*Published in: Festschrift Peter Schaumann, Hannover 2014, doi:10.2314/GBV:77999762X*

# Substructures for offshore wind turbines
# Current trends and developments

**Dr.-Ing. Marc Seidel ***

* Senvion SE, Osnabrück, Germany, marc.seidel@senvion.com

**Abstract:**
Substructures for offshore wind turbines are huge structures – with total masses of 1000t or more for wind turbines of 5MW. As the current trend is towards larger turbines of 6MW or more and deeper waters of 30m or more, demands on efficient substructure design increases. This paper will review the state-of-the-art and current trends as perceived by the author, who is actively participating in the industry since more than 10 years. It is shown that monopiles and jackets will likely dominate the market during the next decade and the design challenges especially associated with large monopiles in deeper waters will be highlighted.

**Keywords: Substructure Monopile Jacket Deepwater**

## 1 Introduction

Offshore wind energy has been developed over more than 20 years now. In this paper I will share my personal view on the development of substructures – with a focus on the second half of this period, where I have actively participated in the offshore wind industry.

## 2 State of the art

The first offshore wind farm has been built nearshore in Vindeby/DK in 1991. In the 23 years since that milestone, very significant development has happened. It is impossible to list all the individual steps of that development, especially with regards to turbine technology. As this paper focusses on substructures, some of the more important steps are listed in the following:

- The monopile concept was introduced in Lely(NL) in 1994. Since then, this substructure has been used for the majority of all projects.
- In 2003, the first turbine with a rated power of more than 3 MW and with more than 100m rotor diameter has been installed in the Arklow Bank project – again on monopiles.
- In 2006, Senvion (at that time known as REpower Systems) installed the Senvion 5M (with 5 MW rated power and 126m rotor diameter) in the Beatrice field. This project still holds the world record with regards to water depth (45m LAT). It was also the first project using jacket substructures and a “complete turbine” installation technique [1].
- In 2009, the test field “alpha ventus” was installed in Germany. This project features six Areva M5000-115 turbines on tripods and six Senvion 5M turbines on jackets.
- In 2013, the first 6 MW turbine (a Siemens 6DD type) was installed on a monopile in the Gunfleet Sands III project.

Apart from these great achievements, many other advances have of course been made and it is acknowledged that this list is very subjective.

### 2.1 Monopiles

As has been mentioned, monopiles had the greatest success story in offshore wind – but also some failures, which I will mention later. Weight and diameter have increased continuously – currently, several projects are under construction which use monopiles of more than 800t weight and more than 6500mm diameter, in water depths up to 30m LAT. A few years ago, such a size was unthinkable and the common perception was that monopiles would only be suitable up to around 20-25m water depth (and potentially only for smaller turbines up to 3 MW). The reasons why this development has changed [2] are numerous:

- As the monopile has been used in many projects, it is generally seen as “proven technology” – which is something banks and insurances like. As these have a very large impact on every offshore wind project, this is very important.
- Alternative structures for deeper water, mainly jackets, tripods and tripiles, turned out to be quite expensive – I will return to that later.

- Fabricators have upgraded their facilities and are now capable to produce monopiles up to 10m diameter and 1500t weight. As of 2013, at least half a dozen suppliers were able to or have announced new facilities in this range. A few years ago, the limit was significantly lower.
- Most importantly, installation vessels have grown in size to install the large turbines of >5MW rated power. These vessels are also capable to install large monopiles and today, around a dozen vessels with lifting capacities of 800-1000t (and still half a dozen up to 1200t) are on the market. Only a few years ago, there was hardly any vessel capable to install a monopile of more than 500t!

Due to this change in the market, it can now be anticipated that monopiles will continue to have a large market share also for 6 MW+ turbines in water depths exceeding 30-35m.

### 2.2 Jackets

Jackets are widely perceived as the best option “beyond monopiles”. Their commercial use for offshore wind turbines started – as mentioned above – in 2006 with the Beatrice project. In total, 86 offshore turbines on jackets have been erected with Senvion turbines and another 48 turbines will be installed in 2014. Adding the onshore prototype in Bremerhaven, this adds up to 135 turbines on jackets. So far, the experience has been very good, with no failures or damages to the primary structures to report!

Design methods for integrated simulation are an important element for jacket structures. The fully coupled simulation of wind turbine with a complex support structures has been a major step to allow optimized designs to be realized [3].


Figure 1: Senvion 5M turbine on jacket (Ormonde project)

### 2.3 Tripods

Tripods have been used in several projects with Areva (formerly Multibrid) turbines. From my perspective, this is surprising, as the tripod is very heavy compared to the jacket and features difficult welding in the central node. When we did the Beatrice project, previous studies had also come up with two different tripods as the preferred options – but we managed to convince Talisman Energy (the owner of the project) that jackets were the better option. There seems to be a wide consensus in the industry now that tripods are not the most economical option and most likely they will disappear from the market.

### 2.4 Tripiles

Tripiles are an exclusive development of the BARD group. The main idea of having a structure which was easy to install and to mass-fabricate seemed appealing, but actually the tripile concept has many disadvantages:

- Due to the three relatively slender piles (4.2m in diameter), it is horizontally soft and experiences a lot of wave excitation, which increases fatigue loads.

- The transition piece is complicated steelwork and quite heavy (more than 400t).
- Total weight including piles and secondary structures is around 50% higher compared to a jacket.
- Secondary structures, esp. boat landings, are difficult to attach to the piles.

As BARD will probably not build further offshore projects, this concept will most certainly die out.

## 3 Innovative concepts

A lot of effort is spent to find “innovative” structures which promise to lower installed cost. Some of the more realistic candidates are discussed below. My personal view is that investment in these structures is the wrong decision at this stage for the following reasons:

- As mentioned earlier, banks and insurances like “proven technology”. Any new structure by definition isn’t proven and therefore needs demonstration projects and a slow ramp-up to gain trust in the community. As such a development is slow (even more today than 10 years ago!), at least 5 years are needed from a first prototype to large-scale industrial application.
- Focus needs to be on improving cost of energy within the next 10 years to enable stabilization of the offshore wind market. The best option to achieve this is by optimization and serial production of already proven technologies – monopiles, jackets and GBSs!

Nevertheless, some options are technically interesting. My favourites are:

- The Keystone “Twisted jacket”: This is particularly interesting because it needs a small number of parts for final assembly, which makes it suitable for mass production. Its biggest problem is probably driving noise, as noise reduction is more difficult to achieve for the inclined piles.
- The “Universal Foundation” Mono-Suction-Bucket: This is a nice concept as it eliminates driving noise. Apart from the foundation, it is very similar to the monopile and hence close to “proven technology”. The suction bucket may be the innovative concept which will emerge fastest as a real alternative due to its significant advantages especially in the installation phase.

Additionally, all kinds of floating foundations are discussed and heavily funded. This is very surprising, as these appear to be much more expensive than fixed structures. Some countries may ultimately need them (and energy prices in 20 years’ time will certainly be high enough to justify floating foundations), but within the near future, we will probably not see any large-scale offshore wind farm using floating foundations.

## 4 Failures and mistakes

In general, offshore wind support structures have been a success from a technical point of view with only few problems to report.

The most prominent problem was the “slippage” of grouted connections [4]. This occurred because shear keys had been omitted and plain surfaces have been used. From my perspective, this problem was foreseeable and not using any mechanical means for shear transfer was not good engineering practice – but unfortunately, it was backed by the certification rules from DNV at that time. That incidence clearly shows that certification does not at all guarantee that problems are avoided. It also shows that “good engineering judgement” should always be more important than blindly using codes and standards, especially if they are applied to new construction types.

Another costly fault was the application of a one-layer corrosion protection system on some monopiles, which quickly lead to visible corrosion due to blistering. This was a specific problem of the application for this type of corrosion protection (which was cheaper as applied in one layer only). Multi-layer corrosion protection systems have not had any serious issues as far as publicly known.

Also due to cost reasons, no corrosion protection has been applied inside monopiles below the “airtight platform” as it was assumed that oxygen supply was low enough to prevent significant corrosion. As it turns out, this was too optimistic and therefore inside corrosion protection will probably be used in the future.

Other than that, no serious problems have been reported.

## 5 Technical development

Innovation does not only happen on large scale with completely new concepts, but also on a more detailed level. Some technical areas where progress has been made – with significant contribution from Peter Schaumann and his team – are:

- Weld treatment (UIT/HIFIT)
- Design methods for grouted connections
- Simulation tools for complex support structures
- Welding technologies
- Bolted connections

The main difficulty with technical progress is that implementation in real projects is slow – often simply because rules (either from certification bodies or governmental authorities) do not allow implementation (or make it extremely difficult) as those methods are not yet included in codes and standards. The "best" example is weld treatment, which appears to be a mature technology, but does not emerge in practice as it is not included in the Eurocodes.

## 6 Implications of using large diameter monopiles for the design process

The use of large monopiles has severe implications on the design process. This is due to the fact that wave induce fatigue loads are very sensitive to the structural layout and stiffness. When comparing design processes for monopiles and for jackets, the following statements can be made:

<u>Any installation using jackets:</u>

- Fatigue design is driven by wind loads, as there is no dynamic effect of wave loads.
- Quasi-static treatment of wave loads is acceptable, the dynamic effect of waves on fatigue design is small. For extreme loads, the main challenge is to find proper superposition rules for wind and wave loading in order to avoid unnecessary conservatism [5].
- There is only a very small effect of soil stiffness on eigenfrequency and virtually no impact of soil damping on dynamic behaviour and fatigue loads.

<u>Shallow to intermediate water depth with monopiles:</u>

- Design is still dominated by wind loads for shallow to intermediate water depths, the dynamic effect of wave loads are of some importance – but some compromises can be made. This is illustrated in Figure 2 where it is shown that the contribution of wave loading to overall fatigue loads is within 20%.
- As wind loads dominate, eigenfrequency is still the most relevant parameter for load level and grouping of turbines.

<u>Deep water with monopiles:</u>

- In deeper water, the importance of wave loading increases dramatically and the design is ultimately dominated by dynamic wave loading as illustrated in Figure 3.
- The dynamic effect of wave loads is therefore of primary importance, which implies that sensitivity to soil stiffness and damping is much increased.
- Clustering according to eigenfrequency is not a reliable method any more. Other parameters must also be taken into account, e.g. water depth, eigenfrequency, mode shape (!), geometry within wave loaded zone, damping ratio (may vary due to different soil conditions) and the scatter diagram.

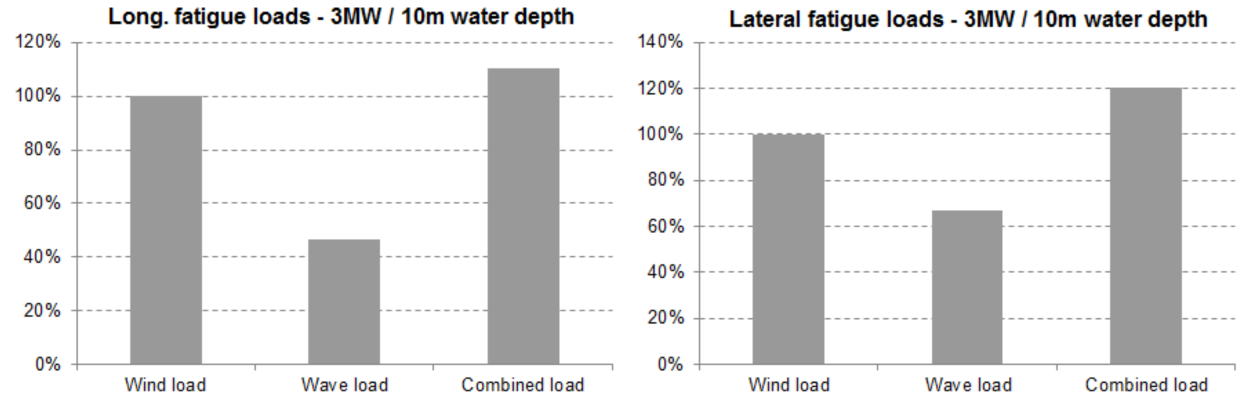


Figure 2: Relative importance of wave loads for monopiles (3MW turbine, 10m water depth)

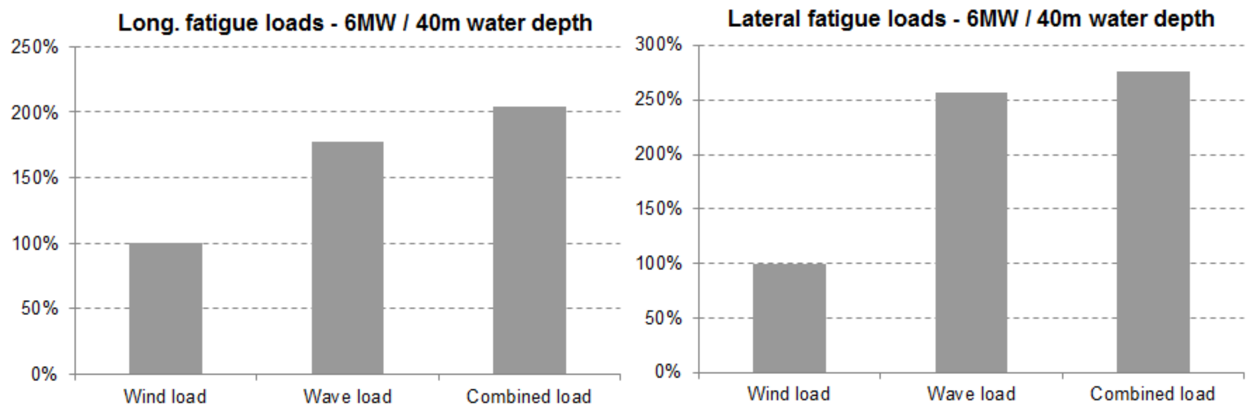


Figure 3: Relative importance of wave loads for monopiles (6MW turbine, 40m water depth)

## 7 Current market trends

The current market trend (at the end of 2013) is very clearly going into two directions:

- Big-diameter monopiles are being investigated for large turbines (with at least 6 MW rated power) and in water depths exceeding 35m. Design work from Senvion shows that a 6 MW turbine with 150m rotor diameter can be installed in the German North Sea in 40m water depths within current limits of fabrication and installation [2].
- Jackets are being perceived as the main alternative which will be used when monopiles are assessed to being non-feasible or too expensive in comparison. Currently, it appears as if projects in Germany may not need jackets any more as water depth is largely below 40m and soil conditions are favourable for monopiles (mostly dense sands). The main market for jackets may therefore be the UK round 3 projects, which often feature water depths exceeding 50m.
- GBSs are constantly discussed as another option, but no project in the North Sea has used them in large scale up to now.
- Tripods and Tripiles do not play a significant role in public discussion any more.
- Innovative concepts are primarily being followed up by the Carbon Trust, with uncertain chances of success during the next decade.

## 8 Authorities and certification bodies

Authorities, e.g. BSH in Germany, and certification bodies can play an important role for the market development in general and regarding the success of specific structural concepts.

There are remarkable differences between countries:

- In Germany, all structures need to pass BSH approval. The BSH rules have been drafted mainly by governmental agencies (BSH, BAM and BAW), certification bodies and university professors – the involvement of the industry and wind farm owners has been very limited.
- In Netherlands and Belgium, there is a requirement that certification is performed, but this is much more general and much less demanding compared to Germany. One important difference is that international practice from the Oil&Gas sector is accepted, while in Germany the design has to follow building regulation according to Eurocodes (see below).
- In UK, there are no requirements from governmental bodies and no approval procedures need to be followed.

In Germany, the role of BSH has severe implications on the substructures, e.g.:

- Axially loaded piles need be designed according to Eurocode 7. The main problem with this is that internationally accepted procedures for pile design (e.g. according to API and ISO 19902) may not be used and dynamic pile testing is required to "prove" pile capacities. This is extremely difficult to align with the project timeline as the design is not finished until dynamic pile testing has been completed – which contradicts the usual (and practical) sequence of events.
- Grouted connections need to go through a "Approval in the individual case" procedure for each and every project. This is a time-consuming procedure, which may also include some bad surprises – such as the demand from the reviewing experts to include steel fibres in the grout or general non-acceptance of internationally proven materials.
- Environmental concerns are raised with regards to Gravity Base Structures (GBS), esp. sealing of large areas with scour protection and turbidity due to soil excavation. This is not yet resolved and prevents GBSs from being a non-risk option in Germany.

Certification is done as a risk-mitigation to ensure proper design – although it has proven in the past that it does not reliably fulfil this role (e.g. in the case of grouted connections). Banks and insurances also require certification as a formal step to de-risk projects. It may be questioned whether the money and effort spent for certification is well invested from my point of view.

## 9 Summary and outlook

Development of substructures for offshore wind turbines has been a very challenging and interesting field within the past 20 years. Currently, it seems that monopiles and jackets will dominate the market within the next 10 years. Although it seems like this is a simple continuation of current industry practice, it has been shown in this paper that monopiles in deeper waters do imply new challenges due to the fact that the loads are now dominated by waves. This requires careful reconsideration of design methods and it can be anticipated that this will lead to the development of new calculation methods. Also steel fabrication is an area where developments are needed as very thick plates (up to 150mm) are certainly much more demanding for the fabrication process..

## 10 References


[1] Seidel, M.: Tragstruktur und Installation der Offshore-Windenergieanlage REpower 5M in 45m Wassertiefe (in German). Stahlbau 76 (2007), Issue 9

[2] Seidel, M.: 6MW Turbines with 150m+ Rotor Diameter - What is the Impact on Substructures? Conference proceedings DEWEK 2012.

[3] Seidel, M. et al.: Validation of Offshore load simulations using measurement data from the DOWNVInD project. European Offshore Wind Conference, Stockholm 2009.

[4] Schaumann, P.; Lochte-Holtgreven, S.; Lohaus, L. and Lindschulte, N. (2010), Durchrutschende Grout-Verbindungen in OWEA – Tragverhalten, Instandsetzung und Optimierung. Stahlbau 79: 637–647. doi: 10.1002/stab.201001357

[5] Seidel, M.; Kelma, S.: Stochastic modelling of wind and wave induced loads on jacket piles. Stahlbau 81: 705-710. DOI: 10.1002/stab.201201599