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SEISMIC INTERACTION OF OFFSHORE WIND TURBINES WITH TRIPOD BUCKET FOUNDATIONS ON LIQUEFIABLE SOILS UNDER WIND LOADING

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The cost-effectiveness and environmental benefits of the tripod suction bucket foundation make it stand out as a preferable option for supporting offshore wind turbines (OWTs) compared to traditional designs like monopile foundations. However, the use of tripod suction bucket foundations in regions with high seismic activity, such as Taiwan, lacks sufficient establishment in current design practices. This study aims to bridge this knowledge gap by investigating the seismic response of a 5MW offshore wind turbine with tripod suction bucket foundations via three-dimensional, fully-coupled, nonlinear finite-element analyses. The analyses showed that earthquake motion increased excess pore water pressure generation, leading to a rise in the excess pore water pressure ratio and, consequently, a decrease in effective stress. The movement of bucket foundations caused by wind loading led to a compressive reaction near the soil on the leeward side, which was observed in the loose sand layer. Furthermore, the presence of wind loading encouraged biases in permanent settlement across the foundation area and the accumulation of soil deformations in the near field, especially in the loose sand layer. This resulted in an accumulation of shear strain parallel to the wind loading direction at the end of shaking. On the other hand, the limited numerical sensitivity study indicated that the magnitude and orientation of foundation rotations were influenced by ground motion characteristics (polarity and velocity impulse) as well as the magnitude and direction of the wind load.Additional research is essential to fully understand the overall impact of velocity impulse and extreme climate loads on offshore wind turbine systems founded on liquefiable soils. A more comprehensive approach involving varied soil profiles, offshore wind turbine foundation configurations, extreme climate load scenarios, and ground motion characteristics is necessary before revised guidelines can be established.

Keywords: Tripod bucket foundations, liquefaction, extreme climate loadings, soil-structure interaction.

1. Introduction

Most studies on the seismic response of suction buckets have primarily focused on the performance of monopod suction buckets, with particular attention given to the accumulation of pore pressure in sand. Emphasis has been placed on understanding how factors such as skirt length and bucket diameter affect the seismic responses of monopod suction buckets. In-depth 3D numerical simulations have also been conducted to investigate the seismic response of monopod suction bucket foundations in both clays and sands (Anastasopoulos 2016; Esfeh and Kaynia 2020). These studies utilized advanced total stress-based and effective stress-based soil constitutive models. While not immediately catastrophic, the results indicated that the accumulation of bucket rotation could lead to the turbine reaching serviceability limits early in its operation. Moving beyond monopod suction buckets, studies on tripod suction buckets have explored the monotonic bearing behavior through centrifuge model tests and 3D numerical simulations (Kim et al. 2014; Cheng et al. 2024). Cyclic loading amplitude and direction significantly affected cyclic stiffness and permanent displacements. While there has been extensive research on monopod and tripod suction buckets in various soil types, there is a significant gap in the literature regarding the seismic response of offshore wind turbines (OWT) with tripod bucket foundations specifically in sandy soils. This is crucial, as sandy soil deposits face two seismic hazards: soil liquefaction during strong earthquakes and the amplification of earthquake acceleration, both of which can adversely impact the stability and performance of OWT with tripod bucket foundations. Hence, this study utilized a series of 3D finite element analyses to explore the impact of pulse-like motions on the seismic performance of OWT with tripod suction bucket foundations

2. Numerical Modeling of the OWT system

2.1.*Modeling of foundation, superstructure, and liquefiable soils*

The model employed in the numerical analyses is shown in Figure 1, following the OWT configuration suggested by Cheng et al (2024). The tripod bucket was arranged in the form of an equilateral triangle with sides of 17.32 meters each. The soil consists of three layers. The bottom one is an 8-m-thick dense sand layer (D_r=74%). The middle one is a 6-m-thick loose sand layer (D_r=45%), overlaid by a 6-m-thick loose sand layer (D_r=33%). All parameters referred to PDMY03 from Khosravifar et al. (2018). Brick elements with the u-p formulation were used to model the soil layers. The fluid bulk modulus was assumed to be 2 × 10^6 kPa at atmospheric pressure. The maximum element size was estimated at each depth based on the soil's empirical small-strain shear wave velocity (V_s) profile, the minimum wavelength of interest, and the possible reduction in Vs due to soil softening. The tower of the wind turbine was modeled using a beam element with two types of sections, as shown in Fig 1. The elastic Young's modulus of the tower structure was assumed as 210 GPa (i.e., steel material). The rotor nacelle assembly (RNA) was modeled as a lumped mass at the top of the tower, while the weight of the tower was lumped equivalently along the tower structure. The brick element stabilized single-point (SSP) integration scheme and linear-elastic material properties were utilized to simulate the tripod suction bucket and its cap. A thin layer of degraded loose sand was placed around the monopile along its shaft and under the tip, representing the soil-pile interface (Liu et al. 2022; Hwang and Tiznado 2024). The properties of the bucket foundation and tower structure are summarized in Table 1.Lastly, aconstant thrust force of about 704 kN was applied at the top of the tower in a positive x direction (in parallel with the earthquake shaking) based on Bernoulli's equation (Lee et al. 2010), considering an average annual wind velocity of 9.61 m/sat Taiwan Strait.

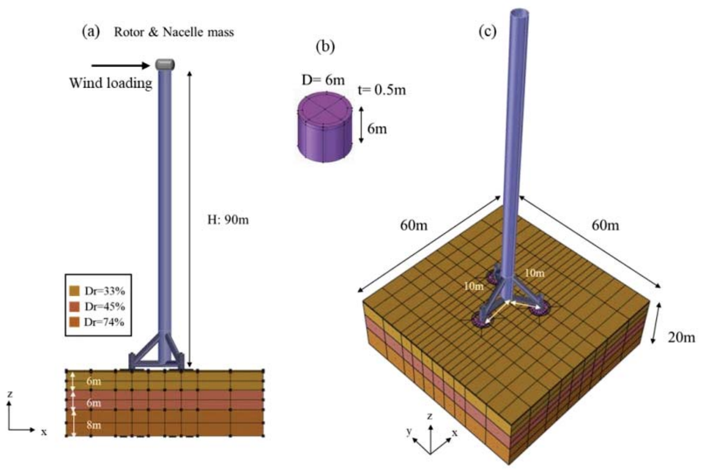

Figure 1. The schematic view of OWT with tripod bucket foundations

Table 1. Model parameters for 5MW wind turbine.

Property	Superstructure				Tripod bucket			
	Rotor & Nacelle mass (kg)	Tower mass (kg)	Tower height (m)	E (GPa)	Diameter, wall thickness (m)	Length (m)	Á$_{eq}$ (kg/m^3)	E_{eq} (GPa)
Value	350,000	347,466	87.6	210	6 m, 0.5 m	6	2478	16.11

2.2.*Boundary conditions and ground motion selection*

To prevent boundary effects from impacting the engineering demand parameters of interest, we assigned lateral boundary nodes with periodic boundary conditions at the same elevation. We increased the domain length 6 times in the x- and y-directions relative to the pile diameter. The base and four surrounding sides of the soil domain were set as impervious boundaries, and the bottom boundary nodes were fixed in all translational directions to simulate the rigid base condition and reduce computation costs. To account for the dynamic characteristics of the bedrock, such as shear wave velocity and mass density, we conducted free-field site response analyses with the elastic-half space assumption in OpenSees. We kept the soil domain size, element selection, soil parameters, and boundary conditions the same. Afterward, we used the acceleration time history recorded at the base of the model in the free-field site response analysis as "within motion" for the soil-OWT model with a rigid base assumption.Two ground motions were chosen for limited sensitivity analysis. The first criterion is the distance to the earthquake rupture (R_{rup}) with a threshold of 10 km, while the second criterion is the presence of pulse-like characteristics identified in the NGA West2 database. The motion with R_{rup} greater than 10 km and no pulse-like characteristics was labeled as non-pulse-like (NP). The motion with R_{rup} less than 10 km and pulse-like characteristics was classified as pulse-like (P). To determine the 1D input motion for the 3D numerical simulations, each pair of horizontal recordings from the selected NP motions was rotated to find the maximum rotated (RotD100) peak ground acceleration (PGA). For the P motion, the two horizontal components were rotated to find the direction with maximum velocity. Figure 2 shows the acceleration and velocity time histories of the selected motions. The earthquake recordings at GRAN SASSO station during 2009 L'Aquila Earthquake was selected as the NP motion, while the earthquake recordings at CHY089 station during 2016 Meinong earthquake was chosen for the P motion.

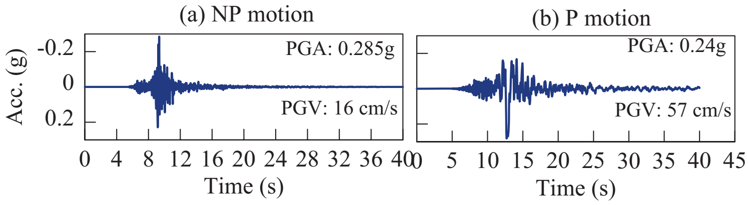

Figure 2. Acceleration and velocity time histories of the NP and P motions.

3. Seismic deformation patterns

Figure 3 shows the contour of permanent in-plane shear strain along the centreline of the OWT system without and with wind loading, respectively. In general, earthquake shaking increased pore water generation and a subsequent reduction in effective stress within the soil. The loss of soil's shear strength led to the accumulation of permanent shear strains and soil deformation near foundations. In the case of the OWT system subjected to pulse-like ground motion, significant shear strains were concentrated near the foundations, as well as the top and middle layers of loose sand.

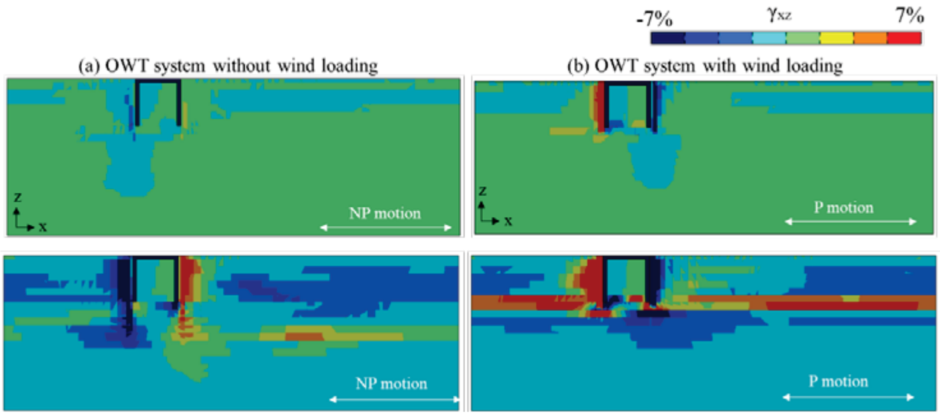

Figure 3. Permanent shear strain contournear the OWT system without wind loading under NP and Pmotions.

The pulse-like motion encouraged the accumulation of in-plane shear strain following the direction of the first major velocity impulse. This is because the velocity pulse increased the peak cyclic stress, which increased the potential for soil liquefaction in both loose sand layers, as compared to the case under NP motion. Overall, compared to the OWT system under NP motion, the P motion encouraged greater foundation settlement and bias in soil deformation across the foundation footprint area, leading to greater foundation tilts. For the cases considered, all tripod bucket foundations exhibited a tendency to rotate counterclockwise. For cases considering the wind loading, Fig. 3 shows that more visible permanent shear strains in the soil were observed near the tripod bucket foundations and at the top and middle loose sand layers, regardless of the type of input motion.The constant wind loading (toward positive x-direction) at the RNA introduced a large overturning moment at the foundations, leading to a significant clockwise rotation. Meanwhile, the ground shaking led to increased pore water pressure in the top and middle layers of loose sand, resulting in a loss of shear strength in the soil. The net outcome of these mechanisms encouraged foundation rotation and movement. The left foundation showed pull-out behavior, whereas compressive behavior was expected at the right foundations. Overall, large shear strains were distributed along the bucket foundation depth and within $1D_B$(i.e., D_B: diameter of bucket foundation)away from the foundation's edge. This effect was particularly evident for the OWT system under P motion.

4. Seismic performance of OWT foundation

Figure 4 shows the average settlement and tilt time histories of the OWT system with/without wind loading under P and NP motions. We first calculated the average settlement of all foundations. Positive vertical displacement indicated foundation settlement, while negative values showed uplift. Then, the tilt of the OWT system was estimated by the ratio of maximum differential settlement between the left and right foundations over the median from the left foundation. A positive tilt indicated clockwise rotation, and vice versa.The permanent foundation settlement of the OWT system under P and NP motions was about 18.5 and 3.1 cm, respectively. Additionally, a greater foundation tilt was observed for the OWT system under P motion (H-0.05 ◦) as compared to the system under NP motion(H-0.02 ◦). For the conditions considered, the amplification in settlement and tilt due to velocity pulse was about 6 and 2.5 times greater than that under NP motion, respectively. For cases considering wind loading, the permanent foundation vertical displacement of the OWT system under P and NP motions was about -5 and -2 cm, respectively, indicating an overall uplifting behaviour. The uplift of the left foundation outweighed the settlement of the two right foundations, due to less pull-out resistance of a single bucket (i.e., left foundation). Similarly, a greater clockwise foundation tilt was observed for the OWT system under P motion (H2.2 ◦) as compared to the system under NP motion(H0.6 ◦). The foundation tilts of the model under wind loading were much greater than those without wind loading and even exceeded the typical serviceability limit (H0.5 ◦). For the conditions considered, the amplification in tilt due to velocity pulse was about 4 times greater than that under NP motion. In general, the limited numerical study suggested that the velocity impulse and the presence of wind loadingwould adversely impact the foundation performance (in terms of settlement and tilt) of the OWT system with tripod bucket foundations, which should be carefully considered for those wind farms close to the active faults.

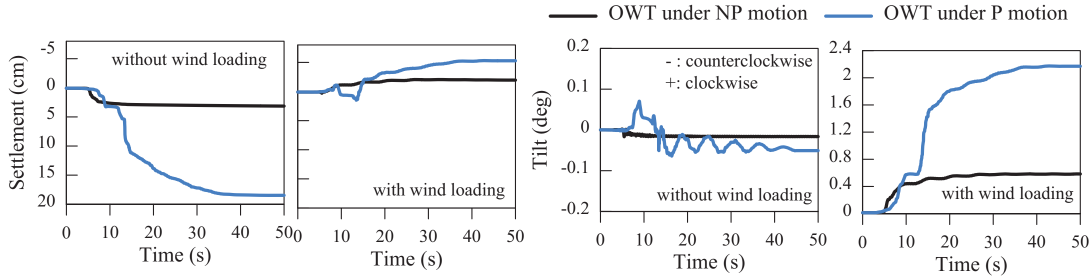

Figure 4. Foundation response of OWT system with/without wind loading under NP and Pmotions.

5. Conclusions

This study investigated the seismic response of a 5MW offshore wind turbine with tripod bucket foundations through detailed 3D, fully-coupled, nonlinear finite-element analyses. The modeling scenario incorporated both pulse-like and non-pulse-like ground motions, combined with wind loading conditions, to simulate realistic operational scenarios. The research utilized advanced soil constitutive models and carefully considered boundary conditions to simulate soil-foundation-OWT interaction.In general, the numerical results showed that the pulse-like ground motions substantially amplified foundation settlement and tilt compared to non-pulse-like motions, with amplification factors of 6 and 2.5 respectively. When combined with wind loading, the system showed overall uplift behavior and increased clockwise rotation, exceeding typical serviceability limits of 0.5 degrees. The velocity impulse and wind loading strongly impacted foundation performance, particularly in loose sand layers where increased pore water pressure generation led to reduced effective stress and subsequent soil deformation.On the other hand, this study demonstrated that the movement of bucket foundations under wind loading resulted in compressive reactions near the soil on the leeward side, particularly observable in loose sand layers. Furthermore, the presence of wind loading encouraged biases in permanent settlement across the foundation area and the accumulation of soil deformations in the near field.These findings shed light on the importance of incorporating both seismic and environmental loads in foundation design, especially for wind farms situated near active faults. Further research involving varied soil profiles and loading scenarios is recommended for developing robust design guidelines.

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