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Letter

Long-term dynamic behavior of monopile supported offshore wind turbines in sand

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ABSTRACT

The complexity of the loads acting on the offshore wind turbines (OWTs) structures and the significance of investigation on structure dynamics are explained. Test results obtained from a scaled wind turbine model are also summarized. The model is supported on monopile, subjected to different types of dynamic loading using an innovative out of balance mass system to apply cyclic/dynamic loads. The test results show the natural frequency of the wind turbine structure increases with the number of cycles, but with a reduced rate of increase with the accumulation of soil strain level. The change is found to be dependent on the shear strain level in the soil next to the pile which matches with the expectations from the element tests of the soil. The test results were plotted in a non-dimensional manner in order to be scaled to predict the prototype consequences using element tests of a soil using resonant column apparatus.

Introduction Harvesting offshore wind energy is a new initiative and a promising option for protecting the environment. Offshore wind turbines (OWTs) are relatively new structures with no long term track record of their performance yet they are to be constructed and meant to produce energy for 25–30 years [1–4]. OWTs, due to their slender nature coupled with irregular mass and stiffness distribution, are dynamically sensitive structures. The first natural frequencies of these structures are very close to the forcing frequencies imposed by the environments and the onboard machinery. Changes of the foundation stiffness under cyclic loading will ultimately result in changes to the natural frequency of the structure. Therefore, the design of foundations and prediction of long term performance are very challenging. The loading on an OWT is complex and is a combination of static, cyclic, and dynamic loads:

(1) the external load produced by the wind and its turbulence, applying approximately one-way cyclic load to the foundation,

(2) the external load caused by waves, which is approximately two-way cyclic,

(3) the internal load caused by the vibration at the hub level due to the mass and aerodynamic imbalances of the rotor (this load has a frequency equal to the rotational frequency of the rotor (referred to as 1P loading in the literature) and is dynamic in nature),

(4) dynamic internal loads on the tower (as shown in Fig. 1) due to the vibrations caused by blade shadowing effects (referred to as 2P/3P in the literature), which is dynamic in nature.

Typical natural frequencies of OWTs are in the range of 0.3–0.9 Hz [1]. The load frequencies that are close to the natural frequency of the turbines can be classified as dynamic load which requires special consideration, i.e., the ratio of forcing frequency to natural frequency (f_f/f_n) and the damping in the system.

A case study Shanghai Donghai Bridge offshore wind farm is one of the first large scale commercial developments [5]. Figure 2 shows the main frequencies for a three-bladed 3 MW Sinovel wind turbine with an operational interval of 8.1–19 RPM (revolutions per minute). The 1P lies in the range 0.135–0.316 Hz and the corresponding 3P lies in the range 0.405–0.948 Hz. The figure also shows typical frequency distributions for wind and wave loading. The peak frequency of typical waves is about 0.12 Hz. It is clear from the frequency content of the applied loads that the designer of the turbine and foundation has to select a system frequency which lies outside this range of frequencies in order to avoid system resonance and ultimately increased fatigue damage.

Three types of designs are possible (see Fig. 2): (1) “soft–soft” design, where the target frequency is placed below the 1P frequency range, i.e., less than 0.135 Hz, which is a very flexible structure

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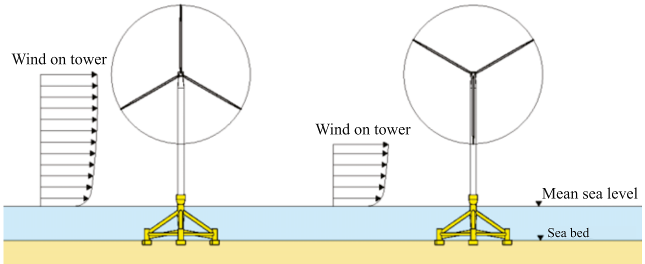

Fig. 1. Cyclic/dynamic load acting on the tower due to blade shadowing effect.

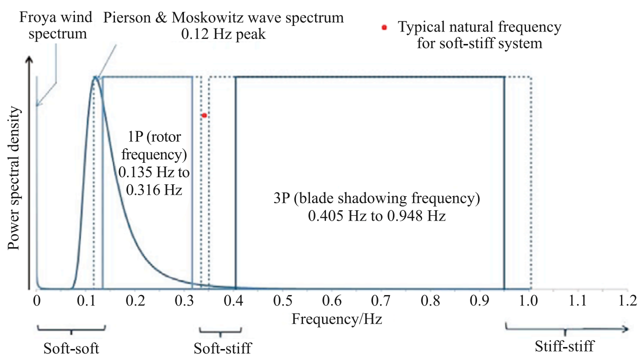

Fig. 2. Forcing frequencies against the power spectral densities for a 3 bladed 3 MW Sinovel OWT.

and almost impossible to design for a grounded system, (2) "soft–stiff" design, where the target frequency is between 1P and 3P frequency ranges and this is the most common in the current offshore development, (3) "stiff–stiff" design, where target natural frequency have a higher natural frequency than the upper limit of the 3P band and will need a very stiff support structure. Det Norske Veritas (DNV) [6] also specified that the system frequency should be at least ±10% away from operational 1P and 2P/3P frequencies, as indicated by the dotted lines in Fig. 2. Therefore, the available range of safe frequency content to place the OWT is narrow.

Prediction of OWT's long term behavior OWTs are subjected to approximately 10^7–10^8 cycles of loading in their life time and two aspects are important with regards to the design of foundations: (1) assessment of the change of soil behavior due to effect of cycling and its impact on the foundation (this is similar to the fatigue problem) and (2) dynamic amplification of the response of the structure over a range of excitation frequencies close to the natural frequency of the system. This would mean higher displacement of the foundation, i.e., higher strain in the soil. This is similar to the resonance problem. Recent observations of wind turbines suggest that resonance is a serious issue [7–10]. Field measurement indicates that the resonance issue is caused by the change of its foundation stiffness after several years of service [2].

Therefore, the design problems are: (1) prediction of the long term tilt in the wind turbine due to the change in the soil properties owing to irregular and asymmetric cycling, (2) long term shift in natural frequency of the system and how close can the frequency be with respect to the forcing frequencies. This is particularly important for "soft–stiff" design as any increase/decrease will impact on the forcing frequency causing higher fatigue damage [11].

Due to its previous successful application in OWTs, monopile is still the prevailing foundation option for supporting OWT for water depth of less than 30 m in standard soils (sand, soft and stiff clay). More than 75% of the OWTs in Europe (i.e., UK, Denmark, Germany, and Netherlands) are supported on monopiles [1]. This paper therefore investigates the long-term dynamic behavior of monopile supported OWT through a series of small scale tests. This is in contrast to the tests carried out in other researchers' work, see for example Refs. [12,13], where the dynamics of the problem is not considered and fatigue type problem is investigated.

Derivation of the correct scaling laws constitutes the first step in an experimental study. Every physical process or mechanism can be expressed in terms of non-dimensional groups and the fundamental aspects of physics must be preserved in the design of model tests. In this paper, the main principle of scaling related to OWTs comprises of geometrical and mechanical similarities between scaled model tests and prototype. And this part has been discussed in detail in Refs. [1,14,15] and the readers can refer to those publications for more information.

Dynamic loading system Previous research [1,14–16] on dynamic testing as shown in Fig. 3(a) used an actuator to apply all the cyclic and dynamic loads at one location (denoted by y_c in Fig. 3(b)) and the methodology to find out the load is shown in Fig. 3(b) [1]. After applying a user defined number of cycles, the actuator is disconnected to obtain the natural frequency through free vibration test. Then, the actuator needs to be reconnected to apply the next set of cyclic loads. This causes not only some amount of inconvenience to the testing but also unavoidable disturbance to the soil around the foundation. Furthermore, the actuator can only provide one directional regular cyclic loads. But in reality, due to the misalignment of wind and wave, the cyclic load is always multidirectional. This led to the development of an innovative cyclic loading system used in this paper.

The physics behind this innovative device is simple and follows the concepts of centripetal forcing, i.e., for a body of mass m, which is rotating about a center in a circular arc of radius r at a constant angular frequency ω, the mass will exert an extra force acting towards the center of rotation in the magnitude of F_n ($F_n = mr\omega^2$, see Fig. 4(a)). Figure 4(b) shows the final design of the device and it produces a harmonic loading in two perpendicular directions when two masses (m_1 and m_2) complete one revolution

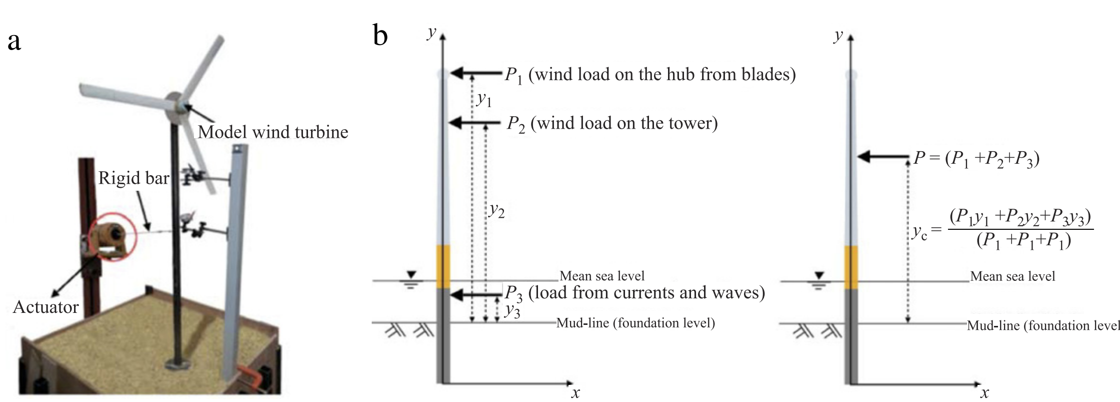

Fig. 3. (a) An actuator used to supply dynamic loads. (b) The method to compute the load P and height y_c.