Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference **www.isope.org**
Kona, Big Island, Hawaii, USA, June 21-26, 2015

ISBN 978-1-880653-89-0; ISSN 1098-6189

A New Fixed Offshore Wind Turbine Foundation and its in-situ Responses to Winds and Waves in East China Sea

Ling Chen[1], Jie Li[2], Jifu Zhou[1], Yifeng Lin[2], Jianying Li[2]

1. Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing, China

2. New Energy Design & Research Section, Shanghai Investigation, Design & Research Institute, Shanghai, China

ABSTRACT

We introduce a new fixed structure supporting offshore wind turbines, which is used in Donghai Bridge windfarm, East China Sea. It is a high-rise-pile-cap foundation. This foundation serves as an in-situ test model for a new type of structure to support offshore wind turbines. In order to monitor the behavior of the new structure, we installed stress/strain monitoring instruments on four steel piles and in the cap, and clinometers on the tower. In-situ measurements of wind speed and direction, stresses of the piles and the cap and inclination of the tower are obtained, based on which we analyzed the dependence of the stresses of the piles and the cap on winds and waves, and the variation of the tower inclination with winds. Particularly, we captured the behavior of the new structure in the case of typhoon Haikui.

KEY WORDS: offshore wind turbine; high-rise-pile-cap foundation; in-situ measurement; Donghai Bridge windfarm.

INTRODUCTION

With the increasing development of world economy and severe environmental problems, underground fossil fuel is no longer a right energy resource. This leads to the very popular concern of exploitation and utilization of renewable energy (Kaldellis and Kapsali, 2013; Zhou and Lin, 2013). In the last decade, Chinese government has attached great importance to offshore wind power development. In 2010, Donghai Bridge windfarm, the first offshore windfarm in China, was completed in East China Sea, which consists of 34 offshore wind turbines of 3 MW.

Above the sea, wind velocity is higher with smaller wind shear and turbulence than inland due to few obstacles (Farmakis and Angelides, 2011). These advantages have made fast development of offshore windfarm, especially in the North Sea where monopile foundation is used. Because the wind turbine at the top of the high tower, which is sitting on the foundation, generally produces large horizontal load and bending moment, it is crucial to design an absolutely safe foundation according to hydrogeological conditions. The hydrogeological conditions in East China Sea are quite different from the North Sea (Lin, Li, Shen and Song, 2007). On the one hand, a series of soft clays with the thickness more than 25 meters cover on the sea-bed. According to the environmental protection requirements and in order to minimize the feedback effects on marine ecology, sea beds in the region should be prevented from a wide range of surface hardening. As a result, monopiles and the jacket foundation for offshore wind turbine are concluded to be inapplicable. On the other hand, severe typhoon frequently hits the area. Furthermore, since there is a fairway across the wind farm, the foundation should be able to endure ship collisions. Therefore, a new high-rise-pile-cap foundation is proposed for the particular request (Lu ZM, 2010).

The new fixed structure supporting offshore wind turbines consists of a circular platform of 14 meters diameter and eight inclined supporting piles of 1.7 meters diameter, see Fig.1. The large circular platform is the surface piercing cap divided into two parts. The lower part is a 3-meter-high cylinder, and the upper one is a frustum of a cone with a half meter high. Inclined piles are evenly distributed around the bottom of the large platform cap with a common center axis and 5 meters radius. The piles are 84.5 meters long with about 65 meters penetrating into the soil. The slope ratio of each pile is 5.5 to 1. A 78-meter-high vertical tower is mounted to the platform cap with a 3 MW wind turbine fixed at its top end. And a transitional steel pipe with 4.5 meters diameter and 60 millimeters thickness is used to connect the tower and the cap. In the end, this new foundation has been proved to take full advantage of the strong horizontal bearing capacity.

This paper is organized as follows. First, the distributions of monitoring instruments are presented. Then, the tower inclination and stress of steel in both the piles and the cap are discussed under the action of winds and waves, particularly under extreme condition of typhoon. Finally, the conclusions are drawn.

MONITORING INSTRUMENTS

Pile wall stress meter

40 pile wall stress meters are installed on 4 piles to monitor the stress. 10 of them are respectively installed on both sides of each pile at heights of -30m, -20m, -10m, -5m, and -1m, with their locations indicated in Fig.2. Another three ones are installed on the transitional zone at a height of 7m, and arranged at an angle of 120° to each other.

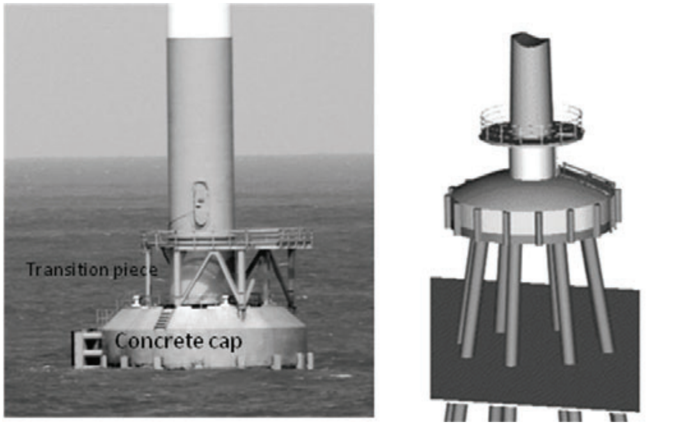

Fig. 1 A new high-rise-pile-cap foundation for offshore wind turbines.

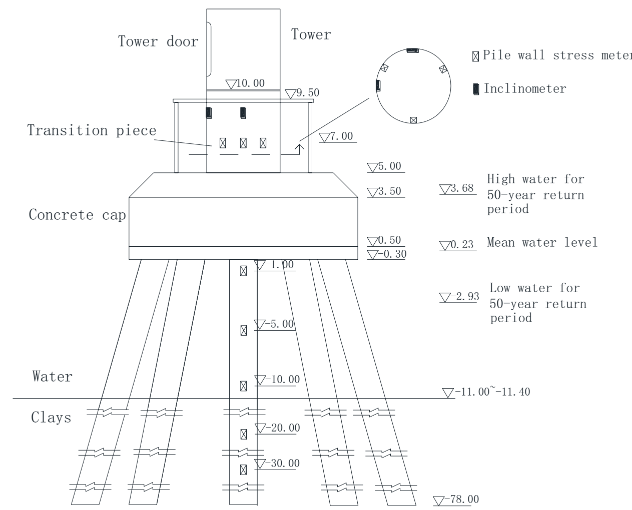

Fig. 2 The distribution of monitors.

Rebar stress meter

12 rebar stress meters are installed on the high-rise cap to monitor the loads on the steels, see Fig.5. Some other auxiliary stress meters are installed nearby, in order to eliminate the effects of the temperature and moisture, and make sure the measurements as accurate as possible.

Clinometer

Two EL clinometers are installed on the inside of the tower in horizontal direction at a height of 9m. One is towards to the north, while the other to the west, see Fig.2. In this way, the inclination angle of the tower caused by winds can be measured.

RESULTS

Tower Inclination

The tower inclination was measured in two orthogonal directions, north-south and west-east. To analyze the structure's response to the wind effect, the magnitude of inclination in time history was calculated and compared with the wind velocity as shown in Fig.3. As indicated in Fig.3, there is an obvious positive correlation between wind velocity and tower inclination. An increase in wind velocity increases the inclination angle of the tower. When the magnitude of wind velocity varies with a severe jump, an apparent increase or decrease of inclination angle of the tower is seen immediately. During February 2010, the inclination angle of the tower has a maximum value of about 3.8 minutes, which is however a small value compared with the design limit of 18 minutes. It may be noted that wind velocity is not the unique factor for the inclination. Effects of other factors may also be included. In February 23, 2010, a low wind velocity is measured, while the tower inclination turns to be relatively large. This suggests that some other factors, such as wave, can also play a significant role in the operating condition. Once the wave frequency is close to the natural frequency of the system, or if we consider a surge wave condition, the vibration and inclination of the tower cannot be predicted simply by analyzing the wind effect.

Stress

Stresses of steel piles. In-situ measurements of stress on the steel piles during September, 2009 to May, 2010 are presented in Fig.4. For the height of -1m and -10m, the stresses almost range from -30MPa to -40MPa, and the two stress lines are in substantial agreement except for partial turbulence. It may be noted that sea bed is at the height of -11m,

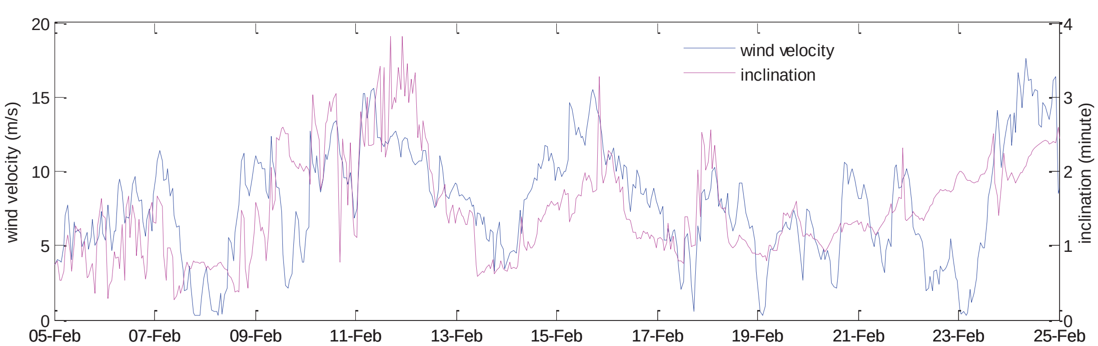

Fig. 3 Time series of wind velocity and tower inclination during February 2010.

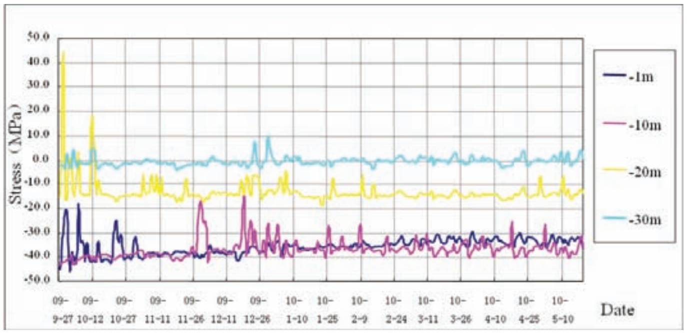

Fig.4 Measured stress on steel piles at four different heights.

and these two curves are measured above the sea bed. Here the main force is found to be the static load of the upper platform and structures due to the gravity. The maximum compressive stress reached 48.4MPa, occurring at the junction of the cap and the steel piles. When the piles penetrate into the soil, the compressive stress is found to decrease with the increasing depth. The reason is most likely related to the friction effect of the soil counteracting the static load. As seen from the curve of -30m height, the stress is nearly equal to zero. Within the height from -20m to -10m, the bending moment is significant. In some situation, under the action of winds, waves and machine operation, the pile surface stress will turn to tensile stress because of the large bending moment. As a result, piles in this section should have ability to endure the frequently changes of tensile and compressive stresses. A further investigation of fatigue should be taken in offshore wind turbine foundation designs.

Stresses of steels in concrete cap. A sketch of rebar stress meters distributed on the cap is shown in Fig.5. Stress meters R4 and R12 are installed in different directions in order to measure the vertical and horizontal stresses respectively. In Fig.6, time histories of the vertical and horizontal stresses are presented during September, 2009 to May, 2010. According to the measurements, steel bars inside the cap bear compressive stress. A maximum horizontal stress reached -17.5MPa, occurring at the location of R12. This value was observed in the early running of the wind turbine, and stress concentration is relatively obvious. After running for several months, the horizontal stress decreases gradually and becomes stationary at about -11MPa. The vertical stress, quite larger than the horizontal, ranges from -21MPa to -29.5MPa. The maximum vertical stress occurs at the junction of the cap and the transitional steel pipe.

Bearing capacity in case of typhoon

Because of the complex and changeable environment, extreme situations should be considered in designing safe enough offshore structures. The Donghai Bridge windfarm is located in East China Sea, nearby Shanghai, which is regarded as a typhoon-prone area. Therefore, in-situ monitoring during typhoon is very necessary.

In August 2012, a strong typhoon named 'Haikui' passed through the East China Sea. The minimum distance between the center of the typhoon and wind farm is about 150 kilometers. The wind velocity at the wind farm exceeded 25 m/s and lasted for at least 12 hours. Surge waves in a height of 4.5 meters and a water depth of 11 meters were observed.

During the Haikui process, the maximum compressive stress of the inclined piles varied from 15.9 MPa to 69.5 MPa, and the maximum tensile stress from 15.4 MPa to 45.1 MPa. Its material has the allowable

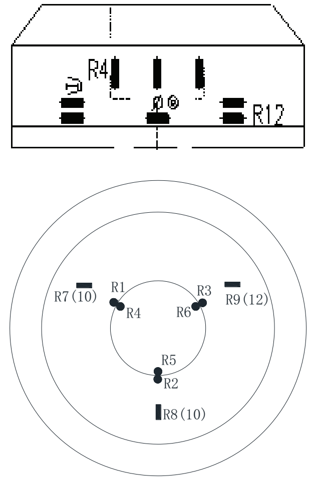

Fig.5 Sketch of distribution of rebar stress meters installed in the cap.

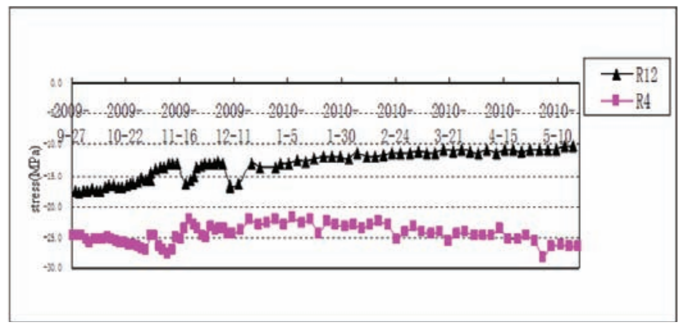

Fig.6 Measured stress at the location of gauge R4 and R12.

compression strength of 197 MPa and tensile strength of 201 MPa respectively according to the design standards. The measured maximum compressive stress of the steel in the inner of the platform cap was from 10.7 MPa to 32.4 MPa, while its material has the allowable compression strength of 360 MPa. The maximum horizontal displacement of the platform cap was from 18 mm to 25 mm, much smaller than the designed allowance of 55 mm. These monitoring results suggest that the new fixed structure has a good bearing capacity in case of typhoon and meets the safety requirements for operation.

CONCLUSIONS

Donghai bridge windfarm is the first large offshore windfarm in Asia. It has promoted the development of offshore wind energy, and serves as a demonstration project in China. In consideration of special characteristics of foundation design and technical difficulties, the behavior of the new structure has been monitored.

For the tower inclination, an obvious positive correlation of wind velocity was found, but some other factors like waves should be considered secondarily. The maximum inclination angle is about 3.8 minutes, which is much smaller than the design limit of 18 minutes. From the measured stress of steel in general operation conditions, both the piles and the concrete cap are in safety. However, in some sections of the piles, the frequent changes of tensile and compressive stresses should be carefully taken into account when designing the fatigue limit.

During the process of typhoon ‘Haikui’, monitoring steel stress and tower inclination was carried out. All the measured parameters are far smaller than the allowable limits.

In conclusion, all parameters monitored meet the specified design requirements. Thus, the new high-rise-pile-cap foundation is a safe one for offshore wind turbines in Donghai Sea.

ACKNOWLEDGEMENTS

We would like to express thanks to the financial support from the National Natural Science Foundation of China under Grant Nos. 11172307 and 11232012 and from 973 program under Grant No. 2014CB046200.

REFERENCES

Farmakis, GE and Angelides, DC (2011). “Fixed Bottom Tripod Type Offshore Wind Turbines under Extreme and Operating Conditions.” *Proc 21th Int Offshore Polar Eng Conf*, Hawaii, ISOPE, 1, 291-298.

Kaldellis, JK and Kapsali, M (2013). “Shifting towards offshore wind energy—Recent activity and future development.” *Energy Policy*, 53, 136-148.

Lin, YF, Li, JY, Shen, D and Song, C (2007). “Structure characteristics and design technique keys of turbine foundation in Shanghai Donghaid-bridhe offshore wind farm.” *Shanghai Electric Power*, 2, 153-157. (In Chinese)

Lu, ZM (2010). “Study on key technologies employed in planning and construction of Shanghai Donghai Bridge offshore wind farm.” *Engineering Sciences*, 12(11), 19-24. (In Chinese)

Zhou, JF and Lin, YF (2013). “Essential mechanics issues of offshore wind power systems.” *Scientia Sinica (Physica,Mechanica & Astronomica)*, 43(12), 1589-1601. (In Chinese)