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Seismic response of suction caisson in large-scale shake table test

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ABSTRACT: With the increasing demand on wind power, offshore wind turbines are being increasingly installed in sites where seismic loading must be considered, as it may affect the design of the supporting tower as well as the foundation. Suction caisson is a relatively recent foundation system that has been introduced to support a wide variety of offshore structures, including offshore wind turbines. To identify the dynamic characteristics associated with the seismic response of suction caissons, a one-g shaking table experiment was conducted on a scaled suction caisson foundation with a wind turbine model, where the shake table was used to generate harmonic excitation. This paper presents the experimental results from an initial shake table test of a scaled wind turbine model with a suction caisson foundation. The experimental data shed light on the basic seismic response characteristics of suction caissons. With embedment of the foundation in a sand, residual relative displacements along the tower were observed by end of shaking, resulting in permanent rotation of about 0.25 degrees. Overall, this suction caisson experiment provides data for calibration of numerical models to further explore the consequences of seismic excitation.

1 INTRODUCTION

The demand for wind energy is increasing rapidly worldwide due to the limited resources of fossil fuel and the associated impact of global climate change. As a clean and sustainable resource, the world capacity of wind energy has exceeded the 539 GW mile stone in 2017 (REN21, 2018). Wind energy includes both onshore and offshore wind. Due to the limitation of space for installation of onshore wind turbines, offshore wind energy is becoming an attractive alternative, especially with its massive energy potential (Breton and Moe, 2009). In United Stated, U.S. Department of Energy sets a goal to build 54 GW of offshore wind power by 2030 (Lindenberg et al., 2009).

For offshore wind turbines, construction of the support structure is considered to be relatively costly. Particularly for shallow water depth (up to 30 meter), its construction requires about 20–30% of the capital cost and 12–25% of the life-cycle cost (Musial and Ram, 2010, Versteijlen et al., 2011). Furthermore, the foundation requires about 60% of the total installation cost for offshore wind plants (Wang et al., 2018).

Types of support structure for an offshore wind turbine are determined based on water depth, turbine size, and soil conditions. Among those, suction caisson is a relatively new type of foundation that has been used for offshore structures for about 30 years. It was firstly introduced as anchors, mainly in clays, and has been used as foundations for offshore platforms (Houlsby et al., 2005). Houlsby and Byrne (2000) revealed that suction caisson foundation is an economically attractive alternative for offshore wind farms. A suction caisson foundation is a hollow cylindrical shaped structure that is closed from the top by a flat lid and open from the bottom. Inside, it can have compartments in a honey-comb shape for instance (Figure 1).

A suction caisson foundation was originally introduced for oil and gas platforms. Byrne et al. (2002) found that load pattern for oil and gas platforms is different from that for wind turbines in many aspects. As such, the existing design criteria for offshore platforms cannot be

Figure 1. Bottom view of the suction caisson showing the honey-comb shaped compartments.

Figure 2. Suction caisson model placed in the laminar soil container.

used directly (Byrne et al., 2002). Therefore, more research should be directed towards understanding the behavior of mono suction caissons under predominant overturning loads and the dynamic soil-structure interaction (Foglia and Ibsen, 2014a).

Recent research showed that suction caisson foundation is a promising solution as supporting structure for offshore wind turbines (Achmus et al., 2013, Foglia and Ibsen, 2014a). Experimental work has been conducted to investigate the vertical, lateral and combined loading capacity of suction caisson foundations (Chen et al., 2016, Wang et al., 2017a, Li et al., 2014, Hung and Kim, 2012, Villalobos et al., 2010), and under cyclic loading (Foglia and Ibsen, 2014b, Nielsen, 2016).

Few researchers investigated the performance of suction caisson foundation under seismic loading, numerically (Kourkoulis et al., 2014, Zafeirakos and Gerolymos, 2014, Athanasiu et al., 2015) and experimentally by means of dynamic centrifuge modeling (Wang et al., 2017a, Yu et al., 2014, Wang et al., 2017b, Choo et al., 2015), or 1-g shake table testing (Yamazaki et al., 2003). A review on the recent advancements of suction caisson foundation was reported by (Wang et al., 2018).

Building on these earlier studies, a 1-g scaled model of wind turbine with suction caisson foundation in a dense sand model was tested using a laminar soil container on a shake table. Particular attention was dedicated to the acceleration and displacement of the tower. In addition, pore pressure and acceleration response of the soil model were measured to evaluate its dynamic characteristics during the shaking events.

The purpose of this study is to get a general understanding of the dynamic performance of the suction caisson foundation installed in dense sand and observe the different response characteristics. For that purpose, harmonic motion was imparted by the shake table in this pilot test.

2 SHAKE TABLE TEST SETUP

2.1 *Suction caisson model*

The model was designed using a scaling factor of 1:32 to represent a prototype 3.45-Megawatt (MW) wind turbine. To scale down, the similitude relationship proposed by Iai and Sugano (1999) was used for shaking table tests on soil-structure-fluid models in a 1-g gravitational field.

presents properties of the prototype and the scaled model. All the components of the tower head are simplified by a lumped mass at the top. The caisson was designed with inner compartments as shown in Figure 1.

2.2 *Soil model*

Ottawa sand F-65 was used to prepare the soil model. The tested soil model consisted of a 1.5 m very dense saturated sand layer, built in 6 lifts. Each 0.25 m lift was dumped and compacted using a plate compactor. Based on the measured weight and volume of the sand layers, in addition to performing sand cone tests, average relative density (D_r) was measured to be about 90%. Upon completion of backfill, soil saturation was performed by dripping water into the model base using Poly-Vinyl Chloride (PVC) pipes and hoses. The final water table was at 0.15 m above the top soil surface. Full details of the experiment are reported in Zayed (2019).

Table 1. Properties of the prototype and the scaled model (Zayed 2019).

Quantity	Full scale (Prototype)	Scaled model (Type III)
Tower top mass	195,000 kg	50 kg*
Tower Height	66.5 m	2.1 m
Shaft Height	40.2 m	1.26 m
Diameter of caisson skirt (D)	16 m	0.5 m
Length of caisson skirt (L)	8 m (L/D = 0.5)**	0.25 m
Fundamental Frequency	0.275 Hz	1.56 Hz

* top mass is adjusted to have the fundamental frequency of the proposed model matching the frequency of the fabricated model

** length to diameter ration (L/D) is kept the same for the prototype and the scaled model

2.3 *Shake table test facility*

The experimental work in this study was conducted at the Powell Laboratory shake table facility, located at the University of California San Diego (UCSD). Maximum table displacement is ±150 mm with a maximum nominal operating frequency of 20 Hz. Performance and construction of the Powell laboratory shake table are detailed in Magenes (1989), and Trautner et al. (2018).

A laminar container with internal dimensions of 3.9 m x 1.8 m x 1.8 m (L x W x H) was constructed at UCSD (Ashford and Jakrapiyanun, 2001). The laminar container was designed to be used with dry and saturated soil models and exhibits minimal boundary effects; simulating a 1D shear stress-strain wave propagation state (Chang and Hutchinson, 2012, Ebeido et al., 2018). Figure 2 shows the tested suction caisson foundation model for this study placed in the laminar soil container.

2.4 *Instrumentation*

Figure 3 illustrates the dimensions of the tested soil strata as well as the instrumentation types and locations. Two arrays of transducers were installed inside the laminar container. The leftmost array (north array) represented the free field response. North instrumentation array had 5 pairs of accelerometers (A#) and pore pressure transducers (PP#), while the middle array, below the suction caisson foundation, had 3 pairs. Four string potentiometers (SP) were connected to the tower and the top mass to measure the lateral deformation. In addition to SP, 6 accelerometers (A#) were attached to the tower and top mass to monitor the tower vibrations.

2.5 *Testing configuration and experimental procedures*

To drive the caisson foundation, the outer 6 compartments (Figure 1) were connected to a vacuum pump for suction. By the end of the installation process, vertical orientation of the caisson foundation was insured. A relatively simple earthquake-like motion with a dominant frequency of 1.4 Hz and maximum amplitude of 0.2g was selected as input excitation for the test model. Under acceleration-controlled mode, the shake table was used to generate a 6-second long harmonic input motion as shown in Figure 4. This motion consisted of 6 cycles including 1 cycle ramping up to the desired amplitude and 1 cycle ramping down at the end of

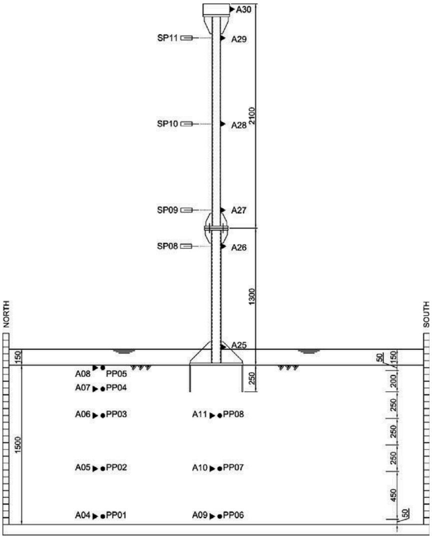

Figure 3. Testing configuration and instrumentation layout (dimensions shown in mm).

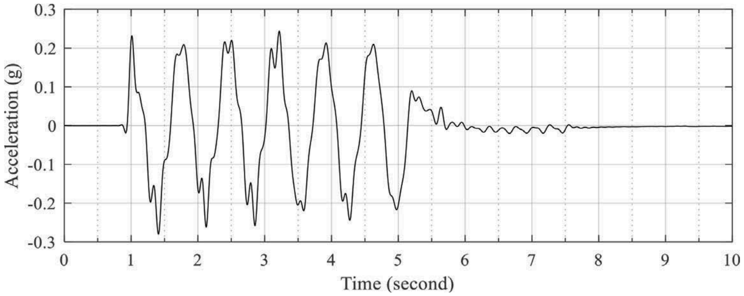

Figure 4. Acceleration history of the shake table input excitation.

the motion, leaving 4 cycles in between with a constant amplitude of 0.2g. The acceleration response of the shake table was slightly noisy due to superfluous friction in the shake table bearings as discussed by Trautner et al. (2018).

3 TEST RESULTS AND DISCUSSION

3.1 *Soil acceleration response*

Figure 5 shows representative measured acceleration along north array (left column) and middle array below the foundation (right column). In addition to the shake table record, the soil acceleration (A04 in Figure 3) was recorded to monitor transmission of the input excitation into the model base inside the container. Comparing the acceleration records in the north, i.e. left, array (Figure 3), it can be observed that the main characteristics of the acceleration are consistent. However, a relatively small amplification can be noted (A04 to A08), compared to the middle array as shown in the frequency spectra plots presented in Figure 6 (left column).

Using two acceleration records (A04 and A08), the dominant frequency in the acceleration response spectrum was 1.4 Hz, associated with the input excitation frequency (Figure 6). Furthermore, secondary amplification was noted at 4.15 and 7 Hz (Figure 6). These frequencies were part of higher harmonics of the main shaking frequency as real loading components and

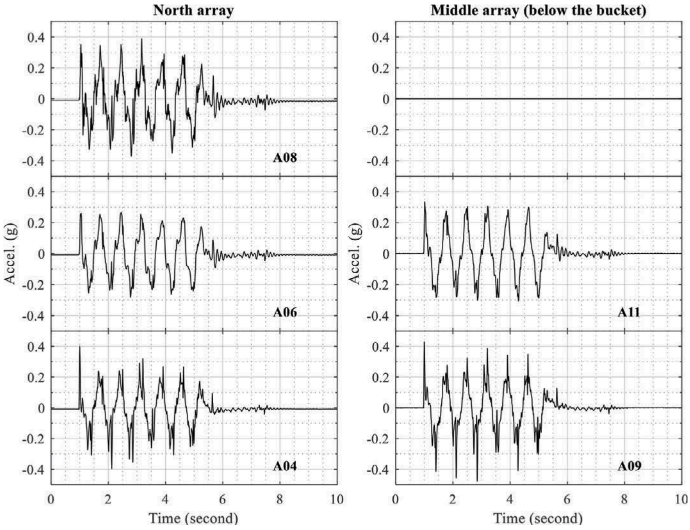

Figure 5. Representative acceleration time histories along the north and middle instrumentation arrays.

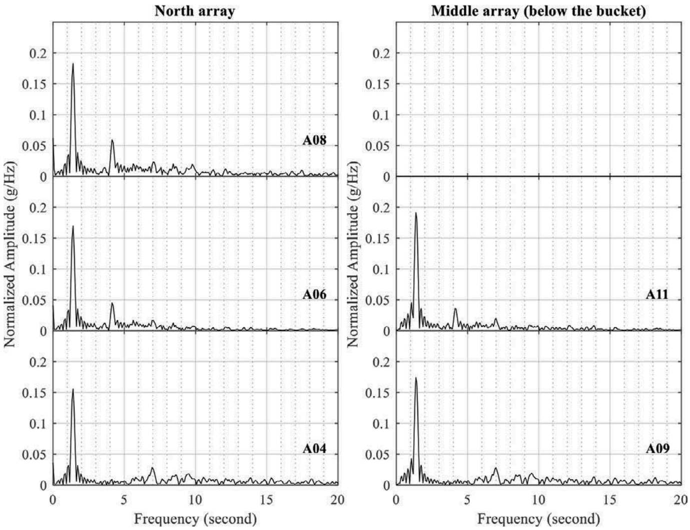

Figure 6. Representative frequency spectrum of the recorded accelerations in the soil model.

not noise (Brennan et al., 2005). Similar response was observed in the middle instrumentation array below the caisson foundation, as presented in the right columns of Figure 5 and Figure 6. Similar amplification was observed in the acceleration amplitude between A09 and A11 to that noted between A04 and A06.

3.2 *Pore pressure response*

Figure 7 shows the recorded pore pressure (PP) response in the north and middle arrays. Except for the lowermost PP in the middle array (PP06 malfunctioned), dilative spikes can be observed in most of PP records. This dilative response matched the dense nature of the sand (D_r = 90%). After shaking, it was shown that the pore pressure slightly increased (not associated with any potential liquefaction). Comparing PP07 and PP08 (i.e., below the caisson) with

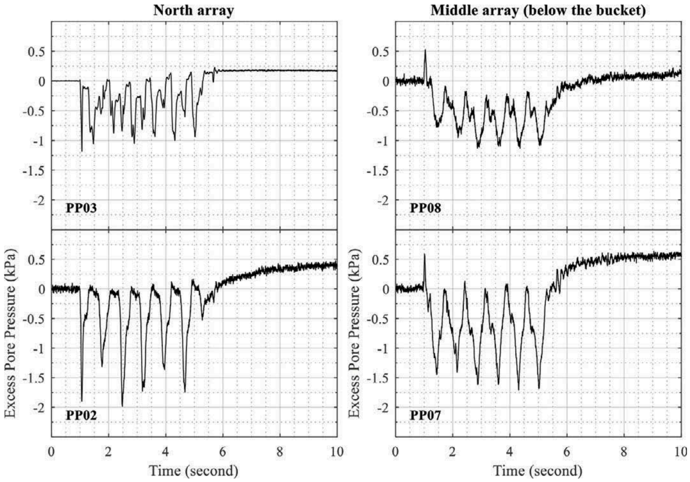

Figure 7. Representative time histories of Excess Pore Pressure (EPP) in the north and middle arrays.

PP02 and PP03 at same elevation but in the free field, might indicate an out-out-phase response (e.g. PP02 at 4 seconds vs. PP07 at 4 seconds). However, main characteristics of the response were maintained in both arrays.

3.3 *Tower acceleration and displacement*

Representative time histories for the lateral relative displacement of the tower are shown in Figure 8. The tower behaved as a single degree of freedom (SDOF) structure, and permanent displacements were observed at different elevations along the tower height. Figure 9 shows the tower rotation estimated using the recorded lateral displacement. The maximum rotation was about 2 degrees while the residual rotation was about 0.25 degrees.

Figure 10 shows acceleration time histories at different locations along the tower as well as the corresponding frequency spectra. It is seen that higher frequency component was noticeable at the lower part of the tower (A26–A28), compared to the top (A29 and A30). In the lower half of the tower (A25–A28), the dominant excitation frequency was 1.4 Hz as observed in the soil (Figure 6). Similarly, the second dominant frequency was at 4.14 Hz (a duplicate of the higher excitation frequency as discussed earlier). However, the dominant frequency for the upper part of the tower was at 1.33 Hz, which is presumed to be the fundamental frequency of the whole wind turbine system with the soil-foundation interaction effects.

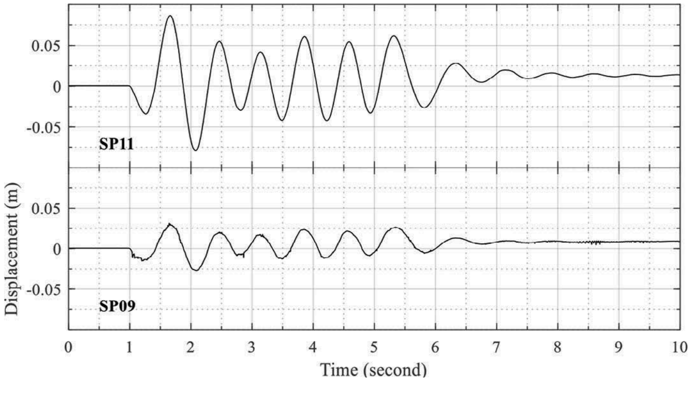

Figure 8. Representative time histories of the lateral tower displacement.

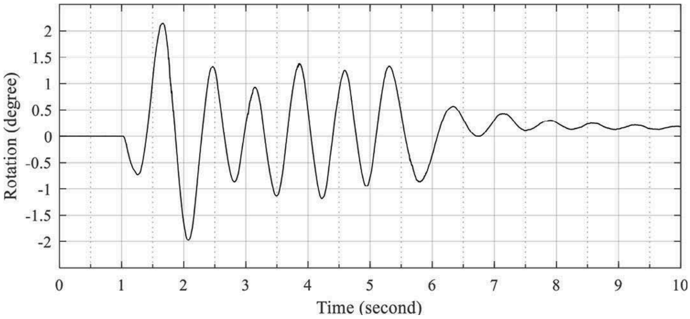

Figure 9. Time history of the tower rotation.

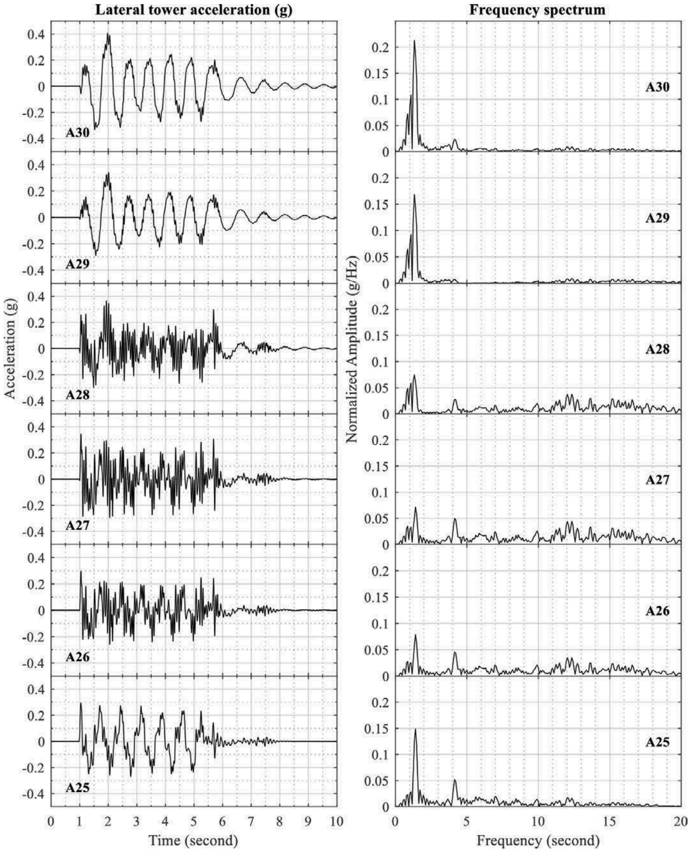

Figure 10. Acceleration time histories along the tower and the corresponding frequency spectrum.

4 SUMMARY AND CONCLUSIONS

A 1-g shake table test was conducted for a scaled wind turbine model with suction caisson foundation placed in a 1.5 m dense, saturated sand stratum. An earthquake-like input motion (1.4 Hz and 0.2 g peak amplitude) was applied to investigate the performance of the suction caisson foundation under seismic excitation.

Main characteristics of the input excitation were maintained during shaking within the soil model and a slight amplitude amplification was observed between the lowermost and the upper most acceleration records. No significant increase in the pore pressure was observed during shaking. On the contrary, clear dilative spikes confirmed the dense nature of the sand model (D_r = 90%). Pore pressure response had the same characteristics in the free field and below the caisson.

It was shown that acceleration measured in the lower part of the tower reflected the input excitation frequency. The tower essentially behaved as a SDOF model under the imparted shaking conditions. The fundamental frequency of the tower model showing the soil-structure-foundation interaction effect was observed in the topmost acceleration records to be 1.33Hz, while the excitation frequency was 1.4 Hz.

Lateral deformation was largely amplified at the tower top and relatively smaller at the lower part of the tower. Residual relative displacements were observed at the end of shaking. Tower rotation was evaluated using the lateral displacement histories. The maximum rotation of the tower was rather large, but was instantaneous during the shaking event, and was recovered by end of shaking. A lower level of permanent rotation after shaking was observed. In general, the wind turbine model showed promising performance (in terms of residual deformation, acceleration amplification, in addition to no significant pore pressure increase) under the employed soil conditions and seismic excitation. Further research is currently underway to use results of the conducted shake table experiment for calibration of numerical models to further explore the consequences of seismic excitation.

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