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Model tests and analysis method on the bearing capacity for suction anchors subjected to average and cyclic loads

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ABSTRACT

The bearing capacity of suction anchors subjected to inclined average and cyclic loads at the optimal loading point was researched using 35 model tests under 1g condition. Results show that the cyclic bearing capacity of suction anchors depends on the average load and the number of load cycles to failure. The cyclic bearing capacity decreases with an increase of the number of load cycles to failure for a given average load. The cyclic bearing capacity decreased from 91% to 75% the static bearing capacity when the number of load cycles to failure increased from 100 to 1000 for the average load which was 0.5 times the static bearing capacity based on model test results. The cyclic bearing capacity increases with an increase of the average load for a given number of load cycles to failure when the average load varies from 0.5 to 0.7 times the static bearing capacity. The cyclic bearing capacity increased from 75% to 84% the static bearing capacity when the number of load cycles to failure was 1000 for vertical failure anchors based on model test results. The paper also presents a limiting equilibrium analysis method to calculate the cyclic bearing capacity of suction anchors using the cyclic shear strengths of soft clays determined by unconsolidated and undrained cyclic triaxial tests. Two procedures to determine the cyclic shear strength of the stratum around suction anchors were suggested for the method. For the first procedure, the normalized cyclic shear strength of each failure zone around anchors is determined based on the normalized average shear stress of the zone. The average shear stress of each failure zone is considered as constant and determined using static equilibrium conditions between the average load and resistances which are expressed by the average shear stress. For the second procedure, the normalized cyclic shear strength of the stratum is determined based on the normalized average shear stress of the stratum around anchors. The normalized average shear stress is determined based on the assumption which is that the ratio of the average shear stress and the cyclic shear strength is equal to the ratio of the average load and the sum of the average and cyclic loads. The relationship between the normalized cyclic shear strength of soft clays and the normalized average shear stress is determined by unconsolidated and undrained cyclic triaxial tests. The cyclic bearing capacity is determined using limiting equilibrium analyses. To check the validity of the calculation method, model test results were predicted using the method. Predicted results are generally less than model test results and most of relative errors between predicted and test results are less than 10%, which show that the method can be used to determine the cyclic bearing capacity of suction anchors in soft clays.

1. Introduction

The suction anchor subjected to inclined loads at the optimal loading point is an important mooring foundation of deepwater floating structures. Because suction anchors are usually installed in soft clays and subjected to static tensional and cyclic loads from the environmental condition along the mooring direction in the deepwater environment, the cyclic bearing capacity is an essential part of the design of suction anchors in soft clays (Andersen et al., 2005; Andersen, 2009). The static tensional load is also called the average load relative to the cyclic load.

So far, some researches are reported on the bearing capacity of suction anchors in clays under cyclic loads. Andersen et al. (1993) researched the bearing capacity of suction anchors subjected to vertical cyclic loads at the anchor top in the over-consolidated clay

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using model tests under the 1*g* condition. Results showed that the cyclic bearing capacity was 66–82% the static bearing capacity. Clukey et al. (1995) researched the bearing capacity of suction anchors subjected to vertical cyclic loads at the anchor top in the normally consolidated clay using centrifuge model tests. Results showed that the cyclic bearing capacity was 61–89% the static bearing capacity. Gharbawy and Olson (1999) researched the bearing capacity of suction anchors subjected to inclined cyclic loads at the anchor top in the soft clay using model tests under the 1*g* condition. Results showed that the cyclic bearing capacity was 78–90% the static bearing capacity. Randolph and House (2002) also researched the bearing capacity of suction anchors subjected to vertical cyclic loads at the anchor top using centrifuge model tests. Results showed that the cyclic bearing capacity was about 84% the static bearing capacity. Chen and Randolph (2007) conducted a series of centrifuge tests on instrumented model suction anchors in normally consolidated clays to investigate the uplift capacity for sealed caissons subjected to sustained loading and cyclic loading. Test results showed that the uplift capacity of suction anchors was found to be 72–86% the monotonic capacity under cyclic loading. However, model test results are few reported on the bearing capacity of suction anchors subjected to inclined average and cyclic loads at the optimal loading point.

Methods to calculate the bearing capacity of suction anchors subjected to average and cyclic loads at the optimal loading point are also few reported. Andersen and Lauritzen (1988) developed a limiting equilibrium method to analyze the bearing capacity of offshore gravity platform foundations subjected to average and cyclic loads and showed the validity of the method using model tests under 1*g* condition and field tests (Andersen et al., 1993). Andersen and Jostad (1999) ever suggested that the cyclic bearing capacity of suction anchors was determined by the method. But detailed calculating steps were not reported. For the method, the key step is to determine the cyclic shear strength based on the average shear stress in the soil prior to cyclic loads (Andersen, 2009; Andresen, Jostad et al., 2011). DET NORSKE VERITAS (DNV) (2005) suggested a procedure to determine the cyclic bearing capacity of suction anchors using the method. For the procedure, the cyclic shear strength is determined based on the assumption that the ratio of the average shear stress and the cyclic shear stress is equal to the ratio of the average load and the cyclic load. The validity of the assumption should be further verified by tests.

The paper researches the bearing capacity of suction anchors subjected to inclined average and cyclic loads at the optimal loading point in soft clays using model tests under 1g condition and presents a method to calculate the cyclic bearing capacity of suction anchors using the cyclic shear strength determined by unconsolidated and undrained cyclic triaxial tests. The general validity of the method is verified by comparing model predictions with test results.

2. Cyclic bearing capacity of suction anchors

2.1. Model test apparatus

Model tests were conducted in a tank which was 1.2 m in length, 1.0 m in width and 1.2 m in height. The test soft clay was taken from Bohai Bay beach of Tianjin, China. The plastic limit, the liquid limit and the plastic index of the clay are 27.01, 44.44 and 17.43, respectively. The model test stratum was prepared using the vacuum preloading method on the bottom (Wang et al., 2012a,b). The height, the average water content and the unit weight of the stratum are 0.9 m, 43% and 17.9 kN/m^3 respectively after preloading. Vane shear tests were conducted at different locations of the stratum and results showed that the undrained shear strength of the stratum was about 6–8 kPa along the depth.

An apparatus was developed to conduct model tests of suction anchors subjected to inclined average and cyclic loads at the optimal loading point, as shown in Fig. 1. The loading device in Fig. 1 is the multifunctional electric servo-controlled loading device developed by Wang et al. (2012a). The inclined load at the loading point of anchors was applied using a cable which was connected with the loading device using pulleys. The loading direction was changed by adjusting the position of the pulley 1 on the oriented plate. Measuring transducers were also shown in Fig. 1. The load cell was used to measure the force along the loading direction. The LVDT 3 was used to measure the displacement along the loading direction at the loading point. The LVDT 4 and the LVDT 5 were used to measure the vertical displacements of the anchor and determine the rotation of the anchor in the vertical plane. The displacement gauge 6 was used to measure the lateral displacement of the anchor. Because the total stress method was used to predict model test results in the paper, pore water pressures in the stratum were not measured for all model tests.

Stainless steel model anchors were used to conduct model tests, as shown in Fig. 2. Parameters of anchors are shown in Table 1. The frictional factor in Table 1 is the roughness factor between the outside wall and the stratum, which was determined by tests (Liu, 2012). Outside walls of anchors 2, 4 and 5 were applied the steel wire mesh to increase the frictional resistance of outer walls, as shown in Fig. 2.

2.2. Model test

Model tests include monotonic displacement-controlled tests and cyclic load-controlled tests. Monotonic displacement-controlled model tests were conducted according to following steps:

The shear strengths of the stratum were measured by vane shear tests before each model test.

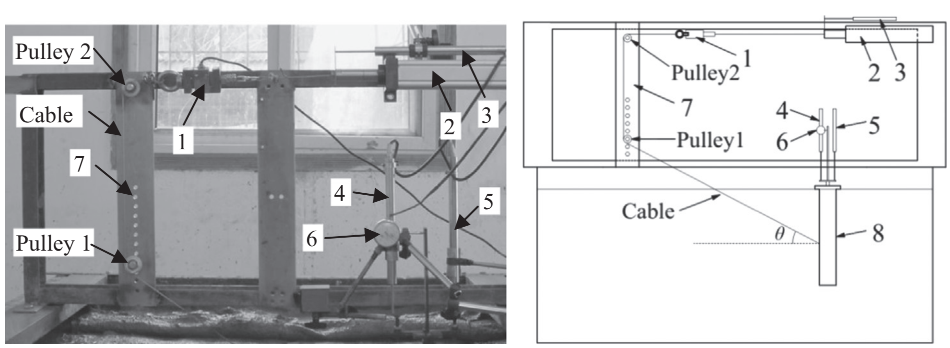

Fig. 1. Model test apparatus and measuring transducers. (1) Load cell, (2) loading device, (3)–(5) LVDT, (6) displacement gauge, (7) oriented plate, (8) model anchor.