Centrifugal Model Behavior of Laterally Loaded Suction Pile in Sand

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Abstract

A series of centrifugal tests were conducted to evaluate the maximum horizontal pullout capacity of a suction pile embedded in sand by varying the diameter and the length of the pile. The loading point was located at 75% of the pile length from the top, and the results were compared with the prediction equations of suction piles. As a result, it is found that the horizontal pullout capacity of a suction pile is proportional to its diameter and the square of length. The equation derived from Rankine's passive earth pressure equation predicts the test results very well. When pulling out the test pile from the left the test pile was apt to rotate clockwise, and its rotational point at the maximum pullout capacity was found to be in the upper part of the pile. In addition, on the basis of the center of the suction pile, the vertical displacements for all the cases appeared to develop toward the ground surface.

Keywords: suction pile, horizontal pullout loading capacity, centrifugal test, sand, rotational point, displacement

1. Introduction

In abroad, suction pile is one of the foundations used in the sea for tension leg platforms and storage facilities. The US Navy proposed suction piles for the purpose of Mobile Offshore Base mooring (Bang et al., 2000). Recently, it has been used for a Met Mast of a wind power plant at sea (LeBlanc et al., 2009). In Korea, suction piles have been used as the foundation of a 50m long breakwater (Bang et al., 2006). In addition, a suction anchor has been used to moor a floating sea wall (Kwag et al., 2008). Suction piles have been used not only for foundations but also for mooring systems of floating structures in the sea (Cho et al., 2008).

In particular, when used for a mooring system by installing padeyes either on the top or the side wall, the suction pile can develop remarkable pullout resistance, since the suction pile and the soil inside it behave simultaneously. Although a few researchers have conducted experiments regarding this phenomenon (Allersma et al., 1999; Hogervorst, 1980; Keaveny et al., 1994; Kirstein et al., 1999; Larsen, 1989), no systematical experiment, such as a full lateral pullout test in the horizontal direction by installing padeyes from the top to the bottom of a suction pile, has been conducted. Kim and Jang (2011) conducted a series of experiments, in which pullout capacities with respect to loading points and inclinations were investigated. They found that the maximum pullout capacity is developed when the loading point is located at 75% of the pile length from the top.

In this study, new experiments were carried out to figure out the pullout capacity variations with respect to diameter, as well as the length of the suction pile. In the test, the inclination and loading point were set to be 0° and 75% of the pile length from the top. In the model test, a matrix of experiments with three different diameters and three different lengths was prepared. In addition, a couple of tests were carried out to verify the similarity on g level. Throughout the tests, the maximum pullout resistance as well as the rotation angle and the displacement of the suction pile at the maximum pullout resistance were analyzed. The horizontal and vertical displacements were analyzed on the basis of the overall shape of the suction pile. Finally, a new equation for lateral pile loading equation was proposed and compared with the existing equations.

2. Prediction Models for Ultimate Lateral Pullout Capacity of a Suction Pile

In general, the ultimate lateral bearing capacity of a pile is evaluated assuming that the head of the pile is exposed above ground, and that lateral force is acting on it. In the evaluation, two conditions are considered. One is that the rotation point is taken into account, and the other is that it is not. The rotation point is assumed to exist within from the ground surface to the bottom of the pile. The ultimate lateral bearing capacity is estimated by determining the unit lateral bearing capacity.

When pushing out the embedded pile in the horizontal direction, the deformation appears to be shown in Fig. 1(a). Broms (1964) assumed that a pile has a triangular type of unit
horizontal bearing capacity when subjected to a horizontal force as shown in Fig. 1(b). Wang and Reese (FHWA, 1999) proposed a wedge shape of the ground resistance range as shown in Fig. 1(c). The wedge shape can be defined in terms of the angles between the pile and the wedge, \( \beta \), and the opening of the apex of the wedge, \( \alpha \). These angles are a function of internal frictional angle. They tried to obtain the lateral earth pressure by either assumption or experiment and to estimate the ultimate resistance. The equation proposed by Broms (1964) and the one by Wang and Reese (FHWA, 1999) based on wedge failure concept do not take into account the rotation point.

In contrast, Petrasovits and Award (1972), and Prasad and Chari (1999) carried out researches considering the rotation point. Petrasovits and Award (1972) found out the rotation point inside a pile by means of trial and error method. By taking a moment on that rotation point, the ultimate horizontal bearing capacity was estimated. Prasad and Chari (1999) conducted an experimental approach to evaluate the unit horizontal bearing capacity was estimated. Prasad and Chari (1999) carried out researches considering the rotation point.

The ultimate lateral bearing capacity of a pile, \( p_H \) based on the wedge failure concept by Wang and Reese (FHWA, 1999) is as follows:

\[
p_H = \frac{2}{3}K_p\sigma LD
\]  

The equation proposed by API RP-2A (2000) is as follows:

\[
P_H = \frac{1}{2}(K_p\gamma' + \gamma_o)DL^2
\]  

According to Eq. (7), lateral pullout resistance is proportional to the diameter and the square of the pile length.

3. Experiment using Centrifuge Model

3.1 Centrifuge Equipment

The centrifuge used in this test was, a C65-20, made by Actidyn, France (Fig. 2). It has 3m of arm and can accelerate up to 200g levels (Park et al., 1998). As a beam type of centrifuge, it has a basket at the end of the arm, and a counter weight at the opposite side to balance a center of weight. This machine can accommodate a payload of up to 12 kN at the 100 g level, which means 5.5 kN at the 200 g level (Fig. 3).

The container used in this experiment is made of steel, with dimensions of 80 cm in length, 50 cm in height and 20 cm in width. In addition, the front of the container is plexiglass 40 mm thick so as to observe the inside. The pullout resistance is measured by load cell, by pulling the wire connected to a suction pile through a pulley, which is installed inside the wall of the