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Centrifuge modeling of offshore wind foundations under earthquake loading

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ABSTRACT

The construction of large offshore wind turbines in seismic active regions has great demand on the design of foundations. The occurrence of soil liquefaction under seismic motion will affect the stability of the foundations and consequently the operation of the turbines. In this study, a group of earthquake centrifuge tests was performed on wind turbine models with gravity and monopile foundations, respectively, to exam their seismic response. It was found that the seismic behavior of models was quite different in the dry or saturated conditions. Each type of foundation exhibited distinct response to the earthquake loading, especially in the offshore environment. In the supplementary tests, several remediation methods were evaluated in order to mitigate the relatively large lateral displacement of pile foundation (by fixed-end pile and multi-pile foundation) and excessive settlement of gravity foundation (by densification, stone column, and cementation techniques).

1. Introduction

In recent years, offshore wind farms have become attractive due to higher quality in wind resources at sea, requirement of no land, and less impact on communities. However, the harsh offshore environment and loading conditions impose high demands on the design of foundations. In particular, the fact that some recently planned offshore wind farms will be built in seismic active regions, such as the coastal regions of Southern Europe, North America, and Eastern Asia, brings even greater challenges to the design of foundations.

Earthquakes can cause significant damage to both foundations and wind towers depending on the performance of the combined system of superstructures, foundations, and surrounding soils. In the offshore environment, soils can be softened by the increased pore water pressure under earthquake loading. In the worst scenario, earthquake-induced soil liquefaction can sharply reduce the bearing capacity and lateral support of the foundation, which may cause excessive settlement and/or tilting of the structures. So far, the understanding of the seismic resistance of offshore wind foundations is very limited.

With little field data and experience, the seismic evaluation and design of offshore wind tower foundations are commonly based on the criteria developed for onshore wind turbines, oil platforms [5,18] or general buildings [10,30,4]. However, these criteria cannot completely address problems with wind turbines due to the different loading environment and structural properties [47]. For offshore wind turbines, the effect of overturning moment induced by heavy superstructure on the foundation is much more severe than that of the vertical load. In addition, the natural frequency of offshore wind turbine systems can be pretty close to the dominant frequencies of an earthquake motion.

Various types of offshore foundations, i.e. gravity base, monopile, tripods, suction buckets, and floating tension leg platforms [39] have been proposed in recent years in order to provide sufficient support for the wind tower. Byrne and Houlsby [11] conducted a comprehensive review on the design of offshore foundations and presented design calculations to investigate the effects of foundation sizes and other critical parameters. Innovative research using centrifuge modeling [46,27,29] has greatly contributed to the design of structures in complex marine environment and the understanding of soil–structure interaction. In recent years, a number of wind farms are located or planned to be

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built in water less than 20 m deep. Gravity base and monopile foundations, due to their simplicity and low-cost, as well as a great deal of existing research and field experience, are the most common and preferred foundations for offshore wind turbines built in shallow water.

A gravity foundation depends mainly on its massive self-weight induced bearing on the seabed to provide stability against the loads transferred either from the superstructure or from the adjacent soil and water. The effect of soil liquefaction on gravity structures was studied by Lee and Focht [37], and Walker and Blair [61]. Dynamic soil–structure interaction under seismic loading was investigated by Ghosh and Madabhushi [28], Srbulov [55], and Dashti et al. [16]. The pile supported structures tend to fail in the form of overturning or tilting as the surrounding soil loses its lateral support during soil liquefaction. Such failures have been reported by Yoshida and Hamada [64], Tokimatsu et al. [57], and Adhikari and Bhattacharya [2]. Both experimental and numerical analyses have been conducted in recent years on the pile structures in order to study the complex soil-pile-superstructure interaction during earthquakes [62,19,32,3]. However, the existing methods have not been applied to the case of offshore wind turbine under earthquake loading. Although some recent seismic investigations were conducted on full-scale turbine models [36,65,48], the results still need to be calibrated and validated by experimental data.

Over the past few decades, a number of techniques have been developed to minimize liquefaction-induced hazards. For example, soil densification has been widely used in the field. The effectiveness of soil densification on the settlement during the liquefaction was evaluated by Liu and Dobry [38], Mitchell et al. [45], and Coelho et al. [15]. The technique of stone column, initially studied by Seed and Booker [54], is currently accepted as one of the most effective liquefaction countermeasures. The installation of stone columns can effectively improve the stiffness of soil and reduce the build-up of pore water pressure, and hence the associated settlement by quick drainage during and immediately after the earthquake [49]. The performance of stone column under seismic loading can be found in theoretical analysis, model tests [50,44,1] and case histories [43]. Cementation of soil is also considered as a feasible technique to stabilize the foundation soil and therefore, to reduce settlement induced by cyclic loading [20,25,31,13]. However, quantitative evaluation on how effective the improvement by using this technique has not been well developed yet.

In this study, a group of earthquake centrifuge tests was performed on two types of wind turbine models with a gravity base foundation or a monopile, respectively. The models took into account the dimensions and masses of prototype wind turbines in order to examine the loss of serviceability, i.e. settlement and overturning, under earthquake loading. Tests in dry conditions were also conducted to highlight the different structural responses and amplified instability in saturated conditions. The experimental results are useful in selecting and designing offshore wind foundations in seismic areas. In addition, some supplementary tests were conducted to evaluate the techniques that can mitigate seismic-induced instability. It was found that the fixed-end pile foundation, simulating a pile penetrating into bedrock, may provide a design to minimize the lateral displacement under earthquake loading. The multi-pile foundation would also effectively reduce the lateral movement without amplifying the seismic response at the tower head. At the same time, the techniques of densification, stone columns, and cementation were found to be effective in mitigating the excessive settlement of gravity base foundation in the offshore environment.

2. Test program

2.1. Centrifuge models

As shown in Fig. 1, two simplified models (dimensions are shown in prototype scale for tests at 50 g) were adopted according to the structural features of offshore wind turbines in the field. Due to the constrain of the size of the centrifuge models, the prototype structure it represents would be a medium size wind turbine. The models with each part labeled in Fig. 1 had the same superstructure but different foundations. The superstructure consists of tower head and wind tower. The tower head was simplified as a lumped mass at the top of the tower rod with large slenderness ratio. Such structure was expected to induce high overturning moment during an earthquake compared with a typically short and broad building model. Details of the model are described in Table 1.

The gravity foundation (Fig. 1a) was modeled by an aluminum block which is much heavier than the superstructure. It was embedded 1.5 m below the ground surface and the average contact pressure of the foundation on the subsoil was about 70 kPa. The pile foundation (Fig. 1b) was fabricated from a solid cylinder with the diameter and length of 0.9 m and 4.5 m (in prototype scale), respectively. In the tests, the pile foundation was fully driven into the soil. The end of the pile was standing on the

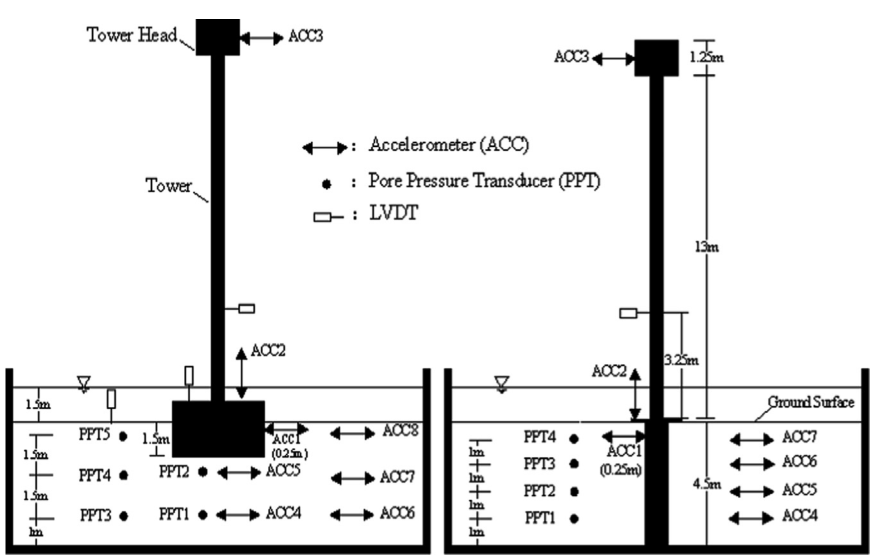

Fig. 1. Centrifuge models with (a) gravity base and (b) pile foundation (dimensions in prototype scale under 50 g).