Ocean Engineering 88 (2014) 149–163

Contents lists available at ScienceDirect

Ocean Engineering

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

Integrated analysis of drag embedment anchor installation

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ARTICLE INFO

Article history:
Received 28 December 2012
Accepted 22 June 2014
Available online 11 July 2014

Keywords:
Drag embedment anchors
Kinematic trajectory
Embedment depth
Line tension

ABSTRACT

During installation of drag embedment anchors (DEAs), the anchor, tensioned mooring line and anchor-handling vessel interact with each other and make up an integrated system. This paper presents an integrated quasi-static model for the anchor, line and vessel for use in simulating the installation of DEAs by moving vessels or stationary vessels. The differences in the anchor's kinematic trajectory, line profiles and tension distributions for these two installation methods were analyzed. The examples indicate that there is a line length for each installation method that optimizes the installation efficiency. The effects of different types and lengths of lines, different types of soil behavior and different fluke–shank angles are also considered in the practical suggestions given for DEA installation.

1. Introduction

Vertically loaded plate anchors (VLAs), which are novel types of drag embedment anchors (DEAs), are increasingly being used in deepwater mooring systems, particularly for mobile offshore drilling units (MODU). The installation of a VLA is much the same as that of a conventional DEA. Initially, the DEA is buried at a shallow depth, and then it gradually penetrates into the soil through tensioning of the attached anchor line. This continuous tensioning is mainly performed by the anchor-handling vessel (AHV). It is well known that the anchor capacity depends on not only its final embedment depth but also its orientation. An additional angle adjuster is typically used to orient the anchor fluke of the VLA until its direction becomes perpendicular to the anchor line force, so that the anchor capacity can be fully mobilized.

A sketch of the installation system, consisting of the AHV, anchor line and anchor, is shown in Fig. 1. The anchor line is divided into three portions. The embedded portion forms an inverse catenary shape under soil resistance and its own tension. If the anchor line is sufficiently long, a portion of the line lies on the seabed between the touch-down point and the dip-down point. The third portion of the line, between the sea level and the mudline, is called the suspended line, which typically forms a catenary shape under its submerged weight.

There are two traditional methods for installing DEAs. With the first method, the AHV moves in a certain direction until the anchor achieves its target depth, while the length of the towed line is held constant. With the second method, the vessel stays in a fixed position, and the anchor line is coiled by a winch on board the vessel. These two methods may result in quite different kinematic trajectories for the anchor, although to date, no such difference has been mentioned in the literature.

There are three methods for predicting the anchor trajectory: the empirical method, the limit equilibrium method, and the plastic limit analysis method. The empirical method (API, 1991; NCEL, 1987) simply predicts the embedment depth and the capacity based on the anchor weight and soil properties. The limit equilibrium method considers the soil forces at the failure condition and presents a simplified closed-form solution that takes into account the influence of the embedded portion of the anchor line (Stewart, 1992; Neubecker and Randolph, 1995; Dahlberg, 1998; Thorne, 1998). Liu et al. (2012) proposed a novel variation of this method that predicts the embedment depth by regarding the anchor kinematic trajectory as a circular arc. A plastic limit analysis is similar to the limit equilibrium method, except that a plastic yield envelope, in terms of forces and moment, is adopted to analyze the fluke–soil interaction during embedding (O'Neill et al., 2003; Yang et al., 2008).

In the studies mentioned, the drag force provided by the AHV and the transmission provided by the anchor line are usually simplified as a drag force acting on the mudline. This drag force on the mudline is assumed to either be horizontal or form a fixed angle to the horizontal, and the influence of the suspended part is ignored. This paper presents a new quasi-static analysis model for an integrated system, as shown in Fig. 1, consisting of the anchor, the line and the handling vessel. The suspended line has been found to have obvious effects on the installation of DEAs.

2. Mathematical formulations

Aubeny and Chi (2010) presented a recursive algorithm based on the yield function proposed by Bransby and O'Neill (1999) to predict

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http://dx.doi.org/10.1016/j.oceaneng.2014.06.028
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Nomenclature

A	Cross section area of anchor line;
A_f	Fluke area;
C_n, C_τ	Drag coefficients in the normal and tangential directions in Morrison's equation;
c_1, c_2, c_3	anchor equilibrium coefficients;
d_e	Effective diameter of anchor line;
E	Elasticity modulus of anchor line;
E_n, E_τ	Normal and tangential multipliers of anchor line diameter;
F_n, F_t	Anchor line force acting on anchor eye in the directions normal and tangential to the fluke;
F_{soil}, Q_{soil}	Soil forces tangential and normal to embedded line;
H	Water depth;
k	Strength gradient of seabed soil;
L	Total length of anchor line;
L_0	Original length of anchor line;
L_f, L_s, L_j	Lengths of fluke, shank and junction plate;
M	Moment in reference to the centroid of fluke;
m, n, p, q	Load capacity interaction coefficients for fluke;
N_c	Bearing factor for anchor line;
N_e	Effective bearing factor for anchor;
N_{nmax}, N_{tmax}, N_{mmax}	Maximum values of the bearing factors under pure normal, tangential, and rotational loading;
R	Installation radius from anchor position to AHV in horizontal direction;
S_t	Sensitivity of seabed soil;
S_u	Undrained shear strength of seabed soil;
T_a, θ_a	Anchor line force at anchor eye and its angle to horizontal;
T_d, θ_d	Anchor line force at dip-down point and its angle to horizontal;
T_t, θ_t	Anchor line force at fairlead and its angle to horizontal, also drag force and angle for AHV;
t_f	Fluke thickness;
U	Water velocity;
w_w, w_s	Effective weights of the anchor line in water and seabed soil per unit length;
x,z	Horizontal and vertical coordinates;
θ	Angle of anchor line to horizontal in each segment;
$\theta_{as}=\theta_a-\theta_s$	Angle of anchor line force T_a relative to the orientation of shank;
θ_{fs}	Fluke–shank angle;
θ_s, θ_f	Angles of shank and fluke from horizontal;
ρ_w	Density of sea water.

the anchor kinematic trajectory during its installation. The embedded anchor line is described by a closed-form solution of Neubecker and Randolph (1996), and the profile of suspended line above the mudline is calculated by the classical catenary equation. These assumptions are reasonable with a small anchor line angle and a dig angle of 0°. But at the later stage of installation, the anchor line will be tautened and cannot meet the conditions. In this paper, the whole anchor line is discreted and solved in a numerical way to seek the effects of a tautened line.

The following basic assumptions are made in the mathematical formulation of this problem:

(1) The vessel, anchor line and anchor remain in the same vertical plane during the entire installation process.
(2) The travel direction of the anchor fluke in each step is parallel to the orientation of the fluke.
(3) The axial deformation of the anchor line is in accordance with Hooke's law.
(4) The anchor shank is considered sufficiently thin that no soil resistance acts on the shank.

2.1. Anchor kinematic equations

The model presented in this paper adopts an idealized anchor configuration that consists of a rectangular fluke and a cylindrical shank (Aubeny and Chi, 2010). Fig. 2(a) shows a sketch of an anchor with a fluke length L_f, a shank length L_s, a fluke–shank

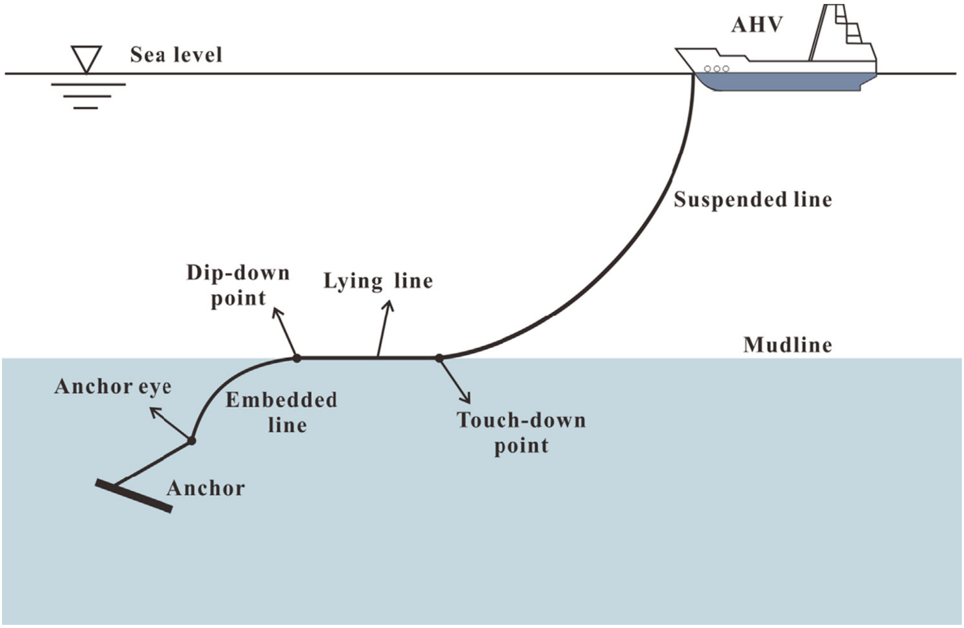

Fig. 1. Sketch of installation system.