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APOR-1390; No. of Pages 11
ARTICLE IN PRESS
Applied Ocean Research xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Applied Ocean Research
journal homepage: www.elsevier.com/locate/apor

Experimental investigation of the vertical pullout cyclic response of bucket foundations in sand

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A R T I C L E I N F O

Article history:
Received 25 September 2016
Received in revised form 22 May 2017
Accepted 26 June 2017
Available online xxx

Keywords:
Bucket foundation
Accumulated displacement
Unloading stiffness
Sand
Cyclic vertical pullout load
1 g model tests

A B S T R A C T

A series of 1 g model tests was conducted to investigate the accumulated vertical pullout displacement and unloading stiffness of bucket foundations embedded in dry and saturated sands. The foundations were subjected to vertical pullout cyclic loading with different load amplitudes. Cyclic load was applied up to 10^4 cycles. Test results showed that the accumulated vertical pullout displacement increased with the increase in the number of load cycles and cyclic load amplitudes. The unloading stiffness of the bucket foundations decreased with the increase in load amplitude and number of cycles. Empirical equations were proposed based on the test results to evaluate the accumulated vertical pullout displacement and unloading stiffness of the bucket foundations in saturated sand. These equations can be used for the preliminary design of single or tripod bucket foundations.

1. Introduction

Offshore wind turbines are constructed as renewable energy sources worldwide (e.g., Europe and North America). An offshore wind turbine includes a tall tower with a turbine that produces high overturning moment at the tower base due to wind and wave forces. The tower is supported by several types of foundations, such as gravity base, gravity base with a skirt, jacket pile, and monopile. Suction bucket foundations are competitive foundation types which supports offshore wind turbines. A bucket foundation consists of a circular surface foundation with a thin skirt around its circumference. The foundation is installed in the seabed by using its self-weight and suction force to confine the soil within the foundation.

Offshore wind turbines with low power rates are installed at shallow water depths. However, offshore wind turbines with large power rates should be installed at deep water depth, in which they are subjected to strong horizontal loads and overturning moments. Tripod bucket foundations could support offshore wind turbines at deep water depth. Tripod bucket foundations combine three single bucket foundations in a triangular shape. The basic definition of the tripod bucket foundation is shown in Fig. 1.

Previous investigations indicated that offshore wind turbines exhibit design issues, such as the accumulated displacement and unloading stiffness of the foundations under cyclic loading [1–3]. The accumulated displacement or rotation of bucket foundations increases with the increase in the number of load cycles.

Byrne [4] performed static and cyclic vertical pullout load tests on a suction bucket embedded in sand. Sand was saturated with silicon oil. The cyclic load test was limited to approximately 100 load cycles under vertical cyclic load. Similar to the test on a bucket foundation under cyclic horizontal load, the accumulated vertical displacement increases with the increase in the number of load cycles. The static vertical pullout tests were performed with displacement control at different vertical pullout velocities (from about 0.001 mm/s to 0.5 mm/s). The results showed that failure vertical pullout load is relatively independent of vertical pullout velocity. Although Byrne [4] performed the test extensively, the limitation of 100 load cycles performed might not fully represent the general behavior of bucket foundations under cyclic vertical pullout loads.

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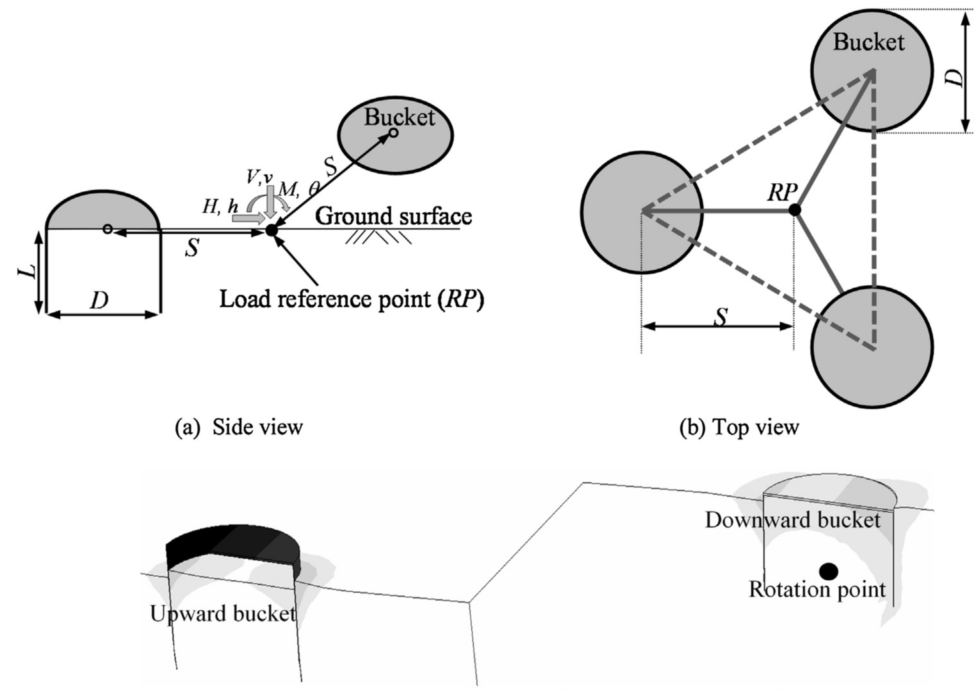
http://dx.doi.org/10.1016/j.apor.2017.06.006

Please cite this article in press as: L.C. Hung, et al., Experimental investigation of the vertical pullout cyclic response of bucket foundations in sand, Applied Ocean Research (2017), http://dx.doi.org/10.1016/j.apor.2017.06.006



(a) Side view (b) Top view

(c) Upward and downward buckets in a tripod foundation

Fig. 1. Geometry of the tripod bucket foundation and the load and displacement conventions.

Kelly et al. [5] and Kakasoltani et al. [6] discovered that the static vertical pullout load-displacement of suction bucket foundations in sand exhibits softening behavior, and the failure tension load is reached at a small displacement. Houlsby et al. [7,8] presented a simple analytical approach to determine the tensile bearing capacity of suction caissons under monotonic loading in sand. They considered the bucket foundations under various conditions, including drained and partially drained, as well as the effects of displacement rate.

Thieken et al. [20] performed numerical analyses to investigate the behavior of suction buckets under static vertical pullout loads. Vertical pullout capacity was found to be influenced by different factors, such as loading rate, sand permeability, and bucket dimension. A large heave of the bucket is necessary to mobilize suction pressure in the foundation.

Other studies have reported that the stability of tripod bucket foundations is mainly governed by the pullout displacement of the upward bucket, with the rotation center of the tripod located in the downward bucket, as shown in Fig. 1(c) [9–11].

These discussions reveal the importance of understanding of the accumulated displacement and unloading stiffness of the upward bucket of a tripod bucket foundation under cyclic loading. The behavior of a tripod bucket foundation can be investigated using a single bucket foundation under cyclic vertical loads because the upward single bucket governs the stability of a tripod bucket foundation. However, no study has experimentally investigated the accumulated vertical pullout displacement of a bucket foundation in sand under a large number of load cycles. Therefore, this study investigated the accumulated pullout displacements and unloading stiffness of single bucket foundations in dry and saturated sands under fully drained and partially drained conditions. A series of 1 *g* experimental tests was conducted on two model bucket foundations with embedment ratios of $L/D = 0.5$ and 1, where D is the foundation diameter and L is the skirt length. Up to 10^4 cyclic vertical load cycles (N) were applied at varying load amplitudes. The obtained results are applicable to the preliminary design of tripod bucket foundations for offshore wind turbines.

2. Model tests

2.1. Testing equipment

Fig. 2 shows a schematic of the test equipment used in this study. A loading equipment, which is similar to that presented by Leblanc et al. [12] was designed and manufactured. This equipment comprises four pulleys, two weight blocks (m_1, m_2), two steel loading wires with a diameter of 1 mm, and a load lever attached to a load driving motor that was connected to a steel frame. The steel frame can be rotated around a rotational pivot during loading. The driving motor could stably produce loading frequencies from 0.01 Hz to 1 Hz.

A load cell was used to monitor the vertical pullout load. The load cell was connected to the foundation by a long steel loading wire through a pulley system. The measurement error in the load cell is expected. Therefore, the load cell was calibrated by fixing one end of the steel wire in the initial stage of the test program. The calibration conditions, such as load cell position and wire length, was set to be identical for all tests. Two linear variable displacement transducers (LVDTs) were used to measure the vertical displacement of the bucket foundation during loading. A pore water pressure (PWP) transducer was placed inside the bucket lid to measure the suction pressure in the bucket during cyclic loading. Load, displacement, and pore water pressure were recorded using the NI 9235 data logger and LabVIEW (version 2012) produced by the National Instrument in the USA.

The working mechanism of the test equipment can be briefly described as follows. Weight m_2 in the beginning of a test was equal to the total weight of the driving motor, load lever, steel frame, and weight m_1. The steel frame with the driving motor can be arbitrarily inclined at any angle θ to the horizontal direction, and θ was set to 90° from the beginning of a test (Fig. 2). The bucket foundation was subjected to the sinusoidal load when the driving motor was rotated because the additional moment was mobilized in the load lever by the rotation of weight m_1.