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Pullout resistance of group suction anchors in parallel array installed in silty sand subjected to horizontal loading – Centrifuge and numerical modeling

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ABSTRACT

This study investigates the performance of group suction anchors installed in silty sand and subjected to horizontal pullout loading. The group anchors in this study consist of two or three unit suction anchors rigidly connected to each other in parallel array to improve the pullout resistance. The performance of these group anchors was studied extensively using centrifuge model tests and numerical simulations. The pullout resistances of the group anchors were compared with that of a single anchor. To quantify the improvement, the efficiency of a group anchor was defined as the ratio of the pullout resistance of a group anchor to that of a single anchor multiplied by the number of the unit anchors, and the improvements are discussed. Additional parametric studies were performed using numerical models to study the effect of the physical conditions of the group anchor. The parameters include the L/D ratio of a unit suction anchor, and the spacing between unit suction anchors.

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1. Introduction

Suction anchors (or bucket foundations) are a type of anchor system used in offshore installations that consist of a top plate and peripheral skirt (in the shape of a pipe). The skirt confines a plug of soil and transmits the mooring loads below the mudline to deeper, and often stronger, soil. This setup enhances the pullout resistance. The suction anchor is initially installed via self-weight or a jacking in a process. In the latter process, the difference between the hydrostatic water pressure outside the cylinder and the reduced water pressure inside (created by pumping water from the inside) provides a differential pressure or suction that acts as a penetration force (referred to as suction-assisted installation).

Suction anchors have been widely used in the oil and gas industry to secure various floating offshore platforms and support subsea structures, such as pipeline manifolds (Andersen and Jostad, 1999; Tjelta, 2001; Randolph and House, 2002; Sparrevik, 2002; Aubeny and Murff, 2003; Jeanjean et al. 2006). Currently, offshore floating structures require greater anchoring capacity because they have become larger to support the development of offshore infrastructures, e.g., large floating energy complexes, floating liquefied natural gas (LNG) storage, floating islands, and floating tunnels. Thus, there is a need for the development of high-capacity anchor systems. Theoretically, the suction anchor does not suffer from any limitations in the design of large-size suction anchors that provide a high pullout capacity. However, large single suction anchors are difficult to implement due to the economics of manufacturing, installation, and supplementation (chains). Thus, this study introduces a group configuration of small suction anchors that consists of two or three single suction anchors rigidly connected to each other in a line to improve the pullout resistance.

The concept of multiple buckets configured in a group has been used in several fields, i.e., the Snorre TLP (Tension Leg Platform) in the North Sea (Andersen and Jostad, 1999), the Bualuang field in the Gulf of Thailand, and the Ceiba field in the Gulf of Guinea (SPT offshore, 2013). The subsea soils of these fields consist primarily of clay. Dyvik et al. (1993) and Andersen et al. (1993) reported results from large-scale model tests on a clustered anchor with four buckets installed in clay and subjected to operational static and cyclic inclined loading. A few studies have investigated the holding capacity of suction anchors installed in sand, as presented by Cho and Bang (2002) and Bang et al. (2011). Kim et al. (2013a) and Choo et al. (2014) studied a clustered bucket arrangement for an offshore wind tower in which small buckets were applied in a group to support the tower. Because investigations of group suction anchors are still rather sparse, their behavior is not well understood, especially when installed in sandy deposits.

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This study aims to investigate the response of group suction anchors in parallel array installed in silty sand and subjected to horizontal pullout loading. First, the improvement of the group configuration compared with a single anchor was studied by defining the efficiency of a group anchor, η, as the ratio of the pullout resistance of a group anchor to that of a single anchor multiplied by the number of unit anchors. This efficiency can be used to estimate the capacity of a group anchor based on that of a single anchor. Thus, an extensive investigation was conducted on the performance of group anchors using centrifuge model tests and numerical simulations. The aim of this part of the investigation was to obtain insight into the behavior of a group suction anchor by quantifying the corresponding improvements in geotechnical performance and highlighting its applicability and efficiency. Second, additional parametric numerical studies were conducted to investigate the effect of the configuration and conditions on the efficiency and performance of the group anchors. The parameters include the L/D ratio of a unit suction anchor, the pad-eye location, and the spacing between unit suction anchors.

2. Centrifuge model test

2.1. Suction anchor model

The group suction anchors in this study consist of two or three unit suction anchors that are rigidly connected in parallel array. Two types of group anchors were prepared, i.e., double and triple anchors. A double anchor consists of two rigidly connected unit anchors, and a triple anchor consists of three rigidly connected unit anchors, as shown in Fig. 1.

The single suction anchor in Fig. 1a was fabricated from a steel material with an outer diameter of $D_{s,m}=50$ mm, a skirt length of $L_m=100$ mm and a skirt thickness of $t_{s,m}=1.5$ mm (the dimensions are on the model scale). The widths of the double and triple anchors on the model scale were 100 mm ($W_{d,m}=2\times D_{s,m}$) and 150 mm ($W_{t,m}=3\times D_{s,m}$), respectively.

The centrifuge model tests were conducted using a beam centrifuge located at KAIST in Daejeon, Korea (Kim et al. 2013b). The centrifuge tests were undertaken at a centrifugal acceleration of 70 G; therefore, all prototype dimensions of the anchors are equivalent to 70 times the model dimensions. The prototype diameter (D_s), skirt length (L), and skirt thickness (t_s) of the single suction anchor are 3.5 m, 7 m, and 0.105 m, respectively. In addition, the prototype widths of the double (W_d) and triple anchors (W_t) are 7 and 10.5 m, respectively.

Each single anchor in the group anchor is welded to the other anchors, and four additional reinforcing bars are welded on the front and rear sides of the group anchors. The loading point (which denotes the pad-eye) is located at 2/3 of the length from the top-lid, which is referred to as *the optimal loading point* and results in a minimum rotational movement of the anchor. The skirts of all of the suction anchor models have four circular grooves, and total pressure transducers are attached to the front (loading-ward side) of these grooves. The total pressure transducers were located at depths of 0.7 m (0.1L), 2.1 m (0.3L), 3.5 m (0.5L), and 5.25 m (0.75L) (prototype scale) from the top-lid in the case of the single anchor and at depths of 1.05 m (0.15L), 2.45 m (0.35L), 3.85 m (0.55L), and 5.95 m (0.85L) (prototype scale) from the top in the cases of the double and triple anchors.

2.2. Soil sample preparation

Silty sand is a common seabed soil on the western coast of the Korean peninsula and in the Yellow Sea between China and Korea. The particle size distributions of the samples collected from four typical sites along the western coast in Korea are compared in Fig. 2 (Choo et al. 2012; Kim et al. 2013a). The particle size distributions of these samples were analyzed using sieve analysis as well as hydrometer and laser analysis and found to be comparable. All of the samples were classified as SM (silty sand) according to the Unified Soil Classification System (USCS). This sand material is primarily composed of silicate mineral. The basic properties of these samples are provided in Table 1. The soil sample for the centrifuge models was collected at the Saemangeum site (Site 4 in Fig. 2).

The seabed soil specimen was prepared in a cylindrical container. The soil container is 900 mm in diameter and 700 mm in depth (internal dimensions), representing a prototype seabed of up to 63 m in diameter by 49 m in depth at a 70 G centrifuge acceleration. The soil specimens in the container were prepared in a total of nine layers. First, a batch of soil for a given layer was weighed, and its water content was controlled. Next, the soil was poured into the container. Each layer was compacted by dropping a circular steel plate from a constant height of 500 mm for a constant number of repetitions and by subsequent flattening with a static pressure of approximately 800 kPa. Thus, each layer was controlled to a desired unit weight equivalent to 70% relative density. The total depth of the soil specimens was 450 mm.

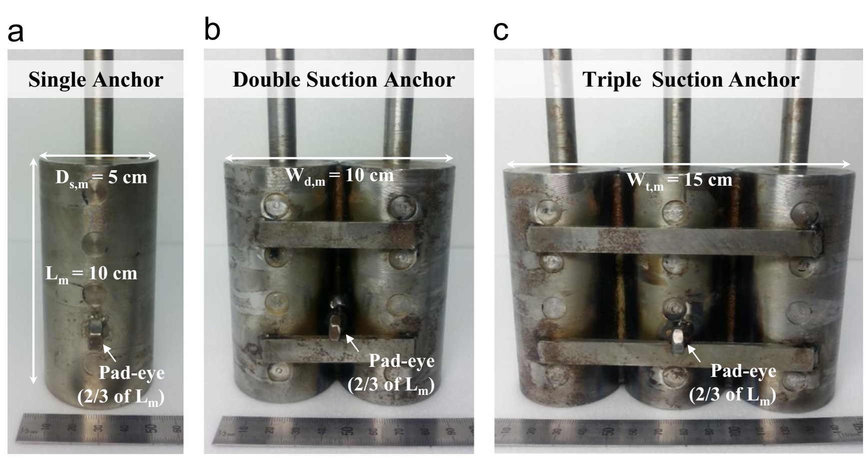

Fig. 1. Suction anchor models: (a) single suction anchor, (b) double suction anchor, and (c) triple suction anchor.

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