Ocean Engineering 131 (2017) 231–243

Contents lists available at ScienceDirect

Ocean Engineering

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

Keying behavior of suction embedded plate anchors with flap in clay

Jun Liu*, Lihui Lu, Long Yu

State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Keywords:
Plate anchors
Numerical modeling
Plasticity model
Offshore foundation
SEPLAs

ABSTRACT

Suction embedded plate anchors (SEPLAs) have been applied extensively in deepwater projects due to their high efficiency and low cost. In this paper, a new plasticity model was developed to simulate the keying behavior of SEPLAs. The model was based on three groups of yield envelopes, which considered three different states between the flap and the main plate. Thus, the plasticity model can consider the flap rotation relative to the fluke. The anchor shank was also considered to investigate the three dimensional (3D) effects of the actual SEPLA shape when deriving the yield envelops. A three dimensional large deformation finite element (3D-LDFE) model with flap rotation and shank considered was also set up. Then 3D-LDFE analysis was carried out to verify the plasticity model. The results given by 3D-LDFE analyses agree well with those by plasticity analyses. The effects of the flap on the embedment loss and pullout capacity, and the effects of loading eccentricity and pullout angle on diving behavior are investigated. Optimal padeye offset and pullout angle to drive the anchor diving are proposed.

1. Introduction

Suction embedded plate anchors (SEPLAs) are anchoring systems that use a suction caisson for installation (Wilde et al., 2001). After installation, the mooring line attached to the plate anchor is then tensioned, causing the plate anchor to rotate or 'key' to an orientation that is perpendicular to the loading direction. Installation and keying process of SEPLAs are illustrated in Fig. 1.

SEPLAs are constituted by a shank, a fluke and a flap, as depicted in Fig. 1. The flap is connected with the fluke by four hinges and they constitute a locking mechanism. The flap can only rotate outward, i.e., only in the direction away from the anchor shank. The rotation angle of the flap relative to the fluke is less than a specified value, usually about 30°.

Keying behavior of SEPLAs has been investigated extensively. Early studies focused on the embedment loss during keying, by means of 1g model tests (Wilde et al., 2001), centrifuge model tests (Gaudin et al., 2006, 2010; O'Loughlin et al., 2006) and large deformation finite element analyses (LDFE) (Yu et al., 2009; Wang et al., 2013). Recently, a plasticity model based on the yield envelope under complex loadings was proposed and was used to analyze the keying behavior of a SEPLA (Yang et al., 2012; Cassidy et al., 2012). It saves much computational cost compared large deformation numerical analyses. More recently, the effect of padeye offset on the plate anchor re-embedding, namely the "diving" behavior, has attracted more attentions (Tian et al., 2013, 2014a, 2014b, 2015a, 2015b). Results indicated that the padeye offset can enhance the ability of the anchor to dive and hence the loss of the embedment can be reduced, but at the detriment of the ultimate anchor capacity factor. Moreover, the simulations become more accurate by considering more factors in detail, such as the shank, the flap, the interaction between anchor and chain, etc. These studies are summarized in Table 1.

As summarized in Table 1, there were mainly two numerical models to simulate the keying process of SEPLAs: LDFE model and plasticity model. The latter has advantages in computational costs. However, most of the existing plasticity analyses ignored the anchor shank and the flap which can rotate during keying. Thus, in this paper, a plasticity model of three dimensional plate anchors with shank and flap was proposed. The start and stop conditions for flap rotation relative to the fluke in plasticity model were also proposed. The yield envelop of the model was derived from three dimensional small strain finite element analyses of plate anchors with shank and flap. A 3D-LDFE model was also set up to simulate the keying behavior of a plate anchor with shank and flap. The results from LDFE analyses were used to validate the plasticity model. A large amount of plasticity analyses were carried out to investigate the effect of the flap, the diving behavior and the ultimate embedment depth of the plate anchor, and the effects of the padeye offset angle. The optimal offset angle at various pullout angles was suggested to offer maximum plate anchor performance.

---

* Corresponding author.
E-mail addresses: junliu@dlut.edu.cn (J. Liu), 465994808@qq.com (L. Lu), longyu@dlut.edu.cn (L. Yu).

http://dx.doi.org/10.1016/j.oceaneng.2017.01.008
Received 16 April 2016; Received in revised form 2 November 2016; Accepted 7 January 2017

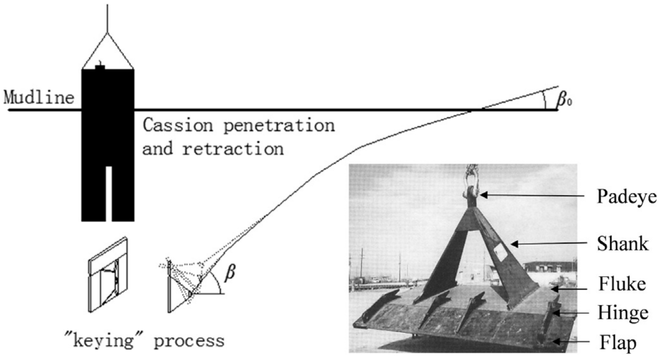

Fig. 1. Installation and keying process of the SEPLA (after Yang et al., 2012 and McCarron, 2011).

Nomenclature

A	bearing area of pullout load on the anchor
A_{fluke}	bearing area of the fluke of the anchor
A_{flap}	bearing area of the flap of the anchor
B	total width of anchor
B_{fluke}	width of the fluke
B_{flap}	width of the flap
d_{bar}	nominal chain stock diameter
Δx	cumulative displacement in horizontal
Δy	cumulative displacement in vertical
E	Young's modulus of soil
E_{n}	effective chain width multiplier
e_{n}	padeye eccentricity (normal to fluke)
e_{s}	padeye offset (parallel to fluke)
F_0	pullout load at the mudline
F_{n}	normal load
F_{s}	sliding load
F_{t}	pullout load at the padeye
$F_{\mathrm{n}}/(As_{\mathrm{u}})$	normalized load along the normal direction
$F_{\mathrm{s}}/(As_{\mathrm{u}})$	normalized load along the sliding direction
$F_{\mathrm{nmax}}/(As_{\mathrm{u}})$	normal uniaxial capacity factor
$F_{\mathrm{smax}}/(As_{\mathrm{u}})$	sliding uniaxial capacity factor
F_{nmax}, F_{smax}, M_{max}	normal, sliding and rotational uniaxial capacity of the anchor
f	yield surface function
h_{c}	initial embedment of the anchor centroid
k	gradient of soil strength
k_{t}	stiffness of tension spring
k_{c}	stiffness of compression spring
L	total length of the anchor
L_{t}	length of tension spring
L_{c}	length of compression spring
M	rotational load
$M/(ALs_{\mathrm{u}})$	normalized moment load
$M_{\mathrm{max}}/(ALs_{\mathrm{u}})$	rotational uniaxial capacity factor
m, n, p, q	exponents defining shape of three-dimensional yield surface
N_{c}	Bearing capacity factor
s_{u}	undrained shear strength of anchor reference point at current depth
s_{um}	undrained shear strength at mudline
t	thickness of the fluke and the flap
W'	submerged weight of the whole anchor
W_{fluke}'	submerged weight of fluke
W_{flap}'	submerged weight of flap
z	embedment of the anchor reference point
z_{padeye}	current vertical depth of padeye
α	rotation angle of fluke
α_{f}	rotation angle of flap
β	pullout load inclination angle at the padeye
β_0	pullout load inclination angle at the mudline
γ	anchor final travelling angle
ψ	angle between the flap and the fluke
θ	padeye offset angle
θ_1	minimum padeye offset angle for anchor to have diving trend
θ_2	maximum padeye offset angle for anchor to have diving trend
θ_{p}	padeye offset angle for anchor to have maximum diving trend
δx	displacement increment in horizontal
δy	displacement increment in vertical
δu	displacement increment in normal respect to the anchor
δv	displacement increment in sliding respect to the anchor
δn	normal displacement on the top of the flap
δd	displacement increment of the anchor in finite element analysis
Δ	net movement of padeye
υ	Poisson's ratio of soil
μ	Frictional coefficient of chain
η	Padeye offset ratio, equals to $e_{\mathrm{s}}/e_{\mathrm{n}}=\tan(\theta_{\mathrm{p}})$

2. plasticity model

2.1. Yield locus under combined loading

The concept of plasticity analysis is that the yield envelope can be used to determine the relative magnitudes of the plastic displacements. The yield envelope is the function of the load combination in normal (F_{n}), sliding (F_{s}), and moment (M), which defines the allowable load on the anchor. The yield envelope adopted is based on the formula proposed by Bransby and O'Neill (1999) and Murff (1994).

$$f=\left(\frac{|F_n|}{F_{n\,\max}}\right)^q+\left[\left(\frac{|M|}{M_{\max}}\right)^m+\left(\frac{|F_s|}{F_{s\,\max}}\right)^n\right]^{1/p}-1=0 \tag{1}$$

where F_{nmax}, M_{max} and F_{smax} define the surface size and the exponents m, n, p and q define the shape of the yield surface. Concrete calculation procedure to get parameters of the yield envelope has been introduced by O'Neill et al. (2003) and Cassidy et al. (2012).

Variables used in the subsequent analysis can be seen in Fig. 2. The normal direction is perpendicular to the plane of the anchor fluke/flap, while the sliding direction is parallel to the plane of anchor fluke/flap. The load combination is the resultant of chain load, F_{t}, and the submerged weight of the anchor in soil, W'. The pullout angle, β, at the padeye to the horizontal is greater than that at the mudline, β_0, when the mooring chain is tensioned in clay due to the drag resistance of the clay. This can be continually updated by solving the Neubecker and Randolph (1995) chain solution. The definition of the following mentioned variables are also depicted in Fig. 2. The variable δn denotes the normal displacement on the top of the flap. The angles α and α_{f} are the rotations of the fluke and the flap respectively from the initial vertical position. The angle between the flap and the fluke is ψ. The location of the chain load applied at the padeye, relative to the centroid, is defined by the eccentricity e_{n} normal to the fluke and the offset e_{s} parallel to the fluke. Prespecified values of these variables are determined based on previous researches by Cassidy et al. (2012) and Tian et al. (2014b) and listed in Table 2.