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Penetration depth of torpedo anchor in cohesive soil by free fall

Wenkai Wang, Xuefeng Wang, Guoliang Yu *

SKLOE, CISSE, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Developing deep sea technologies, many marine novel facilities have been introduced; and mooring systems, however, have become more expensive, complex, and hard cooperative in deep-water marine industry. The torpedo anchor is regarded as a modern technology benefits from easy installation, cost efficiency, and high level of anchor force. In this study, the penetration depth of a free falling torpedo anchor into cohesive soil has been laboratory investigated. 128 Sets of tests have been conducted with nine different torpedo anchors not only in shape, but also in size. Three anchor aspect ratios and three different types of muds were tested while mud rheological properties such as the yield stress and flow curves were also measured. Finally, a formula calculating the penetration depth of the anchor, regardless of soil separation has been proposed based on energy conservation principle and experimental measurements. Results indicate that the predicted penetration depth has a good conformity with the measured penetration depths in laboratory and field tests. Static undrained shear strength values should be reduced in formula when the impact velocity exceeds a critical value. Soil separation occurs depending on the anchor nose angle and surface roughness, and also soil properties. Nevertheless, the critical impact velocity resulting into soil separation and its degree require further study in the future.

1. Introduction

Torpedo anchors or "torpedo piles" has been regarded as a new mooring type of anchor withstanding vertical loads and circumventing problems associated with other types. It provides the required dynamic penetration force, which makes it much more costly and operatively effective than others such as suction, driven, drilled, and grouted piles, in addition to drag embedment anchors (Sabetamal et al., 2013). The anchor is rocket-like in shape embedded into the seabed by free-fall from a designated height using heavy weights as the driving kinetic energy.

The structure of a typical torpedo anchor usually contains four components (Medeiros Jr., 2002; Brandão et al., 2006; Hasanloo et al., 2012) of a pad-eye connecting the first chain segment of the mooring line to the anchor; a ballasted shaft of carbon steel; four flukes, which are approximately rectangular (torpedo anchors with no flukes are also used); and a conical tip designed to promote the embedment of the anchor. The installation is quite simple, as illustrated in Kunitaki et al. (2008), without requiring drag procedures. Although the deployment of a streamlined, free-falling projectile was recommended 30 years ago to achieve the greatest possible penetration depth in the seabed (Freeman et al., 1984), a high-holding-capacity torpedo anchor was not designed until 2003 (de Araujo et al., 2004). Since then, various floating production systems have been anchored using the torpedo concept. Furthermore, Henriques Jr. et al. (2010) presented a new torpedo anchor with a total weight of 1200 kN and larger flukes to moor floating production, storage, and offloading vessels (FPSOs) in ultra-deep waters.

The holding capacity of the anchor is mainly determined by the penetration depth, which depends on the impact velocity, mass, and shape of the anchor, as well as the seabed soil properties. In order to predict the holding capacity, the penetration depth must be known whilst many related studies have been performed. The impact and travel of projectiles in granular media has intrigued engineers and scientists since the mid-eighteenth century. Over the past century, research has begun in many related areas, including the subsurface investigation of soil and rock, planetary impact, nuclear waste disposal, mining, aircraft landing, and installation of deep-sea anchors and foundations (Omidvar et al., 2014). Studies on the behavior of the penetration of projectiles, including torpedo anchors for anchoring purposes, were initiated in 1969 (Schmid, 1969; Smith, 1969; Young, 1969) and were followed by others (Migliore and Lee, 1971; True, 1976; Young, 1981; Chari et al., 1981; Beard, 1984; Levacher, 1985; Freeman and Burdett, 1986; Freeman et al., 1988; Medeiros Jr., 2002; O'Loughlin et al., 2004, 2013; Gilbert et al., 2008; Richardson 2008; Porto

* Corresponding author. Tel.: +86 13482150851.
E-mail address: yugl@sjtu.edu.cn (G. Yu).

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et al., 2009; Zimmerman et al., 2009; Jeanjean et al., 2012; Blake and O'Loughlin, 2015). The major laboratory and field tests on the penetration of projectiles or torpedo anchors in wet soft soils are summarized in Appendix A.

Much effort has also been devoted to the development of numerical models estimating the penetration depth of anchors (Raie and Tassoulas, 2009; Sabetamal et al., 2013; Luger and Harkes, 2013). As for predictive formulas for the penetration depth, Jeanjean et al. (2012) used the theoretical framework developed by True (1976) and O'Loughlin et al. (2004) to implement calculation procedures estimating the penetration depth of anchors in a Microsoft® Excel spreadsheet, solved via finite difference techniques. However, some of the numerical models have been capable to predict the depth penetration and velocity profiles reasonably well using Lagrange Deformation Finite Element (3D LDFE) analysis. COFS reported results of a torpedo anchor installing through lightly overconsolidated calcareous silt while NGI carried out the project where anchor penetrated into the seabed clay soil (Kim et al., 2014; Sturm and Andresen, 2010).

Experimental study is always required for better investigation and understanding natural behavior of phenomena in addition to validate the existing numerical models which are more efficient in terms of time and cost. Therefore, this study has tried to consider advantages of experimental investigation into penetration depth of free-falling anchor and set some goals to achieve. Objective of the study herein is to enrich the experimental database, examine the influence of torpedo anchor penetration in the saturated sedimentary bed, and propose a formula predicting the penetration depth of a torpedo anchor in a wet soft sedimentary bed. Penetration experiments were carried out in three clusters of natural muddy clay. Based on the results of the penetration experiments, a new formula for penetration depth calculation was proposed. The formula was successfully validated using data presented by former scholars, namely, data from True (1976) and Young (1981), and field data given by Freeman and Burdett (1986), Migliore and Lee (1971), and Medeiros Jr. (2002).

2. Materials and methods

2.1. Model anchors

In 2004, Petrobras developed a new idea of anchoring device known as torpedo anchor. This is a steel pile of appropriate weight and shape that is launched in a free fall procedure to be used as fix anchoring point by any type of floating unit. There were two torpedoes termed T-43 and T-98 which have been shown in Fig. 1 (de Araujo et al., 2004). The project and building design of T-98 was developed with the total mass of 98 metric tons, dimensions of 1.07 m diameter and 17 m long, and four wings with $0.9 \times 1\ m^2$ (width × length). This model has been basically considered in our present study, having dimensional scales of 1:50 to 1:180.

The model anchors were made of stainless steel in three different diameters (d) of 19, 25, and 32 mm, and three slenderness ratios (length divided by diameter; L/d) of 5, 8, and 11 for each diameter, as shown in Fig. 2. Nine different anchor models were used, as depicted in Fig. 3. The geometric parameters of these models along with some further considerations have been listed in Table 1. Each model anchor had four flukes and a conical nose with a taper angle of 30°. The flukes have been vertically connected to the anchor's body and extended into two thirds of its length (L).

2.2. Penetration bed materials

The testing soils with median particle diameter (d_{50}) of 30, 8, and 12 μm, have been collected from Shanghai Jinshan Port, Zhejiang Yueqing Port, and Jangsu Yangcheng Lake, respectively. Soil

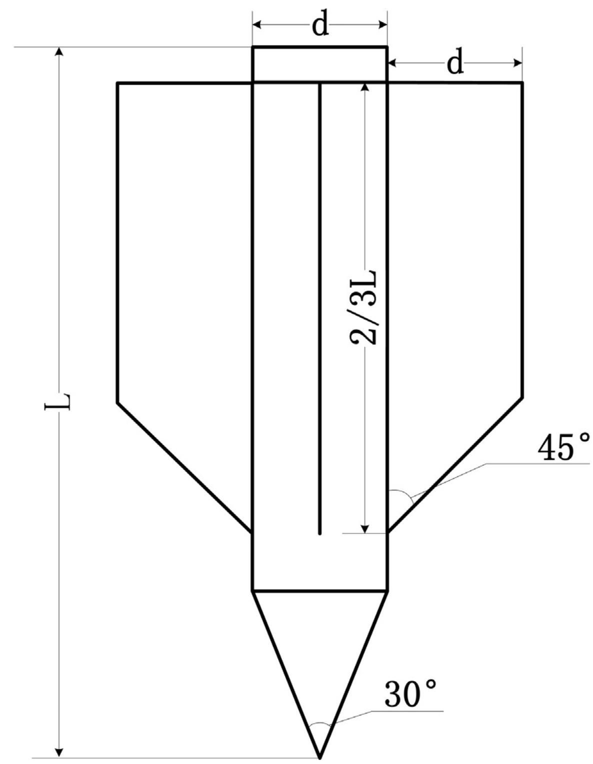

Fig. 2. Geometric parameters of modeled anchors.

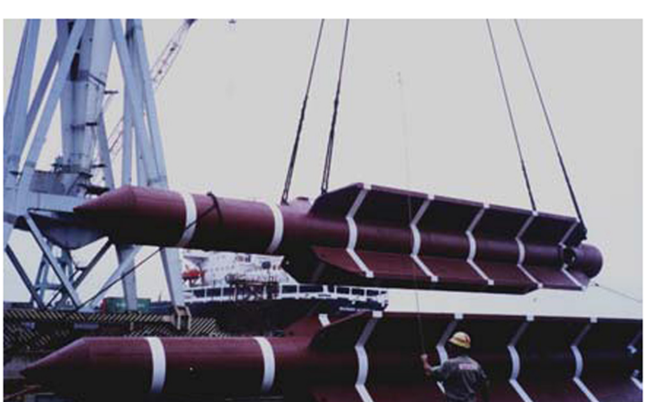

Fig. 1. Photo of the T-98 torpedoes developed by PETROBRAS in 2002.

Fig. 3. Photograph of the nine modeled anchors.