Subsoil load monitoring on monopiles of offshore wind turbines using optical strain gauges.

24SEA has been involved in various projects over the last years all focussing on foundation monitoring. Typically, up to 10% of the foundations within offshore wind farms are equipped with a Foundation Structural Health Monitoring (FSHM) system, consisting mainly of installing accelerometers and strain gauges in the transition piece. In the recent projects, for both the Belgian wind farm Nobelwind and the UK wind farm Galloper, 24SEA teamed up with TUBS and Com&Sens, to equip monopiles with optical strain gauges over the entire length of the monopile. With this innovative set-up, the projects aim to better understand the subsoil dynamics and to validate new design methodologies for the soil structure interaction.

In addition, the subsoil sensors can be used to access the lifetime directly near the critical welds and validate the concept of virtual sensing below the mudline, where strains over the entire substructure are predicted using accelerometers only. In this piece, we will discuss the first results obtained from the optical strain gauges installed on the monopile.

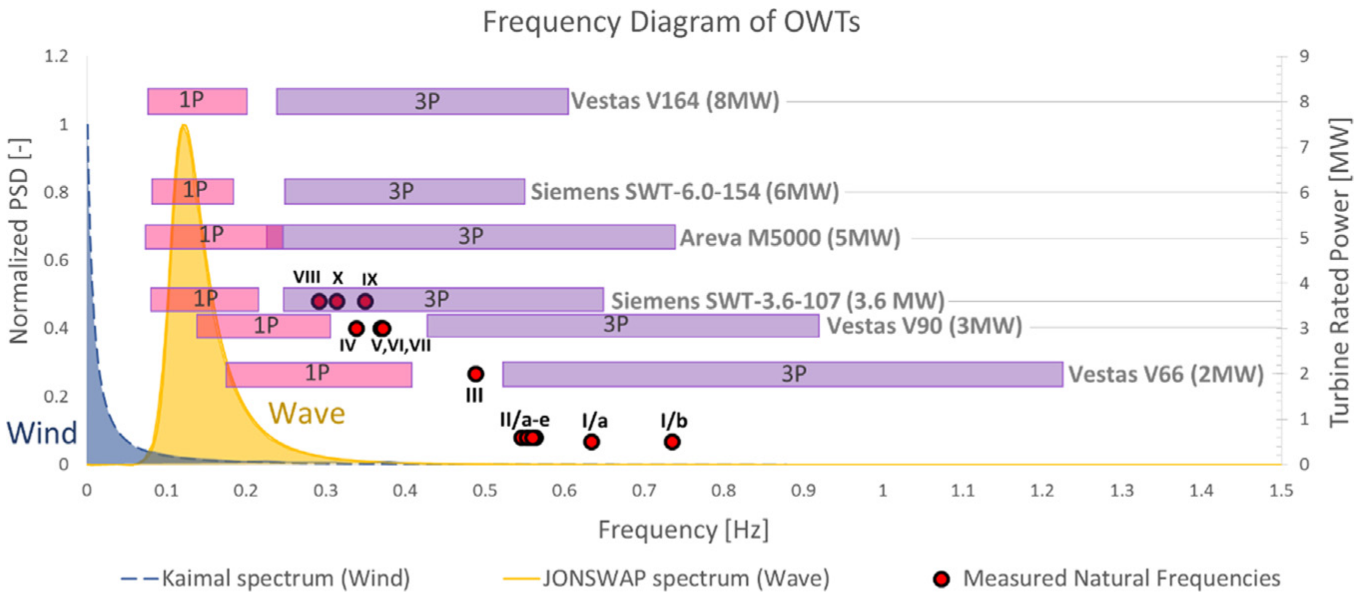
Motivation

Offshore wind turbines (OWTs) are some of the most dynamic civil structures. The substructures of OWTs are loaded by both wind and waves, and agitated by the rotations of the wind turbine on top. The most common substructure design in offshore wind is the so-called monopile foundation, which represents over 80% of all offshore wind turbines. A monopile foundation is a single cylindrical pile with diametres ranging from 4 to 8 metres and lengths up to 70 metres.

The design of an offshore wind turbine on monopile foundation is strongly driven by the dynamic interaction between the periodic wave-loading, the rotor harmonic loads (e.g. unbalances or blades passing) and the first structural resonance frequency. The entire structure is designed 'soft-stiff' in which the 1st resonance frequency is positioned between the 1P (unbalance) and 3P (blade passing) rotor harmonics. With the growing size of wind turbines this frequency has dropped significantly in the past years. As a result the OWT first resonance frequency is closer to the wave period, increasing the resonant behavior and the subsequent fatigue loading.

For an optimised design, it is thus necessary to accurately predict the first resonance frequency based on the geotechnical data available at the site. However, industry often still relies on engineering codes developed for the offshore oil & gas (O&G) industry in the 1970's [Cox, 1974; Doherty, 2011]. However, both the non-slender geometry of the monopiles and the cyclic loads fall outside the original design codes for O&G [Cox,1974]. This limitation in design has led to an industry-wide mismatch between design expectations and the completed OWT. In a large study [Kallehave, 2015] on 400 offshore wind turbines a 10% underestimation of the first resonance frequency was common. This observation was also confirmed by many short-term design verification measurement campaigns performed by 24SEA within several offshore wind farms.

Currently, so-called p-y curves are used to determine the initial stiffness of the soil in the Winkler model. These p-y curves date back to the 1970's and are generated for oil & gas. It is the general consensus of both academia and industry that these p-y curves are incorrect for assessing the stiffness of small displacements, for short and large diameter piles (i.e. monopiles), in particular for clayey soils. Research projects such as PISA and DISSTINCT have targeted the soil structure interaction of offshore wind turbines for this reason.



With the growing size (i.e. rated power) of modern wind turbines this has put the turbines closer to wave loading. An accurate estimate of the resonance frequency is more important than ever during design. [Arany, 2016]

The second motivation for the monitoring of the foundations is the fatigue-driven design of offshore wind turbines. A monopile is designed so that it can withstand 20-25 years of cyclic loading from both wind and wave. In an optimised design, several welds are dimensioned to exactly match this targeted lifetime. In general, the most fatigue critical welds are positioned just below the mudline. As the monopile foundation has no structural redundancy, the lifetime of the foundation is defined by the remaining life-time of the most fatigue damaged weld.

Measurement setup

In both projects three monopiles in the farm were selected based on their position in the fleet, the soil conditions and their dynamic properties. All three monopiles were instrumented during the fabrication of the monopile with 4 optical fibre lines. Each optical fibre line is imprinted with several localised strain sensors positioned above and below the mudline of the monopile foundation. Note that the sensors had to be installed prior to the actual pile driving of the turbine. To assure the sensors survived this process the subsoil sensors were covered with protective sheeting and a driving shoe. During installation some sensors failed during the pile driving. However, the majority of fibres survived and all three monopiles have a functional strain monitoring set-up.

Results

Time series

The optical strain gauges below the mudline were installed to verify the fatigue progression in the monopile. Using state of the art interrogators, these Bragg gratings allow recording the strain history at a sampling rate of 100Hz. The offsets on the strain gauges are removed using an in-house developed scheme for strain gauge calibration.

In the figure below time series recorded subsoil are shown. One can clearly see the cyclic/dynamic behaviour of the strain. It is this continuous cycling of the structure that will potentially cause structural fatigue.

Bending moments

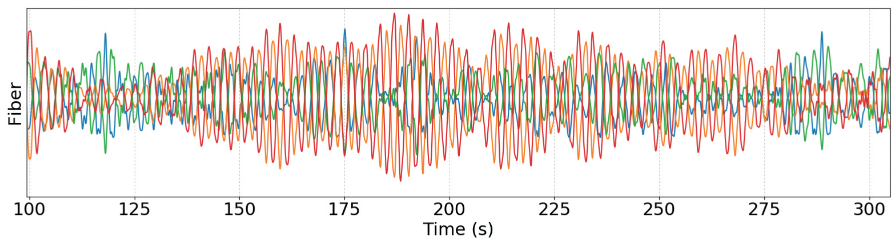
While the fatigue assessment is related to the dynamic content of the recorded strains the bending moment profiles allow the soil properties assessment at the site. In the figure on the next page bending moments are plotted for different windspeeds and for different heigths on the monopile.

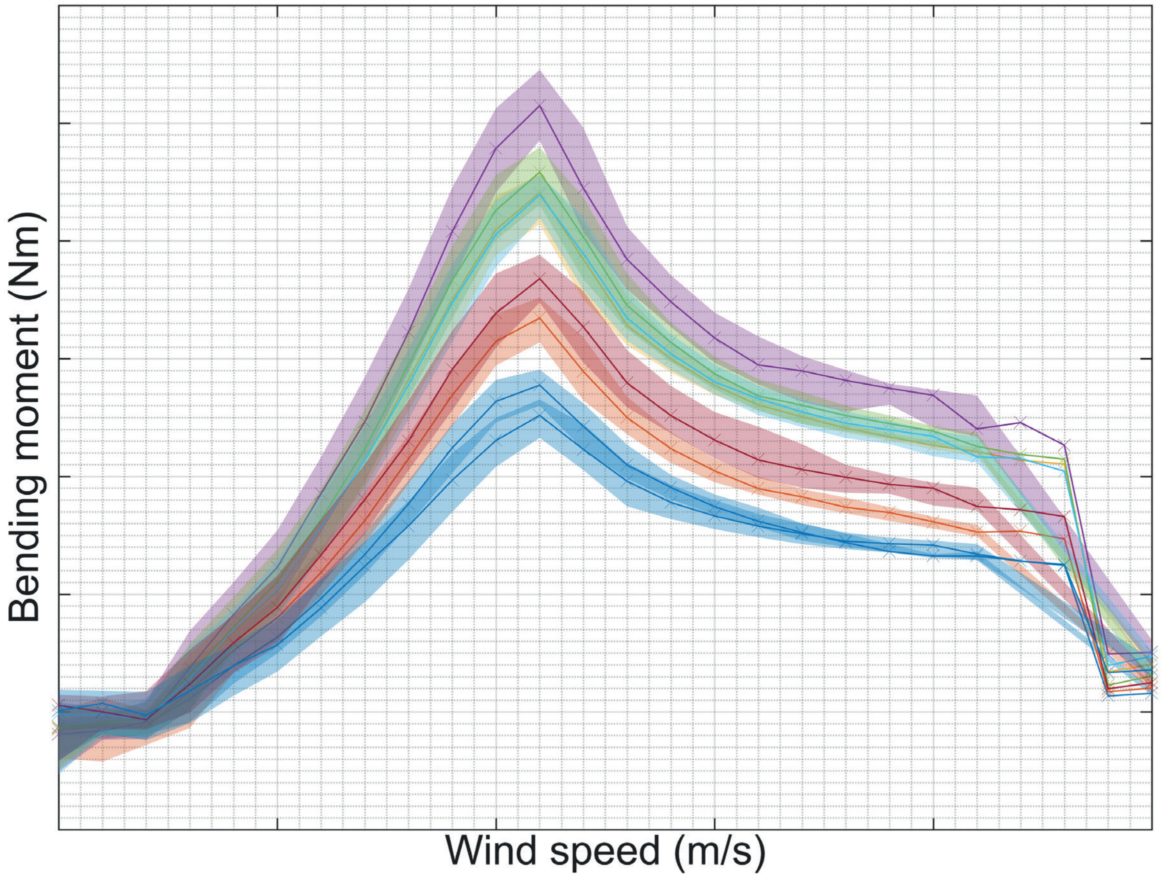
One can clearly see the typical load behaviour of a wind turbine. The bending moment transferred to foundation depends on the thrust loading in the turbine. The results show that beyond a certain wind speed the bending moment starts to decrease. The results also reveal the expected behaviour where the bending moment is reduced for greater depths into the soil.

The set-up is similar to the original setup proposed by Reese in 1974, which led to the first p-y curves and thus, to some extent, allows for determining the p-y behaviour in-situ. In the continuation, the measurements will be compared with the bending profiles predicted by the classic soil models and update the model to the recorded measurements.

Virtual Sensing

The above set-up also allows validating the virtual sensing concept. Virtual sensing is a broad term for techniques that allow reconstructing the strain histories on the monopile, without the need for any direct measurements on the monopile itself. Instead, easy to install and reliable sensors on the turbine tower and the transition





piece are used to extrapolate the dynamic behaviour, to any location on the substructure/foundation, by combining the sensor data with a reduced structural FEM model in the loop and the available SCADA data. A virtual sensing strategy is interesting when no measurements on the monopile are available, which is the most common situation in offshore wind energy.

Conclusion

We can conclude that the first results show the success of optical strain sensors on the monopile for offshore wind turbines. The measurements allow recording the strain history at a sufficiently high frequency and the calculations of the bending moments over the entire length of the monopile for fatigue assessment. The measurements also allow validating the concept of virtual sensing to predict strain histories over the entire structure by using classic reliable sensors.

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