Applied Ocean Research 68 (2017) 142–153

Contents lists available at ScienceDirect

Applied Ocean Research

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

A modified method to estimate chain inverse catenary profile in clay based on chain equation and chain yield envelope

Congcong Han, Jun Liu*

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

ARTICLE INFO

Article history:
Received 12 March 2017
Received in revised form 25 August 2017
Accepted 28 August 2017
Available online 5 October 2017

Keywords:
Inverse catenary profile
Chain equation
Yield envelope
Chain-soil interaction
Anchoring systems

ABSTRACT

Offshore floating facilities are fixed by anchoring systems embedded in seabed soils through chains or ropes. The chain inverse catenary profile embedded in soils influences both the anchor failure mechanism and the anchor holding capacity. The chain mobilizes varying soil normal and tangential resistances during motion, hence it is with difficulty to depict the chain profile. The present work proposed a modified method to estimate the chain inverse catenary profile with high accuracy based on the chain equations and the chain yield envelope. A testing arrangement with three load cells and two MEMS (Micro-electromechanical systems) accelerometers included was designed in model tests. By model tests, the loading combinations of the soil tangential and normal resistances on the chain were obtained and the yield envelopes for both chain and rope were determined. In addition, supplemental model tests were performed to validate the modified method proposed in this study, and the testing results indicated that the estimated chain inverse catenary profile was in good agreement with the actual one. Moreover, the testing arrangement is beneficial in investigating the chain-soil-anchor interaction.

1. Introduction

Offshore oil and gas exploration adventures into deeper waters with harsher environments due to the depletion of oil and gas fields in shallow waters. With the water depth even deeper than 1000 m, the floating mooring system is an efficient and cost-saving alternative in contrast with the fixed system [1]. The floating facilities are fixed by anchoring foundations embedded in seabed soils through ropes or chains (Fig. 1). In catenary mooring systems, the chain that interacts with the seabed can be divided into two parts: the horizontal part lying on the seabed surface from the touch-down-point (TDP) to the dip-down-point (DDP) and the inverse catenary part embedded in seabed. In taut mooring systems, the horizontal part is not existing.

The chain-soil interaction is a valuable issue as (1) the chain capacity contribution and (2) the chain inverse catenary profile. Since the padeye position (or termed the attached point) is below the seabed level, the embedded chain offers a portion of capacity for the whole anchoring system [2–4]. Due to the chain-soil interaction, the chain embedded within seabed exhibits an inverse catenary profile thus the chain uplift angle at the padeye (β_a) is larger than the uplift angle at the mudline (β_0 shown in Fig. 2). The anchor failure mechanisms are depended on β_a [5–7]. For instance, the suction embedded plate anchor (SEPLA) and the OMNI-Max anchor exhibit diving property with β_a less than a certain critical value, and the anchors will be pulled out to the soil surface with a larger β_a. It is necessary to estimate the uplift angle at the padeye based on the chain inverse catenary profile.

The chain profile embedded within seabed is depended on the forces acting on the chain, including the chain self-weight, w, soil resistance normal to the chain, F_n, soil resistance tangential to the chain, F_t, and the pulling force, T (see from Fig. 2). As the chain self-weight is relatively small compared with the soil resistance, it usually can be ignored. The chain normal resistance (F_n) is the soil resistance perpendicular to the chain prolongation direction, and the chain tangential resistance (F_t) is the soil resistance along the chain prolongation direction. The chain mobilizes varying loading combinations of soil normal and tangential resistances during motion. When the chain moves in pure normal/tangential direction, the soil normal/tangential resistance reaches maximum. The maximum normal and tangential resistances for chains and cables/ropes in unit length can be expressed as Eqs. (1) and (2).

$$\left.\begin{aligned} F_{\text{nmax}} &= N_c s_u A_{\text{bn}} + \alpha s_u A_{\text{sn}} = \lambda_n N_c s_u d \\ F_{\text{tmax}} &= N_c s_u A_{\text{bt}} + \alpha s_u A_{\text{st}} = \lambda_t \alpha s_u d \end{aligned}\right\} \text{for chain} \qquad (1)$$

---

* Corresponding author.
E-mail address: junliu@dlut.edu.cn (J. Liu).

http://dx.doi.org/10.1016/j.apor.2017.08.016

Nomenclature

A_B	Cross sectional area of the ball penetrometer
A_{bn}	End bearing area for chain moving in normal orientation
A_{bt}	End bearing area for chain moving in tangential orientation
A_{sn}	Frictional area for chain moving in normal orientation
A_{st}	Frictional area for chain moving in tangential orientation
a_x and a_y	Acceleration component measured by MEMS accelerometer
B_A	Anchor fluke width
D_B	Diameter of the ball penetrometer
d	Chain nominal diameter
d_{bar}	Diameter of the bar from which the chain is fabricated
e_n	Padeye eccentricity
e_s	Padeye offset distance
F_1 and F_2	Loads recorded by load cell-1 and load cell-2
F_n	Soil normal resistance acting on the chain
F_{nmax}	Maximum soil normal resistance acting on the chain
F_t	Soil tangential resistance acting on the chain
F_{tmax}	Maximum soil tangential resistance acting on the chain
g	Gravity acceleration
h_A	Anchor height
N_B	End bearing capacity factor of the ball penetrometer
N_c	Chain bearing capacity factor
s_u	Soil undrained shear strength
T	Pulling force acting on the chain in the embedment depth of z
T_a	Chain uplift force at the padeye
T_0	Chain uplift force at the mudline
t_A	Anchor fluke thickness
w	Chain self-weight
x	Chain projected length in horizontal at the embedment depth of z
$x_{c,e}$ and $x_{c,a}$	Estimated and actual chain projected length in horizontal
z	Soil embedment depth
z_p	Padeye embedment depth
$z_{p,e}$ and $z_{p,a}$	Estimated and actual padeye embedment depht
α	Soil adhesion factor
β	Chain inclined angle at the embedment depth of z
β_0	Chain uplift angle at the mudline
β_a	Chain uplift angle at the padeye
δ	Included angle between F_1 and F_2
$\delta x/h_A$	Normalized padeye displacement in horizontal
$\delta z/h_A$	Normalized padeye displacement in vertical
η	Anchor rotation angle of anchor shaft to vertical orientation
θ	Anchor padeye offset angle
λ_n, λ_t	Multipliers in relation to chain geometry
μ	Chain tangential to normal resistance ratio
φ	Included angle between F_1 and T_a
ψ	Included angle between F_1 and anchor shaft
ω	Rotation angle of MEMS accelerometer

$$\left.\begin{aligned} F_{nmax} &= N_c s_u A_{bn} = \lambda_n N_c s_u d \\ F_{tmax} &= \alpha s_u A_{st} = \lambda_t \alpha s_u d \end{aligned}\right\}\text{for cable/rope} \tag{2}$$

where λ_n and λ_s are multipliers in relation to chain geometry, N_c is the end bearing capacity factor, s_u is the soil undrained shear strength, α is the soil reduced factor due to the interaction between chain and soil and d is the chain nominal diameter. For chains, d refers to the diameter of the bar (d_{bar}) from which the chain is fabricated; for cables/ropes, d is the cable/rope diameter. As the chain is fabricated link-by-link, both the end bearing resistance and frictional resistance need to be considered in F_{nmax} and F_{tmax}. A_{bn} and A_{sn} in Eq. (1) are the end bearing and frictional areas when the chain moves in the normal direction. Similarly, A_{bt} and A_{st} are the end bearing and frictional areas when the chain moves in the tangential direction.

Previous investigations associated with the chain-soil interaction are reviewed as follows. For the section of chain lying on the seabed, specifications of API-RP-2SK [8], ISO 19901-7 [9] and DNV-RP-E301 [10] specify the ranges of the coefficient of friction between chain and seabed soils. Choi et al. [11] and Frankenmolen et al. [12] performed model tests to determine the coefficient of friction between chain and sand. For the section of chain embedded within seabed, DNV-RP-E301 [10] specifies the values of λ_n, λ_s, N_c and α in Eqs. (1)–(2) for chain and rope in clayey soils. Degenkamp and Dutta [13] proposed the equations to calculate the chain normal and tangential resistances and conducted model tests to investigate the chain multipliers of λ_n and λ_s in clayey soils. Neubecker and Randolph [2] extended Degenkamp and Dutta's study and put forward the chain Eqs. (3)–(5).

$$T = T_0 e^{\mu(\beta_0-\beta)} \tag{3}$$

$$\frac{T_a}{1+\mu^2}\left[e^{\mu(\beta-\beta_0)}(\cos\beta_0+\mu\sin\beta_0)-\cos\beta-\mu\sin\beta\right] = \int_0^z F_n dz \tag{4}$$

$$x = \int_0^z \cot\beta \cdot dz \tag{5}$$

where T_a, T_0 and T are the chain pulling forces at the padeye, at the mudline and at the embedment depth of z as shown in Fig. 2, β is the chain uplift angle at the embedment depth of z, x is the chain projected length in horizontal from the DDP to the embedment depth of z, and μ is the ratio of the tangential to normal resistance acting on the chain. According to Eqs. (3)–(5), the chain inverse catenary profile and the pulling force distribution on the chain are derived. The ratio of tangential to normal resistance, μ, can be expressed as Eq. (6). The ratio of μ spans a range from 0 to ∞. It denotes that the chain moves in pure normal orientation when $\mu = 0$ and the chain moves in pure tangential orientation when $\mu = \infty$.

$$\mu = \frac{F_t}{F_n} \tag{6}$$

Model tests have been carried out to investigate the chain inverse catenary profile and the chain capacity in sand [12,14–16]. Frankenmolen et al. [12] reported that the ratio of μ ranged 0.22–0.37, indicating that μ was not a constant during the pulling procedure. Except for model tests, numerical analyses and theoretical analyses [17–20] were performed to investigate the chain-soil interaction. Furthermore, the chain-soil interaction under cyclic loading has been studied by Frankenmolen et al. [12], Rocha et al. [21] and Xiong et al. [22].

Overall, the ratio of μ is a variable as the chain motion mechanism varies during the pulling procedure. For example, when the anchor is inserted deeper into the soil, the attached chains tend to cut through the soil hence the soil normal resistance will be dominated (a reduction in μ). However, when the anchor is raised to the soil surface, the attached chains tend to slide in the soil thus the soil tangential resistance will be dominated (an increase in μ). It should