Marine Structures 49 (2016) 138–147

Contents lists available at ScienceDirect

Marine Structures

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

Simulation of torpedo anchor set-up

M.S. Raie, J.L. Tassoulas*

Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, USA

ARTICLE INFO

Article history:
Received 25 May 2015
Received in revised form 13 November 2015
Accepted 30 May 2016

Keywords:
Anchors
Set-up effect
Numerical modelling
Pore pressures
Offshore engineering

ABSTRACT

Torpedo anchors are used for station keeping of floating offshore platforms and fixing risers to the seabed in deep water. Their main benefit over other anchors is reduction in anchor installation cost via free falling in the water. A torpedo anchor has a steel cylindrical shaft with a conical tip and is ballasted in order to deepen the soil penetration and increase the anchor holding capacity. In order to address the installation effects on the soil strength and consequently the anchor pull-out capacity, first reconsolidation (set-up) of soil next to the anchor after installation is studied by a finite-element (FE) analysis of coupled deformation and fluid flow in porous media. The results of the set-up analysis indicate the rate of dissipation of excess pore-water pressure and soil-strength recovery. These are important considerations in predicting the anchor pull-out capacity at different times after installation. In the absence of a documented complete set of installation and set-up tests, the results are validated qualitatively using available albeit limited field test data.

1. Introduction

Torpedo anchors are used as foundations for mooring deep-water offshore facilities, including risers and floating structures. They are cone-tipped, cylindrical steel pipes ballasted with concrete and scrap metal and penetrate the seabed by the kinetic energy they acquire during free fall. By virtue of fast and easy installation through free falling, torpedo anchors are an economically competitive alternative for conventional offshore anchors. The design of such anchors involves estimation of the embedment depth, prediction of soil reconsolidation (set-up) after installation as well as short-term and long-term pull-out capacities. This paper presents results of coupled deformation and fluid flow finite element analyses undertaken to explore the reconsolidation (set-up) of soil in the vicinity of anchor after installation. The paper extends one that presents development of a procedure based on computational fluid dynamics (CFD) modelling for prediction of the embedment depth of torpedo anchors (Raie and Tassoulas [1]). That paper contains background information to the problem, which is not repeated here. In summary, estimation of the embedment depth is a crucial part of the torpedo-anchor design process in that the pull-out capacity is strongly dependent on the strength of the surrounding soil which typically increases with depth. The CFD model is capable of simulating the installation of the torpedo anchor from the release point in water to the final embedment depth into the soil. The CFD procedure predicts the embedment depth as well as provides estimates of the pressure and shear distributions on the soil-anchor interface. These distributions are of key significance in subsequent computations: soil reconsolidation in the vicinity of the anchor for the purpose of set-up studies, followed by pull-out capacity estimation.

* Corresponding author. The University of Texas at Austin, Department of Civil, Architectural and Environmental Engineering, 1 University Station C1748, Austin, TX 78712-0273, USA.

E-mail address: yannis@mail.utexas.edu (J.L. Tassoulas).

http://dx.doi.org/10.1016/j.marstruc.2016.05.012
0951-8339/

The designers of torpedo anchor and DPA (deep penetrating anchor, a free falling anchor similar to torpedo anchor) predict the embedment depth of anchor by estimating the soil resisting forces and calculating the anchor deceleration using Newton's Second Law (Lieng et al. [2,3]; Araujo et al. [4]). Therefore, the state of stress in the soil at the end of penetration is unavailable and the installation effect on the subsequent holding capacity of anchor is neglected. This method is also unable to predict the recovery rate of soil strength after installation. Lieng et al. [2] estimated the time required for excess pore-water pressure dissipation after installation of a DPA by means of one-dimensional (radial) consolidation analysis. They assumed the equivalent drainage passage is equal to four times the radius of the anchor. Furthermore, considering that the increase in undrained shear strength of the soil is proportional to the degree of consolidation (the degree of consolidation is equal to 1 minus the ratio of current excess pore-water pressure to the initial excess pore-water pressure), they estimated that 70% of anchor capacity is available after two weeks of installation for a clay in Voring Basin, offshore Norway. However, the assumption of one-dimensional consolidation is likely to be rather conservative especially at the tail and nose of the anchor. Also, during anchor set-up, the total stress level is not constant as in one-dimensional soil consolidation under constant load. The total normal stress decreases as the water is drained outwards from the vicinity of the anchor and the soil volume is reduced. To overcome these issues, this study estimates the state of effective stress and pore water pressure at the end of penetration and simulates soil set-up using a coupled deformation and fluid flow finite element analysis.

In the rest of paper, details of the analysis method are summarized and the results of set-up are then validated through comparison with results from available but limited field tests. It is hoped that the results of numerical analysis of torpedo anchor set-up provide better understanding of how the state of stress changes with time after installation in preparation for a study on anchor pull-out response.

2. Numerical modeling

2.1. FE modelling

A finite-element analysis program is used that models the saturated clayey soil using a mixture theory considering the coupling between soil deformation and pore-water flow (Maniar [5], Vásquez [6]). The differential equations of the porous medium are expressed in terms of solid displacements, Darcy's velocities and pore-water pressures. The solid displacements and Darcy's velocities are discretised using eight-node axisymmetric quadrilateral finite elements with reduced integration while the pore-water pressure is discretised using four-node axisymmetric quadrilateral finite elements.

2.2. Constitutive equations

The nonlinear inelastic behaviour of the clayey soil is simulated using the bounding-surface plasticity model for cohesive isotropic soils. This model provides the relationship between the effective stress increment and the strain increment and is capable of modelling the clayey soil behaviour along arbitrary stress or strain paths (Dafalias [7], Dafalias and Herrmann [8]). On the other hand, the level of loads applied on the anchor produces low stresses in comparison with the yield strength of the anchor material. So, a linear elastic model is used for the anchor.

2.3. Soil-anchor interface modelling

The soil-anchor interface is modelled using a contact algorithm based on a slide-line formulation capable of modelling large relative displacement between anchor and soil. The slide-line formulation is defined using soil slave nodes and anchor master surfaces. In the normal direction, the slave nodes are prevented from penetrating into the master surfaces by constraints applied on the solid displacements using Lagrange multipliers. In the tangential direction, the classical Coulomb friction law is specified. It is regularized to ensure continuity in the friction force. The stick and slip conditions are defined on the basis of the relative tangential velocity of the anchor with respect to the soil, respectively, smaller and greater than a (small) threshold value (see Fig. 1).

The maximum friction occurs in the slip condition and is equal to the product of the *effective* (compressive) normal force and the friction coefficient. However, in the stick condition, the friction force changes linearly from the maximum to zero, proportionally to the soil/anchor relative tangential velocity.

3. SET-UP analysis

The set-up analysis is aimed at addressing the installation effects on the holding capacity. The first step in set-up analysis is to estimate the state of effective stress and pore-water pressure at the end of installation. At completion of anchor penetration, the state of effective stress and the excess pore-water pressure in the soil are estimated from the pressure and shear distributions of the CFD analysis (Raie and Tassoulas [1]). These effective-stress and pore-water pressure distributions are imported into a finite-element analysis program capable of modelling coupled flow and deformation in porous media. The results of the set-up analysis indicate the rate of dissipation of excess pore-water pressure and soil-strength recovery. These are important considerations in predicting the anchor pull-out capacity at different times after installation.