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Experimental investigates on hydrodynamic characteristics of gravity installed anchors with a booster

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ABSTRACT

The plate shaped gravity installed anchor (GIA) provides a potential alternative to deepwater mooring systems as its dynamic installation and diving behavior. However, the anchor final penetration depth in seabed soils, especially in soils with high strength gradient, is relatively shallow due to the limited impact velocity and large contact area between the anchor and the surrounding soil. An innovative booster concept is put forward in this study to increase the anchor final penetration depth by increasing the kinetic energy during free fall in water and gravitational energy during dynamic penetration within seabed. The booster is attached to the rear of the anchor during installation and can be retrieved after installation for reuse. The present study performed model tests with the aim of investigating the working efficiency of booster on the impact velocity of the GIA during free fall in the water column. A mini motion tracing device (MTD) is developed to record the anchor free fall history in water. The hydrodynamic characteristics, including the terminal velocity, drag coefficient and directional stability, for the GIA were studied. A series of experimental cases were subsequently conducted to study the effects of the adding booster on the impact velocity and directional stability of the GIA. The testing results demonstrated that both the directional stability and the release height can be improved for the GIA with a booster, thus the anchor impact velocity is increased. The anchor kinetic energy is significantly increased due to the additional mass and increased impact velocity by the booster, which ensures the anchor to be embedded deeper within seabed.

1. Introduction

Gravity installed anchors (GIAs) are raised recently to provide a cost-effective alternative to deepwater anchoring systems. The anchor is released from a predetermined height above the soil surface (i.e. H_e in Fig. 1(a)), allowing it to gain velocity during free fall in the water column before impacting into the seabed. The anchor velocity at the mudline is termed the impact velocity, v_0. Subsequently, the anchor penetrates within the seabed by its kinetic energy gained through free fall in water and the gravitational energy. A higher anchor final penetration depth (i.e. the embedment depth from anchor tip to the mudline, z_e, in Fig. 1(a)) mobilizes higher capacity as typical seabed soils are characterized by increasing soil strength with depth (Richardson et al., 2009).

Torpedo anchors and deep penetrating anchors (DPAs) are the most common GIAs, which feature an ellipsoidal or conical tip and three or four rear fins (Fig. 1(b)). The OMNI-Max anchor is another GIA design, which features three pairs of flukes and a loading arm (Fig. 1(c)). Each pair of flukes is comprised of a larger top fluke and a smaller tip one. The loading arm, which can rotate freely around the anchor shaft, is located towards the anchor tip.

Compared to torpedo anchors or DPAs, the OMNI-Max anchor is a plate shaped GIA and has large surface area (Shelton et al., 2011). The large surface area provides a large contact area between the anchor and its surrounding soil, hence the capacity efficiency is relatively high. However, the large surface area of the anchor will result in a low impact velocity and low penetration depth within the seabed. For instance, field testing results indicate that the impact velocity of the OMNI-Max anchor is usually limited to 19 m/s with a released height of 30 m (Zimmerman et al., 2009), whereas the impact velocity of DPAs could reach 24.5–27 m/s (Lieng et al., 2010). A low impact velocity and hence a low kinetic energy results in a reduction in anchor final penetration depth. Furthermore, the final penetration depth of the OMNI-Max anchor is confined due to the large contact area between the anchor and the surrounding soil during dynamic installation. Zimmerman et al. (2009)

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Nomenclature

A_F	anchor frontal area
A_{fin}	fin planform area
A_r	anchor reference area
a_z	anchor acceleration in the vertical orientation during free fall in water
C_D	anchor drag coefficient
C_{Dc}	chain drag coefficient
C_L	lift coefficient
C_N	drag coefficient in the transverse direction
D_A	ring diameter of the loading arm of the GIA
D_B	shaft diameter of booster
D_R	diameter of the symmetrical ring around the rear fins of booster
D_r	rear diameter of booster
d_{bar} and d	nominal diameter of chain and rope
F_D	anchor drag force
F_{Dc}	chain drag force
H_e	anchor release height from anchor tip to mudline
h_A	length of the GIA
h_{A1}	top fluke length of the GIA
h_{A2}	tip fluke length of the GIA
h_B	length of booster
h_m	sleeve length of booster
h_R	height of the symmetrical ring around the rear fins of booster
h_r	height of the booster rear
k	soil strength gradient, kPa/m
l	anchor characteristic length
l_{eff}	chain effective length
m	anchor mass
m^*	anchor added mass
m_c	chain mass
$m_{c,per}$	chain mass in unit length
Re	Reynolds number
s_u	soil undrained shear strength, kPa
S_z	anchor free fall distance in the vertical orientation
t_A	fluke thickness of the GIA
t_B	fin thickness of booster
t_R	thickness of the symmetrical ring around the rear fins of booster
v_T	anchor terminal velocity
v_z	anchor fall velocity in the vertical orientation
W'	anchor submerged weight
w_A	fluke width of the GIA
w_B	fin width of booster
X, Y, Z	axes in the inertial frame
X_b, Y_b, Z_b	axes in the body frame
x_{CH}	distance from anchor tip to hydrodynamic center for slender object without fins
x'_{CH}	distance from anchor tip to hydrodynamic center for slender object with fins
x_f	distance from fin center to anchor tip
z_e	anchor final penetration depth from mudline to anchor tip
δ	anchor tilt angle from anchor shaft to the vertical orientation
Λ	fin aspect ratio
θ_b	rotation angle around axis Y_b
λ	scale factor
μ	water dynamic viscosity
ρ_w	water density, kg/m^3
ϕ_b	rotation angle around axis X_b
ψ_b	rotation angle around axis Z_b

reported that the average penetration depth ratio (i.e. the ratio of anchor final penetration depth to anchor length, z_e/h_A) was 1.77 for 54 field tests in the Gulf of Mexico. In addition, the anchor final penetration depth reduces drastically in strong soils with high strength gradient. Numerical simulations indicated the anchor penetration depth ratio was 0.87–1.14 with soil strength gradient $k = 3$ kPa/m and impact velocity $v_0 = 15$–25 m/s (Kim and Hossain, 2015; Liu et al., 2016; Liu and Zhang, 2017a). Centrifuge testing results indicated the anchor penetration depth ratio was 1.14–1.46 with $k = 3.3$ kPa/m and $v_0 = 20.53$–29.39 m/s. However, for torpedo anchors and DPAs, the anchor penetration depth ratio is relatively high, and it ranged 1.5–2.9 in kaolin clay from centrifuge results (O'Loughlin et al., 2004, 2009; Richardson et al., 2009; Hossain et al., 2014) and 1.5–2.6 from field results (de Araujo et al., 2004; Lieng et al., 2010; O'Beirne et al., 2014).

Generally, the final penetration depth of a plate shaped GIA is relatively low compared to that of a torpedo shaped GIA. Therefore, this study put forward an innovative booster concept, which aims at improving the impact velocity and directional stability of the plate shaped GIA in water and increasing the anchor final penetration depth embedded within seabed. To investigate the booster working efficiency, model tests simulating the anchor free fall process in water were performed. In the model tests, a plate shaped GIA which has the profile similar to the OMNI-Max anchor was used. The effects of the booster on both the directional stability and impact velocity of the GIA were systematically studied. The testing results are beneficial in design and engineering application. Furthermore, the booster concept may provide a reference for the installation of plate anchors.

2. Booster concept

2.1. Anchor installation process with a booster

The booster concept is mainly generated from the launching of satellites into space using a rocket. The similar method has been used to install suction embedded plate anchors (SEPLAs) and dynamically embedded plate anchors (DEPLAs) with a suction caisson and a slender cylindrical shaft, respectively (Dove et al., 1998; O'Loughlin et al., 2014). The booster is designed with the aim of improving the impact velocity and directional stability in water and the final penetration depth within seabed for the plate shaped GIA. The booster is attached to the rear of the GIA during dynamic installation and can be retrieved after installation for reuse. The installation cost is increased due to the transportation and retrieve of the booster, whereas the benefit of the booster on the anchor impact velocity and thus final penetration depth in soils can outweigh the considerable increased cost.

The installation process of the GIA with a booster is depicted in Fig. 2. The dynamic installation process, including the free fall stage in water and the dynamic penetration stage in soils, is similar to the installation process of GIAs. After installation, the booster is pulled out by tensing the retrieval line at the booster rear. A shear pin is adopted to connect the cylindrical bar located at the rear of the anchor and the reserved slot at the booster tip, permitting the anchor shaft center in line with the booster shaft center. The shear pin is failure when the pullout load is in excess of its limited load, causing the booster to be pulled out and the anchor to be remained in soils.