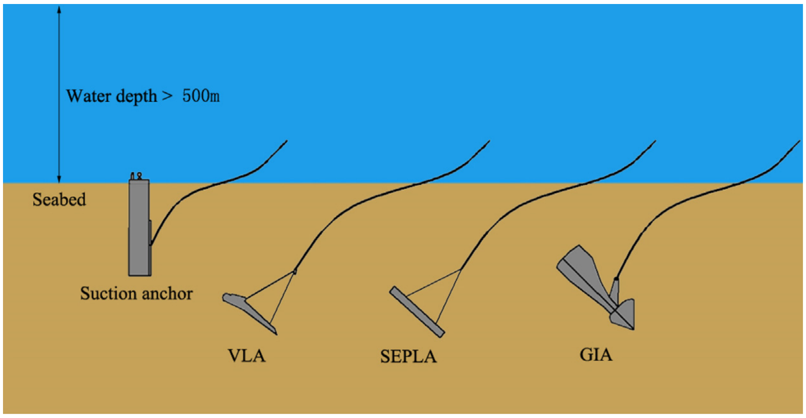

Fig. 1. Illustration of deepwater anchors.

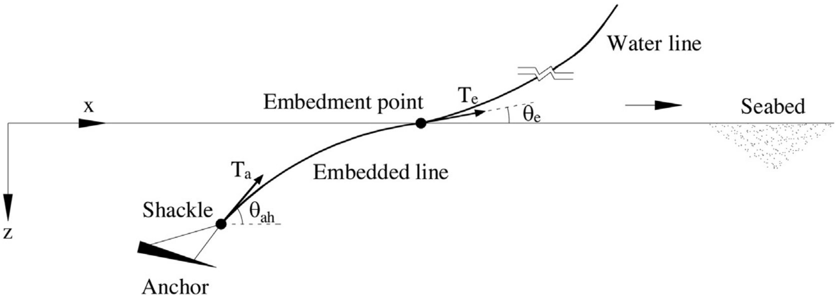

Fig. 2. Interaction between the anchor and anchor line.

was considered by two equations. One is the chain equation to describe the relationship between the drag force T_a and drag angle θ_{ah} at the shackle [3–13,15–18]; the other is the reverse catenary equation to calculate the profile of the embedded line [2,19]. The latter can be derived by integrating the former in the (x,z) coordinate system [19,20]. Based on the governing equations of the embedded anchor line, the chain equation $T_a = f(z_a, \theta_{ah}, \theta_e)$ was obtained [20], in which z_a is the embedment depth of the shackle. The procedure of limit equilibrium methods [3–6] to calculate anchor trajectories generally involves five steps: (1) from a starting point, advance the anchor along a certain direction by a vertical increment Δz, (2) calculate the new coordinates of the shackle (x_a, z_a), (3) calculate the drag force T_a through soil resistances acting on the anchor, (4) update the drag angle θ_{ah} using the chain equation $T_a = f(z_a, \theta_{ah}, \theta_e)$ and adjust the anchor orientation, and (5) advance the anchor by a further Δz, and loop to step (2) until completion of the whole anchor trajectory. In the macroelement plasticity modelling, the entire anchor and surrounding soil were considered as one element, with behavior written directly in terms of the anchors' loads and displacements [11]. With a yield surface and the chain equation, the behaviors of drag anchors [7–10,13,15], SEPLAs [11,12,14,16,17] and OMNI-Max anchors [18] were well simulated. A kinematic model for drag anchors was put forward by Liu et al. [2,19], in which a closed-form drag equation was developed and the anchor trajectory could be explicitly calculated. In the methodology by Liu et al. [2,19], the anchor line effect on anchor trajectories was considered by the reverse catenary equation $f(x_a, z_a, \theta_{ah}, \theta_e) = 0$.

Note that there is an unknown parameter θ_e in both the chain equation and the reverse catenary equation. The drag angle θ_e reflects the effect of the water line on anchor behaviors. During drag anchor installation, to achieve the best anchor performance and enhance the drag embedment efficiency, the uplift angle of the installation line and hence the drag angle θ_e should always remain zero degree [5]. Therefore, most researchers assumed $\theta_e = 0°$ in the prediction of drag anchor trajectories [2–9,19]. Due to restriction of the length of the anchor line during drag anchor installation, the value of θ_e cannot always keep zero degree [5,10,13,15]. In addition, θ_e is at a certain value and varies in the keying of SEPLAs [11,12,17] and diving of OMNI-Max anchors [18]. When the water depth is large, the value of θ_e can be approximated to a constant [11–13,17,18]. By analysis of the catenary line in the water column, Aubeny and Chi [10] and Wang et al. [15] accounted for the effect of variation in θ_e on the trajectory of drag anchors.

In the numerical analysis, the finite element (FE) method is regarded as the main tool for simulating anchor behaviors in the seabed, which always involve large deformations of the soil. The large deformation finite element (LDFE) method can deal with the convergent problem due to large mesh distortions and contact problems. The remeshing and interpolation technique with small strain (RITSS) method [21] and the coupled Eulerian–Lagrangian (CEL) approach [22] are two effective LDFE methods to analyze anchor behaviors in the soil. With the same way described in the theoretical methods, Song et al. [23] and Wang et al. [24] introduced the anchor line effect into the RITSS analysis via the chain equation to simulate the keying of SEPLAs. Force-control was used by Song et al. [23] and Wang et al. [24], in which a force increment ΔT was circularly exerted on the anchor. After each force increment ΔT, the anchor line profile or drag angle θ_{ah} was updated by the chain equation. The variation of θ_e was reflected by Song et al. [23], whereas Wang et al. [24] assumed θ_e be a constant.

As another LDFE method, the CEL approach was wildly utilized to solve geotechnical problems with large deformations [25–32]. To consider the anchor line effect on anchor behaviors, Zhao and Liu [33,34] constructed the anchor line by connecting cylindrical units with each other using connector elements in the CEL analysis. With the constructed anchor line, FE simulations were carried out to investigate comprehensive anchor behaviors in the seabed,