6MW TURBINES WITH 150M+ ROTOR DIAMETER – WHAT IS THE IMPACT ON SUBSTRUCTURES?

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Summary

The rotor size of offshore wind turbines is due to increase in the coming years. While the currently largest offshore wind turbine (the REpower 6M) has a rotor diameter of 126m, this will increase to 150m or even larger in the coming years. This has some implications on the support structures, primarily due to increased lever arm to hub height and increased swept area. Nevertheless, it can be shown that the impact on support structures is limited, as other factors (like wave loading) are of equal importance. With capacities for monopile fabrication increasing, it appears that even 40m water depth is feasible, provided that stiff soil conditions are present. Another interesting finding is that tower head mass does not influence substructure masses as much as thought so far. It can be shown that smaller head masses can even lead to increased substructure weights, depending on site conditions.

1 Introduction

REpower has installed 74 offshore wind turbines to date in five offshore projects with jackets and gravity base substructures. Additionally, design work has been completed on basic design or certification level for several other wind farms, particularly with jacket and monopile substructures, see e.g. [1] and [2]. These designs were made for the REpower 5M and 6M turbines, which both have 126m rotor diameter, as well as for larger rotor diameters. Based on this experience, the implications of using a rotor size of ~150m will be discussed in this paper.

2 General implications of increasing rotor size

2.1 Overall layout

An obvious change when the rotor size is increased is that hub height needs to be increased as well. Current offshore wind farms typically use the minimum hub height which is feasible to maintain sufficient clearance to the platform level and (in the UK) of blade tip to MHWS (mean high water spring) water level. There is hence a change in lever arm to hub height (which increases bending moments) and an increase in tower flexibility (which decreases the first natural frequency). The consequences are explained below.

2.2 Turbine loads

Wind induced loads are depending on the rotor diameter, rotation speed and the aerodynamic characteristics of the rotor blade. Thus, no general statements are possible. An approximation (assuming similar aerodynamic profiles) is that thrust loading increases with swept area, but if turbine loads are part of the optimization process, then this is not necessarily correct.

Compared to a 126m rotor diameter, it is well possible to limit the increase of aerodynamic loads for a 150m rotor to say 20%. The change in lever arm to hub height accounts for another 20% increase of tower bottom loads, the total increase of loads (both ULS and FLS) at tower bottom is thus in the order of 40-50%, which is quite substantial.

3 Jackets

3.1 Impact of rotor size on eigenfrequencies

Typical first eigenfrequencies for the entire system with a jacket substructure are as follows:

126m rotor diameter: $f_0 \approx 0.30$ Hz
150m rotor diameter: $f_0 \approx 0.25$ Hz

Looking at the rotational speeds of the turbine, this is in both cases ideally placed between 3p excitation at cut-in and 1p excitation at rated wind speed. For 150m rotor diameter, the rotational speed range will be about 6…10rpm, hence:

$f_{1P,max}$ = ~10 rpm / 60s = 0.167 Hz
$f_{3P,min}$ = ~6 rpm / 60s · 3 = 0.300 Hz

3.2 Impact of rotor size on substructure weight and cost

Turbine induced loads are primarily relevant for the upper part of the substructure. Towards seabed, wave loads are becoming more important and may govern the design (depending on water depth and wave conditions). The increase in loads can therefore not be directly translated into an increase of steel mass.

Only the tower plus member sizes, structural weight and welding volumes in the upper part of the substructure are strongly influenced by turbine loads. On the other hand, there is a number of cost contributions which are only weakly to moderately influenced by turbine loads, namely:

- Member sizes, structural weight and welding volumes in the lower part of the substructure
- Pile size and penetration
- Assembly (except for welding time)
- Transport & installation
- Corrosion protection

Overall, the cost increase may thus be limited to ~20% compared to a 126m rotor diameter (needless to say that this depends on specific project conditions).

3.3 Influence of tower head mass on turbine loads

The influence of tower head mass has been studied for a typical North Sea project with the following characteristics:

- Turbine: 6M126
- Hub height: 90m
- Water depth: 40m LAT
- Substructure: Jacket
- Tower length: 61m

The first natural frequency for different nacelle masses is as follows:

- M_{nac} = 325t: $f_{0,325t}$ = 0.31 Hz
- M_{nac} = 200t: $f_{0,200t}$ = 0.36 Hz

Complete ULS and FLS simulations have been carried out with the two nacelle masses. The results were as follows:

1. ULS loads for the substructure are governed by the 50-year-storm load case DLC 6.1. The difference in ULS loads was found to be insignificant, which is logical as the wind load on the rotor (which is unchanged) is the most important factor.

2. FLS loads at tower bottom are 10% higher for the nacelle mass of 200t, compared to the fatigue loads for 325t nacelle mass. The reason for this increase is that the main response of the system is shifted towards higher frequencies, which means an increased number of cycles.

It does hence turn out that a lighter nacelle would in this case require a heavier substructure! This example is deemed to be representative for typical installations on a jacket substructure also for an increased rotor size of 150m.

4 Monopiles

4.1 Impact of rotor size on eigenfrequencies

As the hub height increases, natural frequencies decrease. For a rotational speed of 10rpm, the minimum allowable natural frequency which maintains a 10% safety margin to the 1p excitation is:

$$f_{0,\min} = 1.1 \cdot \frac{10}{60} = 0.183 Hz$$

The period corresponding to that frequency is about T_0=5.5s, which is a typical spectral peak period for sea states with H_S = 1m…2m. Wave excitation is thus an important factor for the design.

4.2 Optimization of monopiles

In order to understand monopile response properly and to optimize the structural layout, REpower has developed an optimization tool with the following features:

- Calculations are based on a frequency domain approach, which is very fast.
- Soil stiffness is considered through a linearized p-y-approach.
- Timoshenko beam elements are included (shear deflection considered).
- Automatic looping / optimization of structures is possible.

Calibration has been performed against full dynamic simulations for several projects. This tool can be used for preliminary design of monopiles and is also ideally suited to study effects of e.g. tower head mass or changes in hub height.

Optimization is always performed for the entire support structure (i.e. tower, transition piece and monopile). This integrated approach allows achieving the optimum total weight.

4.3 Production capabilities of monopile suppliers

Several suppliers are currently planning production capacities for very large monopiles with the following dimensions:

Weight:	up to 1500t
Length:	up to 100m
Diameter:	up to 10m
Wall thickness:	up to 150mm

4.4 Indicative weights and sizes

4.4.1 Assumptions

Weights given in the following assume that transition piece and monopile are connected via a flanged (bolted) connection. If grouted joints are used, then weights would increase due to the “double steel” within the overlap of the connection and due to the fact that the diameter in the wave loaded zone would increase.

Other assumptions made for this study are:

- Wind-wave-misalignment has been assumed to be 30° (as a constant value).
- Damping is assumed to 1% (Lehr damping, i.e. percent of critical damping) for the first mode.

- Extreme wave height is assumed to be 65% of water depth (LAT).
- FLS assessment has been performed with varying detail category along the structure, assuming e.g. category 90 for circumferential welds in the monopile and category 63 for the upper part of the transition piece, where many attachments are present.

In order to find the optimum overall weight, several parameters have been varied systematically:

- Tower diameter: 5500mm … 6500mm
- Monopile diameter: 5500mm … 8000mm
- Embedment depth: 24m … 42m

Calculations have then been made for two different tower head masses, two soil profiles and two scatter diagrams. In total, this sums up to more than 10000 individual optimization loops.

The results are finally filtered to the following criteria:

- First natural frequency: $f_0 \geq 0.183$ Hz
- Wall thickness: $t \leq 120$mm

4.4.2 Results

Results are shown in Table 1 (for a site in the Greater Wash area) and in Table 2 (for a German North Sea site).

Water depth	Tower	Substructure (T.P. plus Monopile)	Support structure total
20m	300t	500t	800t
25m	300t	700t	1000t
30m	300t	950t	1250t
35m	350t	1100t	1450t
40m	425t	1325t	1750t

Table 1: Indicative weights for different water depths (soil conditions: sand with 35° friction angle) for a 6M with ~150m rotor diameter in the Greater Wash area

Water depth	Tower	Substructure (T.P. plus Monopile)	Support structure total
20m	300t	550t	850t
25m	300t	750t	1050t
30m	300t	900t	1200t
35m	375t	1100t	1475t
40m	400t	1400t	1800t

Table 2: Indicative weights for different water depths (soil conditions: sand with 35° friction angle) for a 6M with ~150m rotor diameter in the German North Sea

The following can be seen:

- The weight difference for the two sites, which have different wave climates, is surprisingly small.
- Overall weight of the substructure for 40m water depth is around 1400t, which is still within the planned production capabilities (it should be noted that this weight does not include secondary structures, anodes, etc.).
- The overall support structure weight is about 1700-1800t for 40m water depth, which is 50-60% higher than the combined weight of tower, jacket and piles for the same water depth and site conditions. Considering that also scour protection needs be accounted for, it highly depends on steel price whether such large monopiles can compete economically against jackets.

4.5 Influence of tower head mass on support structure mass

Additionally, the effect of tower head mass has been studied, as it is an often heard assumption that a lower tower top mass results in lower weights for the support structure. Results for identical conditions with just the tower head mass changed are shown in Table 3. It can be seen that the difference in weights is relatively small up to 35m depth – and that for 20m water depth the heavier head mass even results in a smaller support structure weight! The increase in steel weight for the smaller head mass at smaller water depth can be explained by the fact that the natural frequency increases, which shifts it into the region where most of the fatigue waves occur in this particular area. Overall, the impact of head mass on structural weight is not particularly strong for a monopile.

Water depth	Support structure total weight	
	475t head mass	340t head mass
20m	800t	820t
25m	1000t	950t
30m	1250t	1100t
35m	1450t	1300t
40m	1750t	1500t

Table 3: Impact of tower head mass on optimized support structure weights for the Greater Wash area (35° friction angle)

4.6 Influence of rotor diameter

The influence of rotor diameter (and associated shorter tower) is shown in Table 4. The impact is fairly small up to 30m water depth and increases slightly for deeper waters.

Water depth	Support structure total weight	
	~150m rotor	126m rotor
20m	850t	750t
25m	1050t	900t
30m	1200t	1050t
35m	1475t	1250t
40m	1800t	1500t

Table 4: Impact of rotor diameter on optimized support structure weights for a North Sea site (35° friction angle)

4.7 Uncertainties related to monopiles

When considering monopiles, one should be aware that there are some uncertainties, which do not exist for jackets:

1. Soil stiffness is of primary importance for the wave induced fatigue loads. Since almost 10 years the applicability of standard API p-y-curves (which are still widely used) is being questioned by research, without a practical answer to date. This implies a risk both practically and also for certification / approval.

2. (Soil) damping is another important parameter which influences the fatigue load level. Global damping is hard to quantify though and no accepted and validated methods exist to determine modal damping depending on the soil characteristics.

3. Large turbines mounted on monopiles are very soft structures – so far it is not known whether this may cause any adverse effects.

4. Long term behaviour under cyclic loads is another topic which is not yet fully understood. There is an increased risk of long-term settlements (tilting), which can not be reliably quantified.

5. Installation of such large monopiles may be constrained by number of suitable vessels and requirements for noise mitigation as very large hammers will be required.

All these factors are not relevant for turbines mounted on jackets, which improves the risk profile compared to monopiles.

5 Benefit of integrated optimization

The benefit of integrated optimization is apparent from Fig. 1. The dots in the figure show total support structure weights for all possible combinations of:

- Three different tower diameters
- Six different monopile diameters
- Four embedment depths

For each water depth 3·6·4 = 72 geometrical configurations are investigated. The difference between the optimized weight and the maximum weight is considerable – for 35m water depth the values range from 1500t to nearly 2400t. Hence, if some parameters are fixed (e.g. tower diameter or stiffness) then this will lead to unnecessary high weights for the combined structure. It is also not favourable in that respect if optimization of parts of the support structure is performed by different parties in a project. Ideally, this is done by one party, which must normally be the wind turbine manufacturer.

This means that the turbine supplier must have substantial understanding of the support structure design and must be able to execute design work at least on basic design level. This is much more important than a low head as in section 4.5 it has been shown that tower head mass is not a main driver for support structure weights.

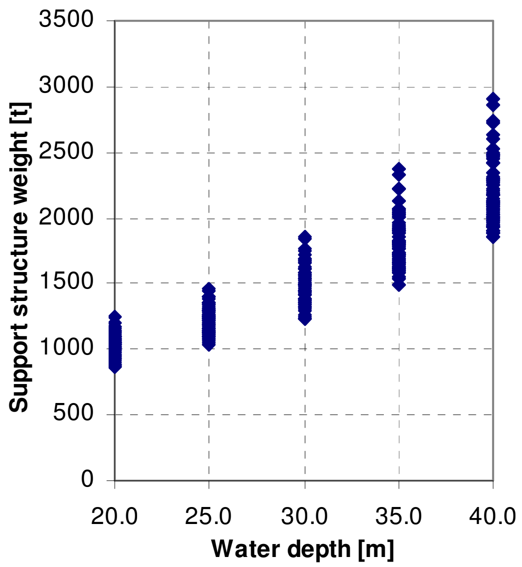

Fig. 1: Total support structure weight (tower, transition piece and monopile) for different configurations

6 Summary

Based on the investigations performed with comprehensive studies, the following conclusions can be drawn:

1. For a 6MW turbine, a weight of 450-500t is ideal to achieve a first natural period within the required limits – regardless whether we speak about 126m or ~150m rotor diameter.

2. A lighter nacelle mass does not lead to smaller loads – on the contrary, governing fatigue loads may even INCREASE when top mass is reduced. Consequently, jackets and monopiles may be heavier for a light-weight turbine!

3. Provided that good soil conditions are present, monopiles can be used up to 40m water depth even for a 6MW turbine with 150m rotor diameter. Optimized support structure weight is significantly higher compared to the optimized total weight with a jacket, though.

7 References

[1] Seidel, M.: Jacket substructures for the REpower 5M wind turbine. Conf. Proc. EOW 2007, Berlin 2007.
[2] Seidel, M.: Feasibility of monopiles for large offshore wind turbines. Conf. Proc. DEWEK 2010, Bremen 2010.