FEASIBILITY OF MONOPILES FOR LARGE OFFSHORE WIND TURBINES

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Summary

Monopiles are the most popular substructure for offshore wind turbines but up to now have not been employed for turbines of the 5MW class. It is shown in this paper that monopiles may be feasible in greater water depths than assumed to date, even for offshore turbines larger than 5MW, while maintaining very reasonable weight and size. This is being achieved by a sophisticated design process which makes use of comprehensive site data, improved optimization methods and efficient design procedures. With these measures in place it is estimated that water depths up to 30m may be feasible with monopiles using large turbines.

1 Introduction

Offshore wind turbines of the 5MW class have not yet been built with monopiles, the predominant substructure for smaller wind turbines, mainly because these larger turbines have been installed in deeper waters where structures such as jackets [1] are more favourable.

The question is often raised as to what water depths monopiles are a viable alternative for bigger turbines, with depths between 10m and 25m often stated. Based on experience from REpower, this paper focuses on reviewing these statements, giving recommendations as to how monopile feasibility can be assessed.

2 Design Basis requirements

Due to different behaviour under wave loads, Design Basis requirements are different for jackets and monopiles [2]. Monopiles are significantly more affected by wave loads, hence all parameters relating to the wave climate are of high importance. This applies to:

- Wind-wave scatter diagram (i.e. dependency of wave height on wind speed at hub height)
- Wave periods
- Wave spectra
- Wind-wave-misalignment

Wind-wave-misalignment is a parameter which has often been neglected in the past, but which is now recognized to be of major importance because of the small amount of damping in the direction lateral to the wind [3].

The second area with great impact on monopile design is the soil. While jackets are not significantly influenced by soil properties regarding global response, the opposite is true for monopiles. In particular, the first natural frequency and associated damping in this mode are driving the design, and these are very dependent on soil input parameters, namely soil stiffness and damping contribution of the soil. For jackets, soil properties typically only have an influence locally (in the lower part of the jacket) and for the design of the axially loaded foundation piles.

3 Design process

The large impact of wave loads on the monopile structure does of course impact the design process. Some aspects are highlighted in the following sections.

3.1 Overall layout

The overall layout of the installation, i.e. choice of platform height, tower length, etc. is driven by several considerations. Operators often try to maximize hub height in order to increase energy yield but this conflicts with structural design, especially in the case of monopiles since it significantly impacts first natural frequency – increasing hub height lowers the first (fundamental) natural frequency. Lowering the first natural frequency leads to increased wave excitation, because the first natural period is shifted towards the peak period of the wave spectrum.

For jackets, such an increase in hub height does not cause any changes in wave excitation. The increase in loads is then purely related to the increase in lever arm due to the longer tower.

3.2 Load simulations

Load simulations are an important part of the design process. For monopiles, the following needs to taken into account:

- Loads can only be assessed reliably in an integrated model, where wind and wave loads are considered simultaneously. Separate calculations are cumbersome because aerodynamic damping and impact of wave induced motions on controller behaviour can not be taken into account easily.

- Stand-still conditions are important because wave loading causes global loads due to the resulting excitation of vibrations in the first natural mode. For jackets, stand-still is not important because global vibrations are not excited.

The global effect of wave loading can easily be seen in the example simulations shown in Fig. 1 and Fig. 2. The figures show bending moments at tower bottom for two cases:

- Wind and wave are aligned, i.e. both from 0°, which causes the largest bending moment around the y-axis (longitudinal moment) – red curves

- Wind and waves are misaligned by 90°, i.e. wind is still coming from 0° and waves are coming from 90° - black curves.

In Fig. 1 the impact of the waves on the longitudinal bending moment at tower bottom can be seen. As the aerodynamic damping is large in this direction, the waves do not change the response behaviour significantly.

For the misaligned case in Fig. 2 a dramatic increase in bending moments can be observed. This needs to be taken into account when designing monopiles and it can only be done when substantial information about wind-wave-misalignment is available.

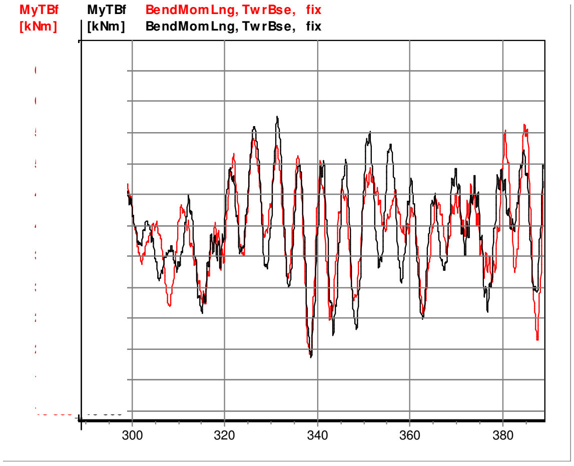

Fig. 1: Longitudinal bending moment at tower base (red: wind and wave aligned, black: wind and wave misaligned by 90°)

The consequence for the design process is that simulation effort has to be increased significantly to take into account wind-wave-misalignment. If 30° sectors for wind and waves are used, the total number of simulations for each wind speed could be up to 12·12·6·3=2592 time series (12 wind sectors combined with 12 wave sectors, with 6 seeds and 3 yaw misalignment angles each). For 27 wind speed bins (from 3m/s to 30m/s for the REpower machines), this would result in 69984 time series for power production.

Even if opposite directions are added and intelligently combined with seeds and yaw misalignment, this leads to a large number of required simulations for production and idling cases (at least around 1000 simulations for each).

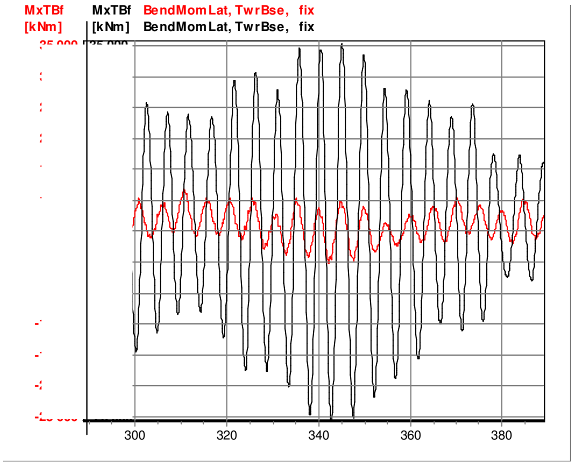

Fig. 2: Lateral bending moment at tower base (red: wind and wave aligned, black: wind and wave misaligned by 90°)

3.3 Structural design

Interaction between stiffness and loads, especially fatigue loads, is much larger for monopiles than for jackets. For jackets, even significant changes to wall thicknesses and pile stiffness do not cause major changes in loads. For monopiles this is completely different, hence the iteration process between load calculations and structural design is much more sensitive and time consuming.

REpower has also experienced the situation where wrong conclusions are easily drawn when monopile feasibility is assessed based on preliminary, non site-specific loading information. In several projects, monopile feasibility could be proven by detailed load calculations, where it had previously been negated based on preliminary loading information. This shows that early involvement of the turbine manufacturer is a prerequisite for making the right decisions in a project!

4 Optimization potential

The special characteristics of a monopile under wave loads also stipulate different optimization methods. The following measures would be almost non-effective for jackets, but have great potential for monopiles:

- Advanced controls: Feedback control, which uses modified pitch controller settings to reduce vibrations, is predominantly known and employed to reduce longitudinal vibrations. This must be expanded to also work effectively for lateral vibrations, which may be much more important for monopiles.

- As stated, significant fatigue loads may also be induced during idling conditions. This applies to normal situations below and above the operating wind speeds as well as for fault conditions within the interval of operating wind speeds. Active idling control in these situations can be a significant contribution to limit fatigue loads.

- A mechanical means to reduce vibrations are vibration dampers (mechanical or liquid dampers), which are well-known techniques from chimneys and buildings.

Using these measures helps enable monopiles for sites which have not previously been feasible.

5 Potential sites and recent design examples

Whether monopiles are an option for a specific site does therefore depend on the site parameters, specifically wave and soil conditions.

Regarding wave climate, conditions in the UK are often more benign compared for example to the German North Sea, see Fig. 3. An example for typical wind-wave-correlations is shown in Fig. 4, where it can be seen that wave heights are much smaller in the Greater Wash area compared to the German North Sea. This does of course significantly impact required monopile size or stiffness requirements.

Based on comparison of the 100-year significant wave height ($H_{S,100}$) it does seem probable that some areas of the Round 3 projects in the UK can (partially) be built with monopiles if this turns out to be the most economic solution.

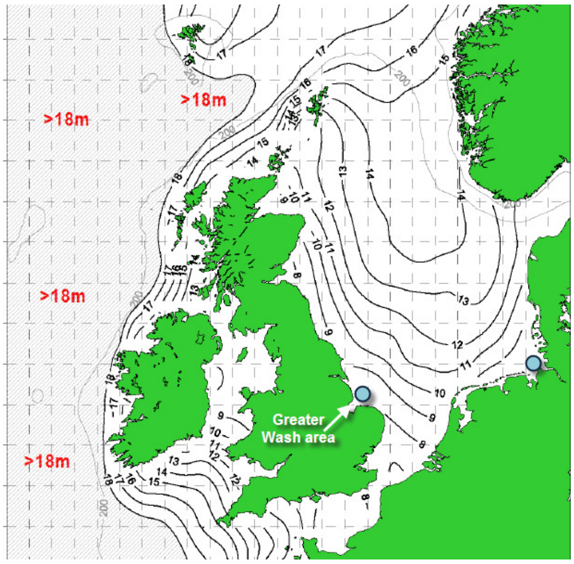

Fig. 3: Contour map of 100-year significant wave height [4]

Indicatively, all sites with $H_{S,100}<10$m, good soil conditions and water depth less than 30m should be considered as candidates for monopiles.

REpower has recently developed several designs for German and UK sites and, based on the design principles stated above, very reasonable monopile designs were achieved. Two examples are given below. Approximate locations are marked with blue dots in Fig. 3.

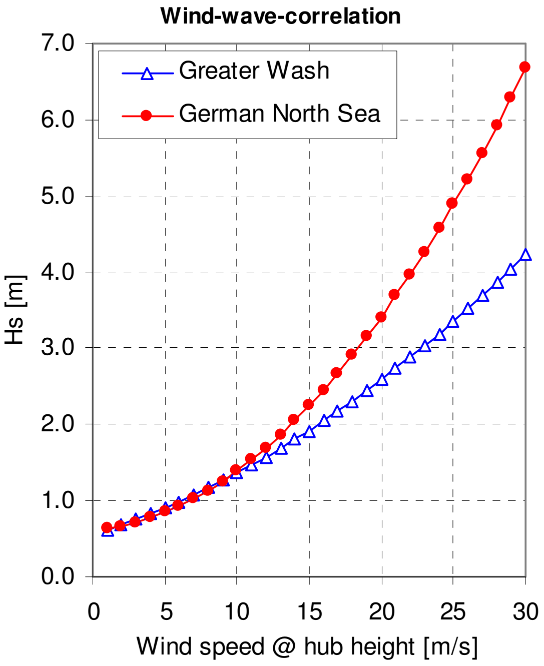

Fig. 4: Indicative wind-wave-correlation function for Germany and UK (in similar water depth)

5.1 Example 1: UK site, Greater Wash area

The first example is from the Greater Wash area in the UK, the main site characteristics are:

- Water depth: 22.0m LAT
- Hub height: 90.0m LAT
- Soil: Clay and chalk
- Monopile: D=6500mm
- Weight: app. 650t (Monopile + T.P.)
- 1st natural frequency: $f_0 = 0.24$ Hz

It can be seen that the combined weight of monopile and transition piece (T.P.) is very reasonable, and also that the diameter of 6500mm does not differ significantly from the size already known in the market for use with smaller turbines.

5.2 Example 2: German North Sea

The second example is located in much more demanding conditions, particularly regarding the wave climate. In this case the combined weight of monopile and transition piece increases but is still within practical limits.

Water depth:	21.5m LAT
Hub height:	90.0m LAT
Soil:	Sands, medium to dense
Monopile:	D=6500mm, conical to 5200mm
Weight:	app. 820t (Monopile + T.P.)
1st natural frequency:	$f_0 = 0.23$ Hz

5.3 Guesstimates for maximum water depth

Based on these and other design examples the following guesstimates for maximum water depth feasibility can be given:

German North Sea, typical soil with dense sands:

- app. 24m with 6500mm Monopile
- app. 28m with 7500mm Monopile

Greater Wash area, stiff soil:

- app. 28m with 6500mm Monopile

6 Cost comparison

When making the comparison between jacket and monopile, the following must be taken into account:

- As loads (especially fatigue loads) are lower for a jacket, the tower will also be lighter (and less expensive).
- At least for some jackets the interface height is several meters above the platform [1], leading to a shorter tower.
- Scour protection is typically not required for jackets while it is mandatory for monopiles (at least in sand).

This is reflected in the cost comparison shown in Fig. 5. The combined steel weight of jacket and foundation piles is about 20% less than the combined weight of monopile and transition piece in this case. The unit fabrication price for the jacket is of course higher than for the monopile, which results in higher structural costs. This is balanced though by the lower cost for the tower (which is shorter and lighter) and the omitted scour protection.

For the installation, it was assumed that jacket installation is more expensive than monopile installation as three or four piles need to be driven.

In total, the jacket is assessed to be only marginally (by 2% based on installed cost) more expensive for this example.

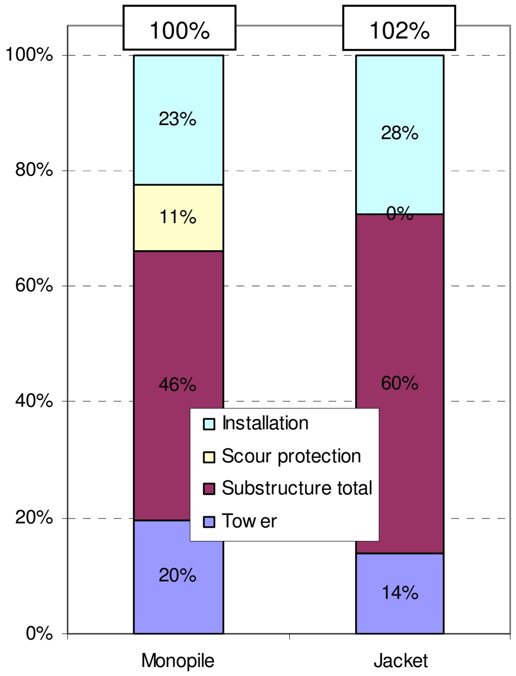

Fig. 5: Indicative cost comparison for monopile vs. jacket for a North Sea site in 22m water depth

7 Summary and conclusions

Due to advanced design methodologies, which have been refined in the past years, monopiles can be foreseen for large turbines like the REpower 6M in areas which have previously not been assessed to be feasible. In addition masses and dimensions are much more practical compared to estimates made some years ago.

In order to arrive at the correct dimensions, certain design principles need to be followed and project owners must provide more comprehensive site data in their Design Basis documents. Finally, early involvement of the turbine manufacturer to devise accurate fatigue loads is a key factor to achieve an economic design.

8 References

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