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Soil Liquefaction Effects on the Seismic Response of Monopile Foundation for 10-MW Offshore Wind Turbine in Taiwan

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This paper is to study the influence of soil liquefaction on the seismic response of a monopile foundation for the Technical University of Denmark (DTU) 10-MW reference wind turbine (RWT) on the west coast of Taiwan. Taiwan is located in seismically active regions, and the soil conditions of Taiwan's offshore wind farms are softer than those in Europe. Therefore, there is significant interest in assessing the behavior of a wind turbine subjected to seismic load. Based on the flexible volume method and the practical, two-surface plastic constitutive model for sand (P2PSand), the two foundation models of the DTU 10-MW RWT are employed to carry out a series of seismic design load cases as defined in DNV-RP-0585. The results show that soil liquefaction has significant influence on the dynamic response of the DTU 10-MW RWT with monopile foundation under the local environmental conditions in Taiwan. In particular, vertical displacements and rotations are significantly amplified by soil liquefaction during strong ground motions. It means that without considering the potential effect of soil liquefaction, structural responses, including displacement and rotation angle, may be greatly underestimated.

INTRODUCTION

Wind power is regarded as one of the most promising renewable energy resources. Over the past decades, the advancement of technology and maturity of supply chains have made offshore wind power an increasingly viable option for renewable energy. The 2022 Global Wind Energy Report showed that 21.1 GW of new offshore wind capacity was installed worldwide in 2021, a twofold increase from that of the previous year (GWEC, 2022). Reducing the levelized cost of energy (LCOE), wind turbines with larger rated power capacities have increased significantly to more than 9.5 MW in recent years. However, several challenges remain unresolved. Among them are: 1) potential resonance in larger wind turbines (Von Borstel, 2013; Buckley et al., 2018), 2) site selection, and 3) selection of substructure type.

With the continuous advancement of offshore wind technology and the growth of global energy demand, offshore wind farms are gradually shifting from nearshore to far shore and from shallow to deep waters. Various types of support structure for offshore wind turbines (OWTs) have been successively developed to meet the market changes. Nevertheless, more than 90% of OWTs are supported by fixed foundations, and the monopile foundation is the most widely used type in water depths up to 30–50 m because of its simple structure and low cost (Igwemezie et al., 2019). However, the new generation of offshore wind turbines must be installed in deeper water to harvest more powerful wind resources, which poses challenges to traditional monopile foundations due to the need for higher-capacity generators and larger blades. Regions with high seismic activity, such as Taiwan, the United States, China, and India, are also deploying OWTs. This makes seismic loading critically important in the design of wind turbine foundations, as earthquakes could cause catastrophic damage to these wind farms.

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The literature focuses primarily on the dynamic response of the upper structure for an OWT induced by earthquakes (Prowell and Veers, 2009; Zhang et al., 2014; Han et al., 2017; De Risi et al., 2018; Dong et al., 2018; Mo et al., 2021), as well as the influence of soil/foundation interaction on the dynamic response and natural frequencies of the OWT (Prowell et al., 2010; Damgaard et al., 2014; Wang et al., 2021). In addition to the dynamic response resulting from interactions with the dynamic loading and blade vibrations, excess pore pressure can develop in the liquefied soil layer during an earthquake, leading to soil liquefaction and settlement. Soil liquefaction during an earthquake in offshore areas may cause severe damage to the whole structure system. Moreover, resonance may occur due to the softening of soil during liquefaction. Despite the significant effects on a single pile-soil system, studies on liquefaction evaluation for OWTs remain limited (Carswell, 2015). Patra and Haldar (2021) developed a model of a monopile-tower system using OpenSees software to investigate the dynamic response of the monopile foundation in liquefiable soil. Demirci et al. (2022) investigated liquefaction effects on the fundamental frequency of a monopile supported reference 8 MW wind turbine. Wang et al. (2017) carried out nine centrifuge tests to investigate the seismic response of a suction bucket foundation in dry and saturated soil conditions; then, Wang et al. (2020) conducted a series of centrifuge shake table tests to investigate the seismic response and liquefaction characteristics of innovative hybrid monopile foundations in dry and saturated soil conditions.

Most simulations and experiments in the literature focused on small-diameter monopiles and other types of foundation (Boulanger et al., 1999). However, the soil–structure interaction (SSI) and liquefaction mechanisms for high-rated-power OWTs supported by large-diameter monopiles have not been systematically investigated. Moreover, with the increasing rotor diameter and hub height, wind load plays a more critical role in the ultimate-limit-state and serviceability-limit-state design. The coupling of wind, wave, and earthquake loads under various conditions may influence the liquefaction depth, which has not been previously discussed. Therefore, this paper provides insight into the behavior of a large-diameter monopile, supporting the Technical University of Denmark (DTU) 10-MW reference wind turbine