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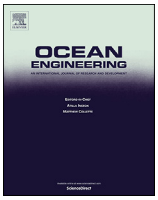

Model tests and finite element analysis for the cyclic deformation process of suction anchors in soft clays

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ABSTRACT

More attentions have been focused on the ultimate bearing capacity rather than the cyclic deformation process of suction anchors under cyclic loads in previous researches. Few researches are reported about the finite element analysis for the cyclic deformation process of suction anchors in soft clays, because lacking the suitable constitutive model that can not only describe reasonably the cyclic stress-strain responses of soft clays but also can be easily implemented into 3D nonlinear finite element analysis codes. The cyclic deformation process of suction anchor subjected to the combined static and cyclic loads are investigated by conducting model tests under 1 g condition, and the cyclic behaviors are simulated using the finite element method based on the UMAT subroutine for an elastoplastic bounding surface model proposed by the authors. The predictions show that the cyclic deformation process of suction anchor in soft clays can be simulated well by using the constitutive model and setting appropriate finite element calculation parameters. The cyclic displacement-time history and load-displacement response of the suction anchor can be predicted by the finite element analysis and the predictions are in good agreement with the test results. The failure modes of anchors can be predicted well because the predicted displacement components along vertical and horizontal directions are basically consistent with the experimental results. In addition, the cyclic bearing capacity of anchors can also be determined according to appropriate displacement failure criterion.

1. Introduction

Suction anchors subjected to inclined loads at the optimal load attachment point are important mooring foundations of deepwater floating structures (Ravichandran et al., 2015). They are usually installed in soft clays and subjected to static tensional and cyclic loads along the mooring direction in the marine environment (Anderson, 2009), so analyzing the cyclic deformation process of anchors is very important to evaluate their stability under the combination of static and cyclic loads in soft clays. If the cyclic deformation process is properly analyzed, the failure mechanisms of the suction anchors can be well understood, meanwhile, the design capabilities of foundations can be improved.

So far, some researches have been reported on the model tests of suction anchors under cyclic loads. Andresen et al. (Dyvik et al., 1993; Andersen et al., 1993) conducted field model tests in clays to study the bearing capacities of suction anchors under vertical cyclic loads. Clukey and Morrison (Clukey et al., 1993) conducted centrifuge model tests in clays under 10 g condition to study the uplift bearing capacity of suction anchors under vertical cyclic loads. El-Gharbawy and Olson (1998, 1999) conducted laboratory model tests of suction anchors under 1 g condition, and studied the effects of cyclic frequency and drainage condition etc. on the bearing capacity and failure modes of suction anchors when the top of anchor was subjected to vertical or inclined cyclic loads. Allersma et al. (2000a, 2000b). conducted centrifuge model tests of suction anchors under cyclic and long term vertical loading in clays and sands separately, and studied the effects of aspect ratio of anchor, cyclic load amplitude and loading rate etc. on the bearing capacity. Chen and Randolph (Chen and Randolph, 2007a; Chen and Randolph, 2007b; Chen et al., 2009) conducted a series of centrifuge tests of suction anchors in normally consolidated, lightly over-consolidated and sensitive clays to investigate the uplift capacity and external radial stress changes of the anchors under sustained loading and cyclic loading. Wang and Li (2015) conducted a

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series of model tests under 1 g condition to research the bearing capacity of suction anchors subjected to inclined average and cyclic loads at the optimal loading point. As we can see above, more attentions have been focused on the ultimate bearing capacity and the relevant influencing factors such as cyclic loading frequency, loading amplitude and rate etc. in previous researches. The researches about the cyclic deformation process of suction anchors subjected to inclined average and cyclic loads at the optimal loading point are relatively less.

Some researches have also been reported on the finite element analysis of suction anchors under static or cyclic loads so far. Sukumaran et al. (1999) presented a technique of finite element analysis to determine the capacity of suction anchor subjected to lateral loads in soft clays under undrained condition. The linear elasticity model with the Von Mises strength criterion was used to describe the deformation and strength of clays during finite element calculation. Cao et al. (2003) developed a finite element model for simulating the behavior of suction anchors subjected to vertical loading in normally consolidated clays. The Modified Cam-Clay model was used to describe the stress-strain behavior of the porous soil material, and the contact surface approach was used to set the interaction of soil and anchor. Maniar (2004) proposed a computational procedure based on ABAQUS software package that can simulate the installation process and the load-displacement response of anchors subjected to axial and inclined loads. Nonlinear behavior of the clayey soil was described by means of a bounding surface model. The soil domains were discretized using water-saturated porous finite-elements while the anchor was discretized using the solid finite-elements. Monajemi and Razak (2009) presented a finite element study of suction anchor subjected to the combined V-H-M loading. The effects of soil properties on the failure mechanism and ultimate capacity of the anchor were investigated by conducting the non-linear analysis using a simplified elastic-perfectly-plastic model for saturated clays. Wang et al. (2011) developed a preudo-static elastoplastic 3D finite element method based on the concept of cyclic shear strength of soil to evaluate the cyclic bearing capacities of suction anchors with the taut mooring system in soft clays. Given the above, the researches are more about the finite element analysis for behaviors of suction anchors subjected to static loads, rather than cyclic loads. Besides, the preudo-static finite element method can only determine approximately the bearing capacity of suction anchors under cyclic loads, but can not simulate the cyclic deformation process.

The finite element analysis for behaviors of suction anchors subjected to cyclic loads in soft clays are few reported. The main difficulty in this aspect is the lack of constitutive models that can not only describe reasonably the stress-strain responses of soft clays under cyclic loads, but also can be easily implemented into 3D nonlinear finite element analysis codes. An elastoplastic bounding surface model that can describe the undrained cyclic stress-strain responses of soft clays has been developed and encoded in ABAQUS through the subroutine UMAT by the authors (Cheng and Wang, 2016). The objectives of this study are to investigate the cyclic deformation process of suction anchor under cyclic loads by conducting model tests, and simulate the cyclic behaviors using the finite element method based on the UMAT subroutine.

2. Model tests of suction anchors

2.1. Model test apparatus

Model tests were conducted in the test tank with 1.5m in length, 1m in width and 1.2m in height. The soft clays for the model tests were prepared using the vacuum preloading method (Wang and Li, 2015) and clay slurry collected from Bohai Bay beach of Tianjin, China. The unit weight, the plastic limit, the liquid limit, the plastic index and the sensitivity of the clay are 17.5 kN/m^3, 27.01, 44.44, 17.43 and 4.0, respectively. The vane shear strength of the soft clay S_u varies almost linearly from 3 to 14 kPa with depth of the stratum, as shown in Fig. 1.

The model anchor was made of stainless steel. The outer wall of the anchor was covered with the metal wire mesh to increase the friction between the outer wall and the stratum, as shown in Fig. 2. The vertical bearing capacity was improved by increasing the friction between them. An air vent valve was set at the top of anchor to penetrate the anchor into the stratum by using the vacuum negative pressure device. A plexiglass window was also set at the top of anchor to observe the variation of soil plug during penetration process. Adjustable loading points were set at the outer wall of the anchor to determine the position of the optimal loading point, as shown in Fig. 2. The diameter of the model anchor is 15.2 cm. The distance from the optimal loading point to the top of anchor is about 27 cm when the angle between loading direction and horizontal direction is 30°. The parameters of the model anchor are shown in Table 1. The value of interface shear strength factor is assumed to be equal to the inverse of the sensitivity (Veritas, 2005), that is equal to 0.25, and it is approximately equal to the value of 0.26 obtained from the vertical pullout tests (Wang and Li, 2015). Because the big disturbance during installation of anchor and the high sensitivity of clay, the value of the interface shear strength factor is relative low compared with the typical value in the prototype test, however, it is closer to the real situation of the model test performed by us.

The oriented loading apparatus was developed as shown in Fig. 3. The apparatus consisted of the loading frame, the oriented plate and oriented pulleys installed on the oriented plate. The upper pulley was fixed and the mooring direction was changed by regulating the location of the lower pulley. The model tests were conducted using the multi-functional electric servo control loading device developed by authors (Wang et al., 2012). The arrangements of displacement and load sensors are also shown in Fig. 3. The LVDT 1 was used to measure the displacement of the load attachment point, and the LVDT 2 and LVDT 3 were used to measure the vertical displacement of anchor and determine the rotation of anchor. The electric displacement gauge was used to measure the lateral displacement of anchor. The load cell was used to measure the force along the loading direction. The additional weight W was applied to the top of anchor to increase the vertical ultimate uplift capacity during loading for part of tests, as shown in Fig. 4.

2.2. Model test methods

Model tests include monotonic loading tests, constant amplitude and variable amplitude cyclic loading tests. The additional vertical weight of 30 kg was applied to the top of anchor to increase the vertical ultimate uplift capacity during constant amplitude cyclic loading tests, as shown in Fig. 4. However, No additional vertical weight was applied to the top of anchor during variable amplitude cyclic loading tests. Four monotonic loading tests were firstly performed to obtain the normalized load-displacement curve and the failure criteria of displacement, and two of four tests were performed with the additional vertical weight. Then, the cyclic loading tests were performed and initial static tensional load was applied to anchors based on the normalized load-displacement curve during tests.

(1) Monotonic loading tests were conducted according to following steps:

Step1: The shear strengths of the stratum were measured by vane shear tests for each model test. The anchor was penetrated into the stratum. The test was conducted after staying one week to decrease the effect of penetration disturbance on test results (Wang and Li, 2015).

Step2: The inclined load was applied to the optimal loading point of the anchor under monotonic displacement-controlled mode with the velocity of 0.01 m/h. The additional vertical weight of 30 kg was applied to the top of anchor to increase the vertical ultimate uplift capacity during loading for two tests. The load and displacement along the loading direction at the loading point were measured as well as the vertical and lateral displacements of the anchor top using the transducers shown in Fig. 3. The failure of anchor occurred and the tests was stopped when the load grew no longer with the growth of displacement along the loading