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Performance of monopile-friction wheel foundations under lateral loading for offshore wind turbines

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ABSTRACT

The new type of foundation which comprises a monopile and a friction wheel is an innovative solution for offshore structures subjected to large lateral loading and has not been extensively investigated. In this paper, two types of friction wheels, namely the solid wheel and gravel wheel, are integrated to a monopile respectively to perform as hybrid foundations. The hybrid foundations are examined under lateral loading via centrifuge tests and three-dimensional finite-element (FE) analysis. The results show that the introduction of the wheel significantly enhances the lateral bearing capacity and stiffness of the monopile. By means of FE analysis, the load transfer mechanism and interaction between the foundations and soils are illustrated to study how the solid wheel and gravel wheel contribute to the performance of the foundation system. Finally, parametric studies about the geometry of the foundations and loading conditions are carried out, which can be used as references for the preliminary design of the monopile-friction wheel foundation.

1. Introduction

Wind energy is considered as one of the major resources of renewable energy. The offshore wind energy industry is gaining increased momentum as the wind is much stronger and steadier off the coasts [1,2]. A reliable and efficient foundation is crucial for offshore wind turbines (OWTs). The costs of foundation can account for up to 30% of the total cost of a project according to the report by Department of Trade and Industry (DTI) [3]. To date, monopile is the most popular offshore wind turbine foundation [4]. For offshore wind turbines (OWTs), foundations are usually subjected to a combined loading of vertical loads (V) from the self-weight of the foundations and upper structures, relatively high lateral loads (H) with the resultant moments (M) induced by wind, current, wave, and ice [5]. In recent years, OWTs are planned to be built in greater sea depths for larger energy production, and the trend is to construct fewer but larger wind turbines with higher output per structure. The trends will bring challenges to the design of foundations for OWTs as the environmental conditions are more severe in deeper seas. The conventional monopile foundation may not be economical or practical for the new generation of OWTs. Hence, various novel foundations and innovative substructure concepts regarding multi-footing configurations, including the bucket foundation [6–10], tripod bucket foundation [11,12], hybrid pile-jacket foundation system [13], etc. are proposed and studied to improve the lateral bearing capacity of the foundations. One type of hybrid foundation with a combination of a monopile and friction wheel has been proposed and proven to have a promising performance against lateral loading conditions for OWTs, as shown in Fig.1 [14].

To date, some research has been conducted and valuable conclusions have been reached. The concept of monopile-friction wheel foundation combines the elements of a circular friction wheel and single pile, which is analogous to pile caps, pile-mat foundations, and piled raft foundations. Mokwa and Duncan [15] developed a field test facility to perform full-scale lateral-load tests on piles with pile caps. The results showed that pile caps provide significant resistance—approximately 50% of the overall lateral capacity in the tests. Rollins and Cole [16] studied the influence of the pile cap on the cyclic lateral performance of group piles by several full-scale lateral load tests. The results proved the considerable contribution of passive resistance on the pile cap to the lateral resistance and pointed out the significant degradation of passive resistances under cyclic loading for deflections greater than 0.5% of the pile cap height. Dash et al. [17] evaluated the performance of pile-mat foundation in liquefied soil and concluded that using a large foundation mat would reduce the risk of sudden collapse and settlement of the foundation. Reul [18] presented the bearing behavior of piled rafts under vertical loading and investigated the interaction of the pile and raft by means of numerical simulation.

Several investigations about a similar hybrid foundation with a

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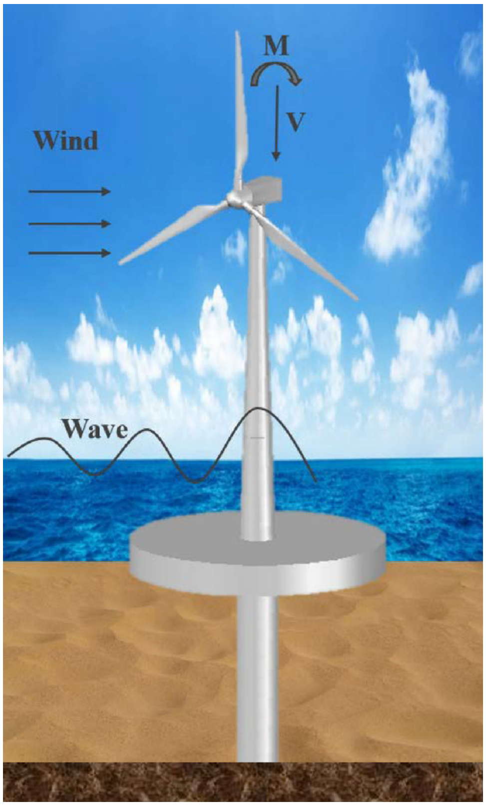

Fig. 1. Typical schematic and loadings of monopile-friction wheel foundation for offshore wind turbines.

circular footing attached to a single pile, called piled footing, have been carried out. Arshi and Stone [19–21] conducted several 1-g tests, centrifuge tests, and 3D numerical modellings on piled footings to examine the performance of the hybrid system. The results verified the promising potential of piled footing in resisting the lateral loads. Some influential factors such as the geometry of the system, the connection between the pile and footing, and the load conditions were considered and tested. It was found that the initial bearing stress applied to the soil by the plate had a significant effect on the ultimate lateral resistance of the hybrid system. Lehane et al. [22] reported several centrifuge tests of piled footing in kaolin clay. The results did not indicate much improvement in the lateral performance. It might be due to that the clay was soft and the ultimate capacity of the system was controlled by the soil strength. The vertical loads from the gravity of the footing would not improve the lateral resistance of pile obviously in that condition. Moreover, the diameter of the footing was relatively small compared with the length of the pile and the capacity of footings in clay was also insignificant. The research was extended to sand by a series of centrifuge tests and supporting 3D FE analyses [23]. The piled footings have substantially larger stiffness and bearing capacity than individual pile in sand and the capacity of the combined piled footing system are greater than the sum of the individual contributions. El-Marassi [24] explored the behavior of the monopile footing foundation under combined loading and depicted the failure envelop. According to the numerical analysis, the resistance was found to rely mainly on the ratio of pile length-to-footing width. Wang et al. [14,25] conducted several centrifuge tests to investigate the responses of the hybrid monopile foundation under static loading and cyclic loading. Analytical methods were proposed to estimate the lateral bearing capacity of the hybrid foundation under static loading and the cyclic lateral displacement of the new hybrid foundation in service conditions, respectively.

The concept of the monopile-friction wheel foundation has been proposed and examined, but only a small amount of results have been published and further testing is required to investigate the performance of hybrid foundations. Three model tests have been conducted on hybrid foundations subjected to lateral loading by Yu and Zeng [26] in geotechnical centrifuge at Case Western Reserve University. The data showed clearly the effectiveness of the monopile-friction wheel foundation in increasing the lateral stiffness and capacity. In this paper, numerical models of the centrifuge tests are built and validated by the test results. The interactions between pile, wheel and surrounding soils are investigated to explore the mechanism of load transfer and to study how the pile and wheel interact positively as a combination in the hybrid system to improve the bearing capacity. Parametric studies on the geometry and density of the friction wheel are carried out to provide references for the optimization for design of monopile-friction wheel foundations. Different load patterns are also considered and discussed.

2. Centrifuge tests

The centrifuge tests were performed in the geotechnical centrifuge at Case Western Reserve University. The payload capacity of the centrifuge is 20 g-ton with a maximum acceleration of 200 *g*. The centrifugal acceleration is 50 *g* for the reported tests, which represents a scaling factor of 50 for data interpretations. A rigid container with internal dimensions of 53.3 cm (length) × 24.1 cm (width) × 17.7 cm (height), which is 26.65 m (length) × 12.05 m (width) × 8.85 m (height) in prototype scale, was used. The soil layers were constructed with 5 m kaolin clay and 0.5 m (in prototype scale) dense sand with a relative density of 70% on the surface. The water level is the surface of the soil. Before tests, the saturated clay soil was consolidated in the centrifuge under 50 *g* for sufficient time in order to replicate the desired density of soil in Lake Erie, where a wind farm is under development.

Three types of foundation models were configured with the same simplified upper structure of a wind turbine (Fig. 2). All data about the models are reported in the prototype scale. Test No.1—monopile only, the monopile is made of aluminum with a diameter of 1.1 m and embedment length of 5.5 m. Test No.2—monopile with a solid wheel attached on the head of the pile, the solid wheel is modelled by cast iron and the dimension is 1.5 m in thickness and 7 m in diameter, hereinafter referred to as solid wheel foundation. Test No.3—monopile with a gravel wheel. The gravel wheel consists of a frame with two connected rings made of Plexiglas and gravel filled in the frame, hereinafter referred to as gravel wheel foundation. The heights of the rings are 1.5 m and diameters of the outer ring and inner ring are 7 m and 2.2 m, respectively. The gravel wheel foundation is designed for potentially utilizing gravel or crushed stones in the offshore area to reduce the cost.

The pile was pushed into the soil by hand to its desired penetration depth of 5.5 m. The solid wheel or the circle frame was then slid along the pile down to the soil surface and contacted with the soil surface firmly. For the gravel wheel foundation, the gravel was poured into the frame afterward. The wind tower is modelled by a steel rod with a diameter of 0.5 m and length of 10 m. The vertical load of the wind turbine was provided via fixing a lumped mass with a mass of 10.6 ton on the top of the tower. The photo of the whole system and the schematic cross-sectional view of the centrifuge model are displayed in Fig.2. Lateral loads were applied at a height of 3 m above the upper surface of the wheel by an actuator. The loads and displacements were recorded by a load cell and LVDT during the loading. More details can be found in the report by Yu and Zeng [26].

3. Numerical modelling

Three FE models are built in the prototype scale of the centrifuge models by the commercial software ABAQUS to replicate the situation in centrifuge tests [27]. Typical finite element meshes of the solid wheel and gravel wheel foundation are shown in Fig. 3. Relatively fine meshes are employed near the interfaces of different parts to obtain the local

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