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Offshore Wind Turbine Foundations State of the Art

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Abstract. The huge growth and intense development in the European offshore wind power sector over the last decade have created significant achievements within the wind turbine foundation technology. The state of the art focusing on geotechnical design aspects for Offshore Wind Turbine (OWT) foundations and important aspects for installation are presented in this paper. In place operational experience based on structural health monitoring campaigns and future trends are also discussed.

Keywords. Offshore wind turbines, foundations, loads, soil conditions, holding capacity, dynamic response, offshore installation, in place behavior, future trends.

1. Introduction

The Offshore wind energy industry has greatly matured during the last decade, presently the annually installed energy capacity exceeds 3.5 GW in Europe, with UK and Germany as the largest offshore wind energy producers, see Figure 1. Europe has a total installed offshore wind capacity of 18 499 MW generated by4 543 grid-connected wind turbines across 11 countries [1].

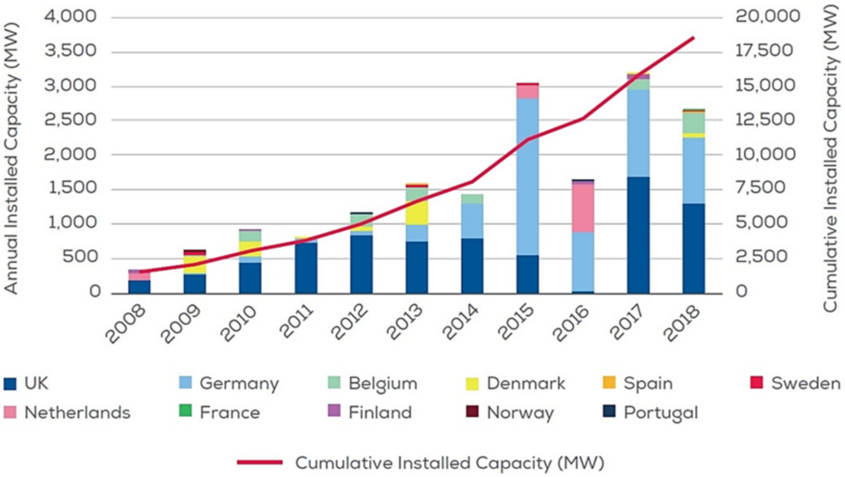

Figure 1. Installed offshore wind energy capacity in Europe and distribution among countries [1]. China is now in the third place globally in terms of offshore wind power (2790 MW in 2017 and rapidly growing).

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The large-scale development of offshore wind farms requires considerable investments. However, as the costs for construction and production of offshore wind power are falling and the energy prices are rising, tenders for new wind farm developments in Europe are now being submitted without subsidiaries. Both the embedded part and the substructure up to the base of the turbine tower are often referred as the "foundation" to the offshore wind turbine (OWT). The wind turbine is the most expensive part, fabrication and installation of the foundation represent the second largest partial cost (25-30%) of the total wind farm development [1]. Therefore, and especially for deeper waters, developers have high focus on optimizing the design and fabrication cost for the foundations and reduce the installation time such that the overall development costs can be cut down.

Figure 2. The Walney Wind Farm operated by Ørsted in the Irish Sea is presently (2018) the world's largest operating offshore wind farm with 189 OWT's producing 659 MW of power (photo: Ørsted).

2. Environmental conditions

The OWT foundations involve significant technical challenges, including design requirements to withstand the harsh marine environment, storm periods with intense wave loading, wind turbulence, fatigue and at least 25 years operational life.

The ideal condition for an offshore wind farm is a location with high and persistent wind speed to ensure sufficient energy harvesting and economic operation considering the required investments. Wind turbines start to operate at wind speeds of 4 to 5 m/s and reach maximum power output at around 15 m/s. At very high wind speeds, gale force winds of >25 m/s, the wind turbines automatically shut down. On site mapping of the wind conditions is therefore performed before the decision of full development is made.

Normally a Met mast is installed at the field 1-2 years in advance, lately Lidar buoys are becoming more popular as these can record the wind profiles on site at much lower total costs and can easily be moved and reused, see Figure 3.

Secondary conditions affecting the total wind farm costs are distance from shore (grid connection and offshore access), water depth, seabed topography and geotechnical conditions. The seabed outside the European coastline many times comprise complex geology and diversified layering.

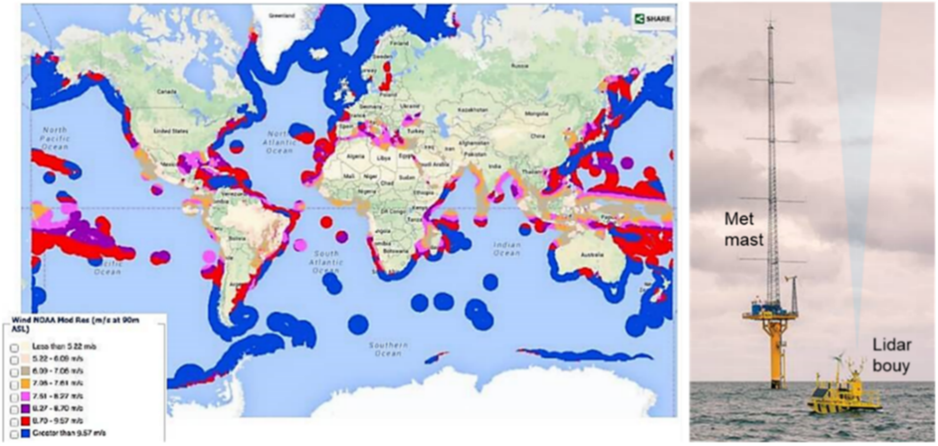


Figure 3. Average wind speed 90m above sea level outside the global coastlines (source: NOAA). Right: Met mast and AXYS Lidar buoy installed at Blyth wind farm for validation tests (photo: AXYS Tech.).

2.1. Foundation loads

An OWT foundation is subjected to a combination of axial loads, low-amplitude cyclic loads, bending and torsional moments generated by waves acting on the upper part of the foundation and the wind loads acting on the turbine and tower, see Figures 4 and 5.

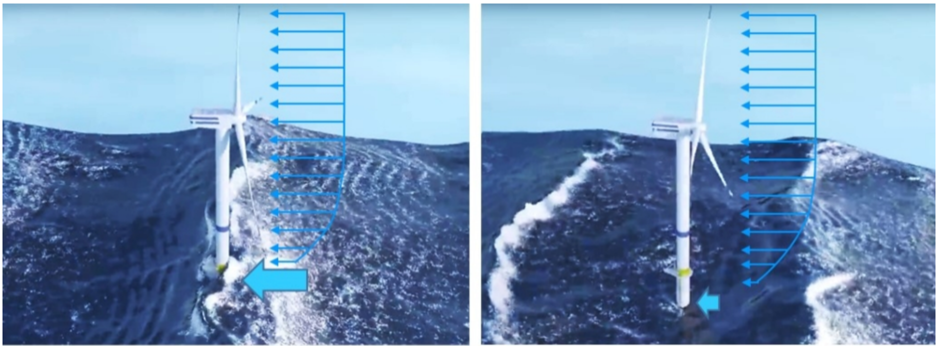


Figure 4. Breaking waves that may occur at shallow banks far out in the sea can be a severe loading condition.

The main design driver is often the dynamic performance (stiffness) of the foundation. To prevent resonance amplification effects, the rotor blades are automatically pitched to change the rotor speed and the turbine eventually shuts down at a certain amplitude of vibrations. With towers, stretching more than 150m above sea level and rotors spanning 160m, the tolerances for differential settlements or tilt are obviously small.

The loads acting on the wind turbine tower are ultimately transferred to the foundation and can be classified into two types: static or dead load because of the self-weight of the components and the environmental loads generated by waves and wind with different peak periods, mean levels and cyclic amplitudes see Figure 5.

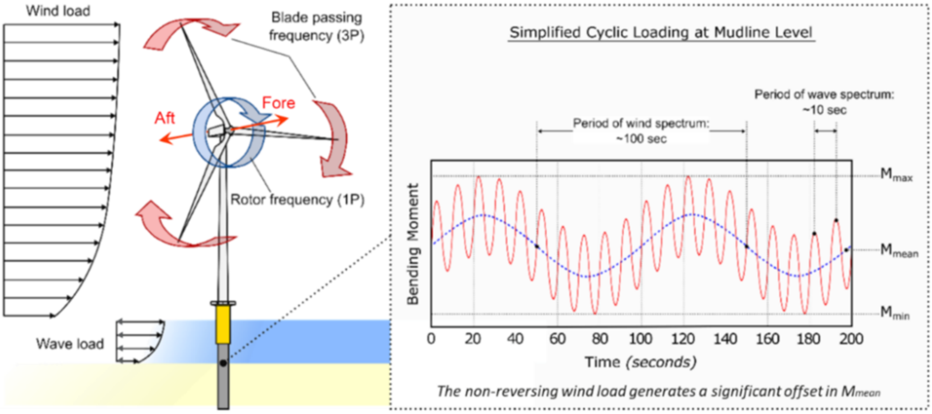


Figure 5. Characteristic of the combined wave and wind loads acting on an OWT foundation [2].

The following categories of dynamic loads are the most significant for design:

1. The lateral load acting at the top of the tower produced by the turbulence in the wind and the drag of the rotating blades
2. The load caused by waves crashing against the foundation substructure. The magnitude of this load depends on the wave height and wave period.
3. The load caused by the vibration at the hub level because of the mass and aerodynamic imbalances of the rotor. This load has a frequency equal to the rotational frequency of the rotor and referred to as the 1P load
4. Loads in the tower because of the vibrations caused by blade shadowing effects and loss of wind load on the tower (referred to as 3P for rotors with three blades), see Figure 6.

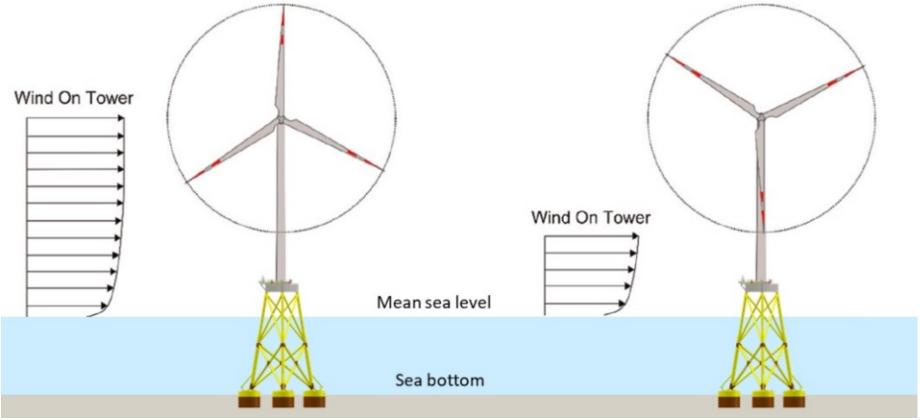


Figure 6. Variation in wind load acting on the tower due to rotor blade shadowing.

Representative power spectra are constructed by means of analyzing site-specific data in the time and frequency domains. The design of the wind turbine and foundation must make sure that the system Eigen frequency do not coincidence with any of the dynamic load peak frequencies. Presently the system frequencies for commercial viable

OWT foundations lies between the 1P and 3P peaks, which is a quite narrow frequency band, see Figure 7.

For deeper waters and larger turbines, the Eigen frequency will decrease and approach the 1P frequency that also will move closer to the wave frequency. Due to limitations in the lateral stiffness this will ultimately limit the feasible turbine size and maximum water depth for a traditional monopile foundation.

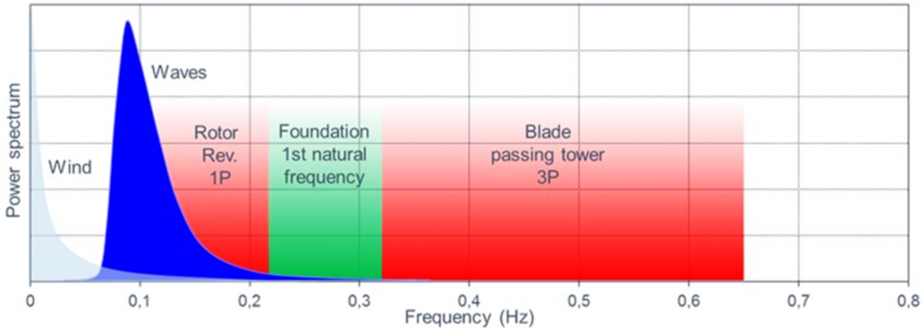


Figure 7. Example of power spectra for forces acting on a monopile foundation.

2.2. Soil conditions and design parameters

An offshore wind farm involves many turbine foundations (tens to hundreds of units) and covers a large area (tens to hundreds of km^2). The ground stratigraphy, the mechanical properties of materials and their lateral and vertical variability should be accurately determined at each OWT location. Furthermore, a solid knowledge of the mechanical properties of the shallow sediments is required along the cable routes, between wind turbines and to the coast.

The development of a wind farm requires significant investment decisions at early stages when in many cases the geotechnical information for many of the proposed turbine locations not is available or only performed to a limited depth. Initially an integrated desk study is performed making use of existing data and knowledge (geology, seabed mobility, depositional environment, formation variability, seismic risk, etc.). Geophysical and preliminary borehole data are key input for the evaluation of future survey strategies, foundation concepts, construction risks and cost estimates of the foundation scope to be used for final investment decisions.

Typical steps to define the soil conditions for a Wind farm development are [3]:

1. Desk study, initial conceptual ground model and risk register
2. Specification and Implementation of geophysical surveys, geotechnical soil investigation and lab testing
3. Geophysical and Geotechnical Data interpretation, including identification of formations, ground boundaries and unitization of relevant layers and derivation of characteristic properties.
4. Compilation of the integrated ground model
5. Derivation of final geotechnical design profiles

At shallow water depths, rather complex soil conditions can be expected at many potential offshore wind farm sites in Europe. For example, the coastal waters in the North Sea around UK consist of diverse materials, such as loose mobile sand banks, glacial till, stiff and soft clay. Along the west coast of Denmark, Germany and Benelux, dense sand with silt layers is dominating. Further south, offshore France, the soil conditions are even more diversified, spanning from soft clay to shallow limestone and chalk-based formations. The Baltic seabed consist mainly of clay but sometimes contains significant chalk layers and boulders, ice conditions must be considered in the Baltic Sea. The diversity of expected soil conditions may call for different foundation solutions also within the same wind farm.

2.2.1. Ground model

The initial and preliminary ground model of the wind farm site is mainly based on geophysical data including seafloor surveys from multi-beam bathymetry and side-scan sonar, see Figure 8. The stratigraphy of different sediment layers is mapped by means of seismic multichannel reflection survey. The data is used to establish the seafloor bathymetry and morphology, to define lithological units and tectonic structures, and to establish the stratigraphic profiles.

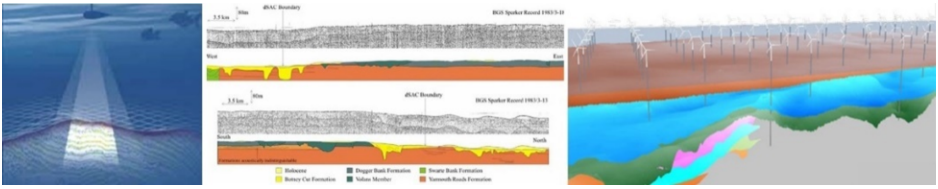


Figure 8. Establishment of ground model based on geophysical data.

In many cases, high quality seismic data can be used for preliminary assessment of suitable types of foundations and required pile embedment length or effect of changed wind farm layout, see Figure 9.

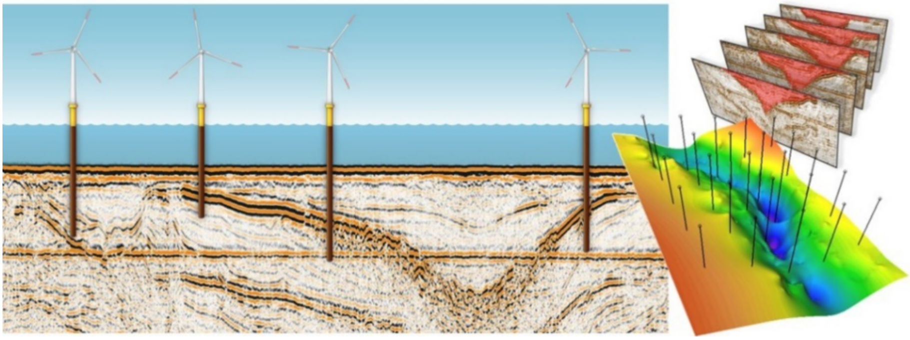


Figure 9. Preliminary pile design based on multichannel high resolution seismic profiles (Illustrations Fraunhofer Institute for Wind Energy Systems).

2.2.2. Determination of soil parameters

The specifications for the soil investigation program are based on the ground model and preliminary wind farm layout. CPT's are normally required at each location of an OWT foundation, see Figure 10. Bore holes and samples for laboratory testing are required to determine the geotechnical design parameters for the different sediment layers.

Figure 10. Left to right: Borehole and wind turbine location plan [5], geotechnical drilling vessel and seabed CPT rig.

Once the geotechnical parameters have been determined for the different layers, the ground model with the stratigraphy of different sediment layers can be used to establish new site-specific soil parameter profiles if the positions of the wind turbines should be rearranged, see Figure 11.

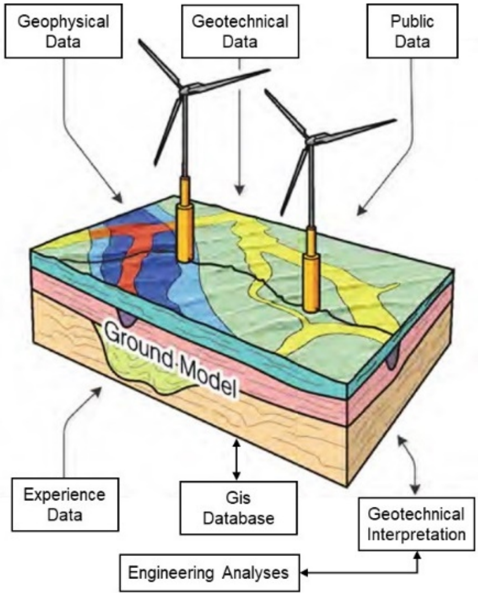


Figure 11. The evolutionary ground model [4].

2.2.3. Other seabed conditions

For seabed with sand at the surface and strong currents (usually tidal) the risk for scour development and hence the need for scour protection must be assed. Significant scour can develop rapidly around seabed foundation and have critical impact on the dynamic behavior and stability of the foundations, see Figure 12. Other conditions that must be investigated is the seabed topography (sand dunes etc.) and the presence of embedded boulders.

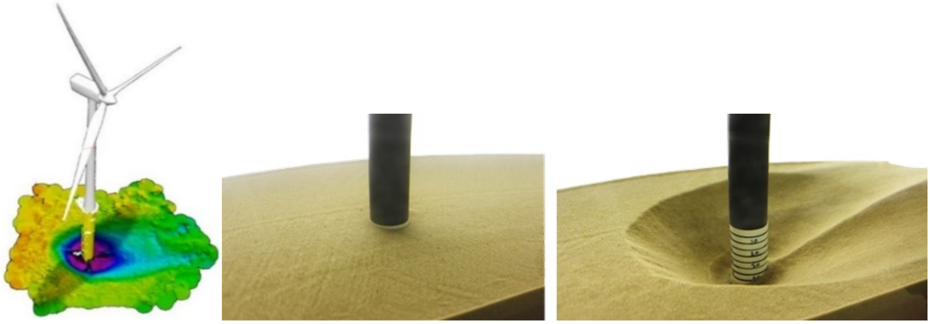


Figure 12. Scour development around a monopile foundation (illustrations: EIWA).

In some areas the presence of UXO's (unexploded ordnance), mainly old mines or shells from the 2nd World War buried in the seabed must be checked, see Figure 13. An UXO survey is conducted by means of sonars, sub-bottom profilers and magnetometer survey methods.

Figure 13. Marine mine (UXO) from 2nd World War.

3. Different types of OWT foundations

Presently, the main alternatives for offshore wind turbine foundations can be divided into four different categories, see Figure 14:

1. Monopiles (or monopods if suction bucket is used), normally relevant for water depths down to 30-50m. Represent 89% of the OWT foundations presently installed in European waters [1].
2. Gravity base structures with skirts, normally relevant at 25 to 60m water depth. Represent 6.6% of the OWT foundations presently installed in European waters [1].
3. Jackets or tripods, pre-piled or with suction buckets, normally relevant at 25 to 60m water depth. Represent 9.8% of the OWT foundations presently installed in European waters [1].
4. Floating foundations, normally relevant from 50m and deeper waters. Represent 0.2% of the foundations presently installed in European waters [1].

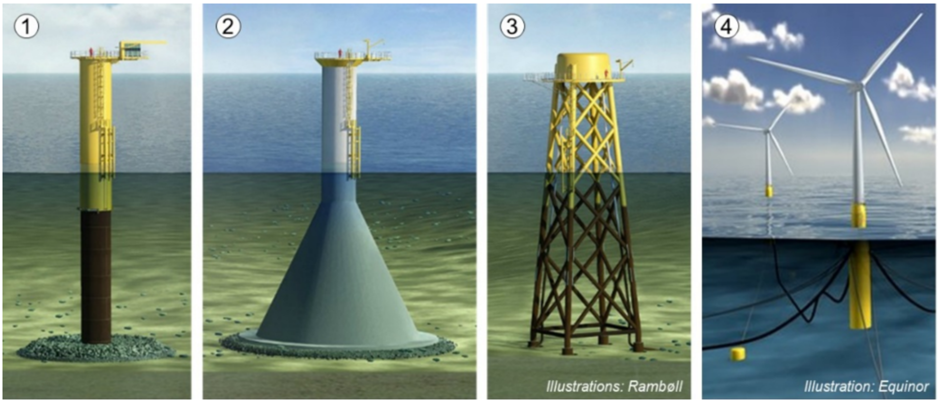


Figure 14. Main foundation alternatives for offshore wind turbines (Illustrations: Ramboll and Equinor).

The monopile is presently the most cost-efficient foundation solution (including fabrication and installation) and has therefore been the dominating type of foundation in Europe, see Figure 15. However, as the trend is larger turbines in deeper waters it is expected that other types of foundation will become more common in the future when the limit for feasible monopile design is met. 12 MW turbines are expected to enter the market in 2020 and more expensive foundation alternatives become attractive if the energy output from each installation can be increased.

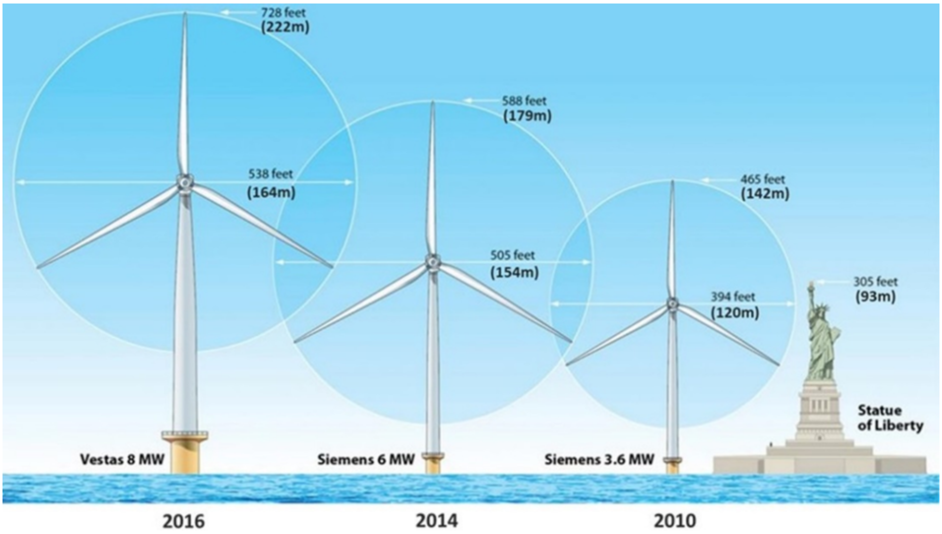


Figure 15. Size trend for wind turbines on monopiles (Illustration: Sierra magazine).

An important aspect concerning offshore wind turbines is the sensitivity to verticality, even for a small inclination a wind turbine loses its ability of effective energy production. Therefore, requirements for Serviceability Limit State, SLS, set the limits on the permanent accumulated inclination (typical 0.25° to 0.5°). As discussed earlier the dynamic motions (vibrations) or stiffness of the foundation are also important for the serviceability and fatigue limit state. ULS (Ultimate Limit State) conditions, requiring the maximum load-carrying capacity, is usually not the main foundation design driver.

3.1. Monopiles

The sizing of a monopile is an iterative process, typically starting with selecting an initial diameter (usually identical for all monopiles in the wind farm). In the second step, the required pile length is determined, primarily govern by the foundation capacity. Due to the sediment stratigraphy varied pile embedment depth may be required at different wind turbine locations within the wind farm, see Figure 16.

Note that the capacity of a monopile is in general defined by a maximum deformation criterion, which is essentially a performance-based design. The wall thickness is typically in the range of 1/80-1/120 of the diameter and is govern by the structural fatigue design. With decreasing length to diameter ratio, the foundation serviceability becomes gradually more important that mainly affects the required monopile diameter. In the early days, the monopile dimensions were determined to meet a certain soil-foundation stiffness values such that the first eigen-frequency of the OWT is in the range between 1P and 3P (see Figure 7). Although this criterion still is relevant, the foundation design should not only be based to meet a certain target stiffness, since other structural components of an OWT support structure may be adjusted more easily.

The actual sizing is often done using distributed Winkler springs, describing the soil response of a loaded monopile. Several different types of Winkler springs have been proposed in the literature. These can be linear elastic or non-linear (elastic). Most commonly used in the past were the non-linear API [5] p-y springs.

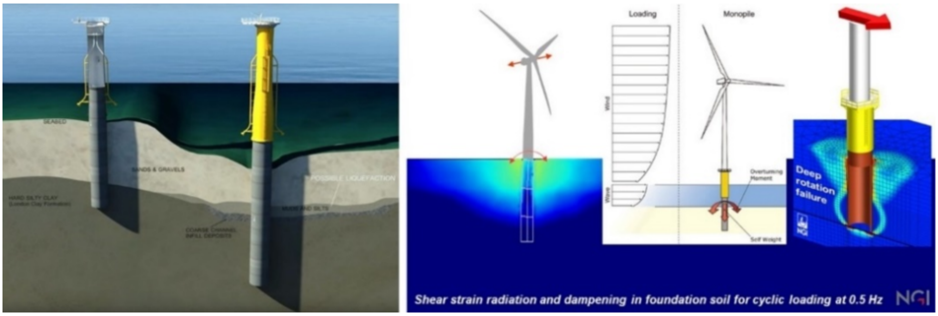


Figure 16. Monopile embedment depth adapted to sediment stratigraphy (illustration COWI/IMS). Soil dampening, transfer of loads and ULS deep rotation failure for monopoles (illustration NGI).

Non-linear springs are crucial for an optimized monopile design but it is demonstrated through numerous of studies that the traditional approach using API springs is not appropriate for the sizing of an OWT monopile foundation with relatively small L/D ratios (where L is embedded length and D is pile diameter). Therefore, offshore monitoring campaigns with strain gauges on full scale monopiles have been conducted as well as large scale onshore lateral pile load tests, see Figure 17.

The performed tests and recorded data from offshore piles suggest that the piles often show a considerable stiffer lateral response than predicted using API p-y curves.

Figure 17. Large scale lateral pile load tests performed for investigation of P-Y response for monopiles: (1) Rødbyhavn (Denmark) - hard clay and driving shoes, performed by NGI/Bilfinger for Equinor (2014); (2) Cuxhaven (Germany) - dense sand and vibrated piles, performed by Bilfinger for RWEinnogy (2014): (3) PISA project, Cowden (UK) - stiff clay and Dunkirk (France) - dense sand, performed by ESG for Carbon trust consortium (2014-15); (4) Gouvieux (North France) - Sandstone, performed by Fugro for EMF (2016).

In the PISA project (3) the monopile design model has been updated with sets of distributed lateral and rotational Winkler-springs [6] for monotonic loading. In the REDWIN Joint research project headed by NGI, the soil-pile system is replaced by a macro element at the mudline [7]. The REDWIN model can reproduce different foundation stiffness during monotonic and cyclic unloading/reloading and foundation damping dependent on the loading history, which is observed in real pile behavior.

By increasing the size of the monopiles, support of 10-12 MW turbines at water depths down to 50-70m is feasible. The so called XXL monopiles have a tapered shape with an outer diameter up to 10m or more at the mudline that is gradually decreased to 5-6m at the top, see Figure 18. The substantial weight will require lifting vessels with upgraded crane capacity and bigger hammers are needed to install the very large diameter piles.

Figure 18. The world's largest monopiles produced by EEW 2016 for the German "Veja Mate" wind farm, total weight 1 300 tons, 7.8m diameter at mudline and 82m long.

A mono bucket foundation appears as a monopile topside, however the complete foundation is integrated and installed in one operation, see Figure 19. Instead of pile driving, the caisson foundation (bucket) is penetrated into the seabed by self-weight and the generated under pressure when water is pumped out from the confined void inside the caisson.

As for monopiles, the rocking stiffness may be design driving and the main limitation for this type of foundation. The moment capacity is mainly provided by skin friction along the skirt walls and contact pressure across the lid of the bucket.

Figure 19. Mono bucket foundation (illustration: Universal foundations).

3.2. Gravity base foundations

The significant weight of the gravity base foundations is distributed across the large base area and provides the rocking stiffness and over turning stability. The hollow base is in general built of concrete with a steel shaft. The structure is floated to site and ballasted by filling the hollow concrete base with sand; see Figure 20. The foundation is suitable for a large variety of soil conditions, bust viable at locations with stiff sediments near the seabed or shallow bedrock. The gravity base foundation is normally equipped with shallows skirts for increased bearing and sliding capacity and to prevent undermining by scour.

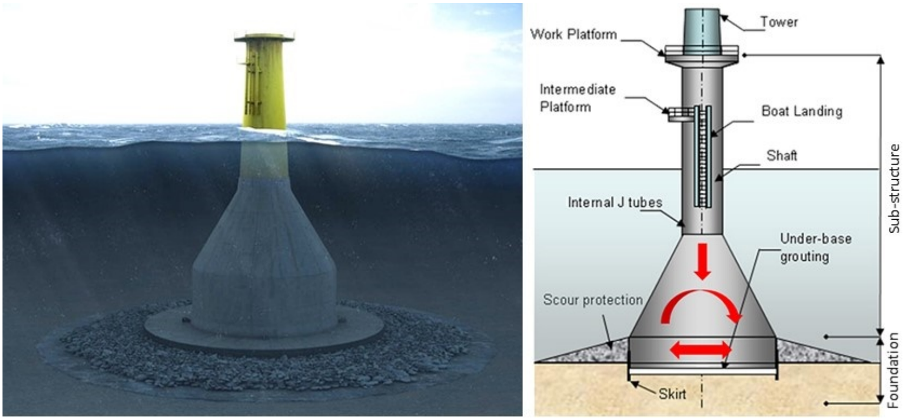


Figure 20. Gravity Base foundation (Seatower) for Offshore Wind turbines.

3.3. Jackets and tripods

Jackets and tripods usually consist of braced steel structures with three or four legs fixed to the seabed by piles or suction buckets. A three-legged foundation constitutes a static determined system and is the most cost-efficient solution for OWT's. The environmental overturning moment loads are mainly transferred to vertical loads on the embedded foundations and the rocking stiffness is high, see Figure 21.

The friction piles are usually pre-installed using a piling template, the jacket with stabs is inserted and grouted to the piles during a subsequent lifting operation. A suction bucket jacket comprises a complete foundation that is installed in one operation.

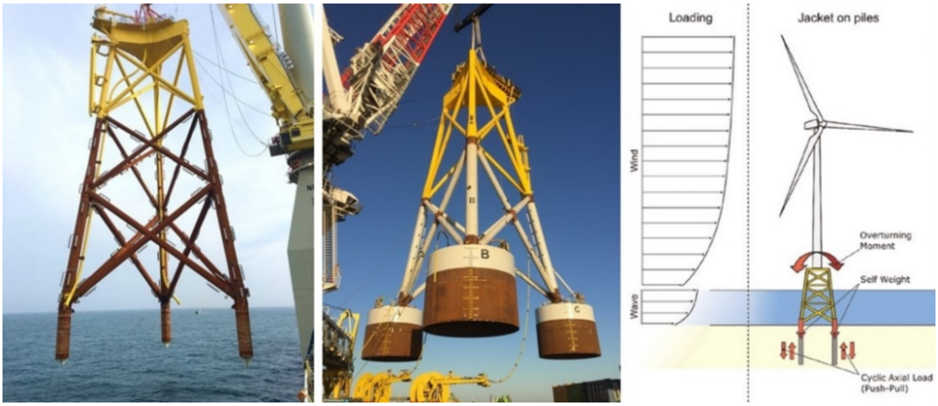


Figure 21. Pre-piled (left) and suction bucket jackets (middle). Loads acting on the jacket foundation (right).

In the design of shallow foundations such as suction buckets, more effort is required to achieve optimized dimensions considering both installation feasibility and in-place performance [8]. The behavior of the suction bucket is especially sensitive to the drainage conditions in the soil during installation, tensile and cyclic loading; see Figure 22.

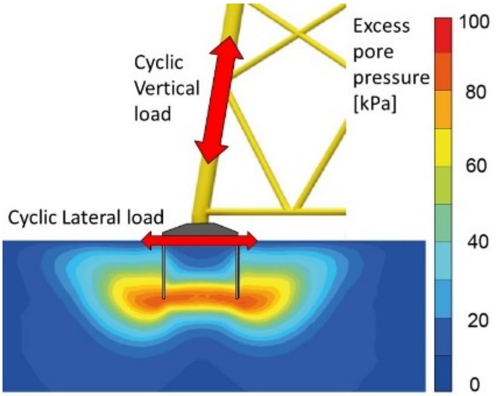


Figure 22 Finite element analysis of pore pressure build up when a suction bucket is subjected to combined vertical and horizontal cyclic loading. The contour plot shows the excess pore pressure at the end of the peak phase during a 35-hrs design storm (source: NGI).

3.4. Floaters

Floating OWT foundations become relevant at water depths >50m and can be placed far out in deeper seas where the wind conditions are favorable. The floater can be of a Spar or Semisubmersible type, see Figure 23. The floater is anchored by catenary or taut leg moorings. The optimal seabed anchors depend on the type of mooring and seabed conditions. Presently suction piles have been used for catenary moored floaters. The amount of seabed anchors can be reduced by combined mooring systems, i.e. several OWT's share common anchor points in the floating wind farm.

Figure 23. From left to right: SPAR, Semisub and TLP type of OWT floaters (Illustration: DNV-GL).

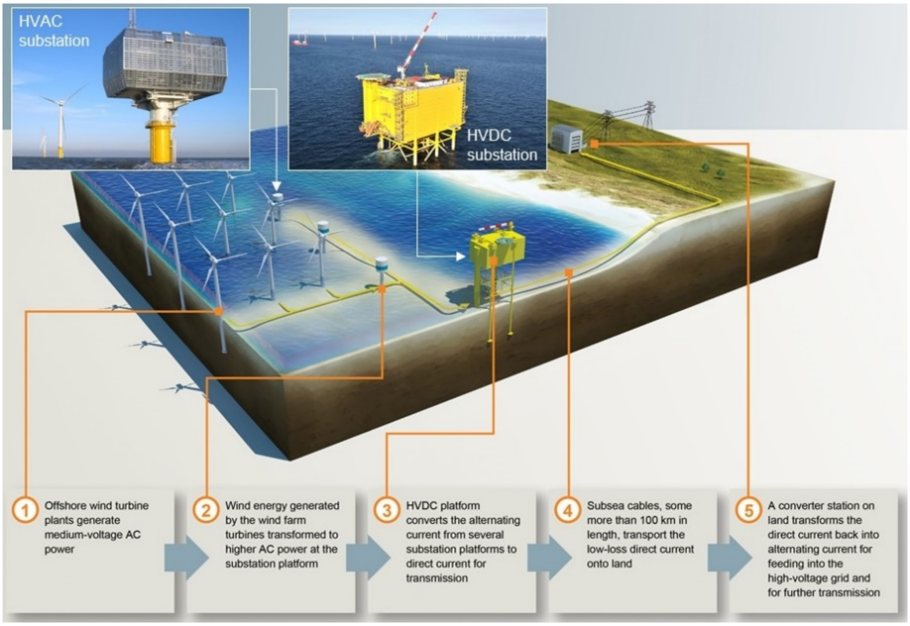
Design of anchors for floating structures follow the standard practice applied in the offshore Oil and Gas industry. The main design challenge is to ensure that the loading response in the mooring system not is affecting the overall dynamics of the floating OWT.

3.5. Offshore substations

An internal grid connects the wind turbines to offshore substations, where the AC voltage is increased to reduce the transmitted current and transmission losses. For clusters of remote wind farms, the High Voltage Alternating Current (HVAC) is converted to High Voltage Direct Current (HVDC) to minimize transmission losses over long distance in the subsea export cable to shore, see Figure 24.

The foundations for offshore substations carry heavy equipment and usually have facilities for accommodation and maintenance acting as a hub for offshore operations. Thus, the foundation loads are dominated by waves and comparable with offshore oil and gas installations. The smaller HVAC stations can be fitted on monopiles, the larger

HVDC stations may require foundations with increased bearing capacity such as multi column gravity base structures or jackets with piles or suction buckets.



1 Offshore wind turbine plants generate medium-voltage AC power

2 Wind energy generated by the wind farm turbines transformed to higher AC power at the substation platform

3 HVDC platform converts the alternating current from several substation platforms to direct current for transmission

4 Subsea cables, some more than 100 km in length, transport the low-loss direct current onto land

5 A converter station on land transforms the direct current back into alternating current for feeding into the high-voltage grid and for further transmission

Figure 24. Transmission of energy captured by offshore wind farms (Illustration Siemens AG). The photos show a HVAC substation on a monopile at Gunflet Sands wind farm (UK) and Dolwin Alpha HVDC substation, (six-legged jacket) 75 km outside the German coast.

4. Offshore installation

The offshore installation work represents a major cost in the development of a wind farm and includes foundations, turbines, grid and shore connections. Optimized operations are a priority for the developers and serial production is required for the large numbers of structures involved. Due to the size and weights of the complete OWT, the standard approach is to first install the foundations and sub-structures and subsequently install the tower and turbines, using vessels dedicated for each task and overlapping operations.

4.1. Monopile installation

The monopiles are normally driven by hydraulic hammers, during initial stabbing and driving the pile is guided by pile grippers controlling the verticality, see Figure 25.

After the piles have been driven to target depth, the transition pieces (TP's) are mounted on top of the piles. The TP's act as an adaptor on the pile top and are equipped with secondary steel components including J-tubes for grid hook-up, boat landing, access ladders with platform, and flange for mounting of the turbine tower at required elevation above the sea surface. Presently the size of the monopiles that can be installed is limited by the vessels lifting capacity and hammer size available in the market.

Figure 25. Monopile driving from a floating vessel with motion compensated pile grippers for control of the pile verticality. The transition pieces are installed after completed pile driving and stored upright on deck to the left in the picture (Illustration: Quest Offshore).

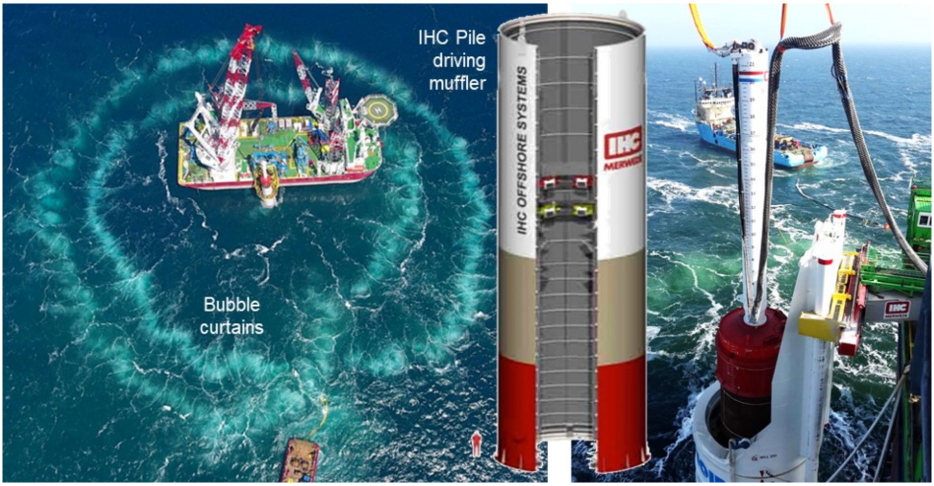


Figure 26. Pile driving with double bubble curtains (left) and with pile driving muffler (right). Images: Geosea and IHC.

In Europe, the noise and disturbance to the marine life during pile driving is a big environmental issue. Arrangement for noise mitigation such as bubble curtains and/or pile driving mufflers is therefore required at many locations; see Figure 26.

To reduce the pile driving noise and fatigue effects on the pile, vibratory hammers can be used for driving the piles. Vibration are especially efficient for pile installation in sand and faster than conventual pile driving. The main question is if and how much vibro-piling may affect the lateral stiffness of the installed pile and the efficiency for drving through clay layers. A large vibro-pile test was conducted in 2014 by a consortium headed by RWE comparing the installation and lateral capacity of large piles in sand installed by impact and vibratory hammers; see Figure 27. Installation of very large diameter monopiles to moderate depth may also be possible by silent suction driving.

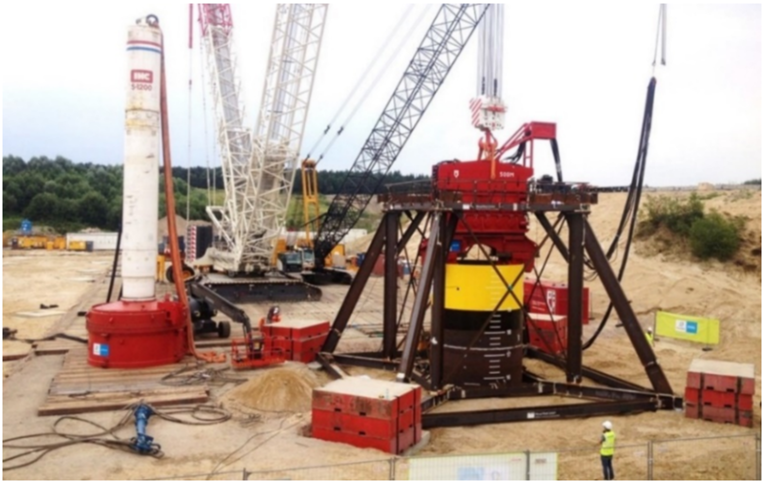


Figure 27. Vibro test in Cuxhaven (Germany), Photo: RWE.

4.2. Pre-piled jacket installation

To optimize the installation process for piled jackets or tripods, the piles can be driven in advance using a seabed template with pile sleeves. The larger (and more expensive) lifting vessels are then only required to deploy the jacket or tripods directly on the pre-piled foundation; see Figure 28. The jacket legs have flanged stabs in the bottom that are inserted into the top of the piles and secured by grouting.

Figure 28. Pile driving using seabed template and subsequent jacket installation (Illustration: Jumbo shipping).

The pre-piling method requires that the pile stick up is monitored during pile driving and the pile top elevation differences must be measured with high precision after all piles in a group are installed. These measurements are directly used for shimming beneath the flange of the pile stab and crucial for final leveling of the structure supporting the wind turbine. By means of instrumented piling templates, the measurements are performed during pile installation; see Figure 29. So far, more than 1000 pre-installed piles are in use for OWT foundations and pre-piling is considered as a proven solution although special skills are required for the metrology. The only uncertainty may be the long-term performance of the grouted pile connections.

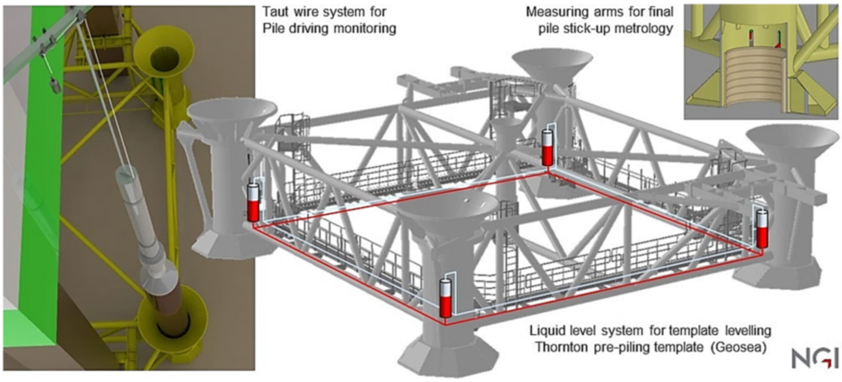


Figure 29. Example of instrumentation provided by NGI for pre-piling metrology.

4.3. Suction bucket jacket installation

The seabed foundations are integrated in the Suction Bucket Jacket (SBJ) and the offshore installation can be completed in one operation. Suction pumps with integrated instrumentation is used to for driving the buckets to the required penetration depth and controlling the installation process, see Figure 30. After the buckets have been landed on the seabed and penetrated by self-weight, the entrapped water inside the buckets is pumped out. Dependent on the penetration resistance a suction pressure is created inside the buckets, driving them further into the seabed. The added driving force by suction can be more than 20 times larger than the complete weight of the SBJ and is a very efficient and silent installation method.

The verticality of the SBJ can be precisely controlled during the suction operations and no further levelling arrangement is required. The ultimate limit of the suction force that can be generated when entrapped water is evacuated is determined by cavitation (vacuum) and may limit the feasible suction penetration in shallow waters (<20m). Normally the gap that may remain inside the buckets after completed suction penetration is backfilled with mortar to improve the effective stress contact between the seabed and the lid of the bucket foundations.

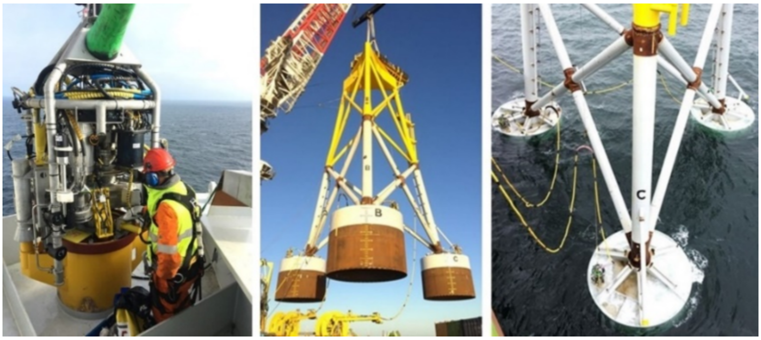


Figure 30. Suction pump arrangement used for Ørsted's Borkum Riffgrund 02 SBJ installation (Photos: NGI-FRAMO).

4.4. Installation of Gravity base foundations

The gravity base foundations are large and floated out to location; see Figure 31. The hollow interior of the foundation is de-ballasted to obtain buoyancy for float-out. During installation the structure is ballasted by water and sand such that the structure sinks down to the seabed. The foundation base is often outfitted with shallow skirts that are penetrated by the increased weight during ballasting. If required, longer skirts can also be penetrated to target depth by the added force from suction driving.

Figure 31. Tow-out of Gravity base foundations constructed by BAM for Blyth offshore windfarm.

4.5. Drilled and grouted piles

For seabed's consisting of weak rock or carbonite soils, the only reliable foundation alternative may be drilled and grouted piles. Special seabed templates and drilling rigs are then required, see Figure 32. The installation operations are usually more time consuming and expensive compared to traditional pile driving.

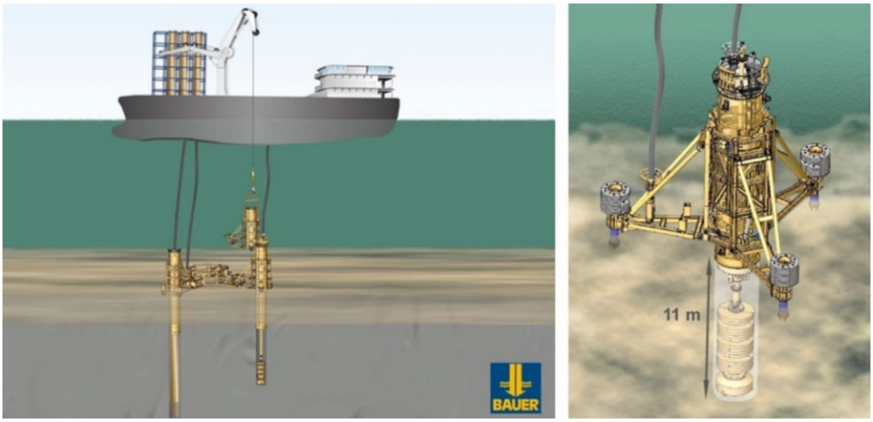


Figure 32. Seabed templates and drilling rigs for drilled and grouted piles operated by Bauer Renewables.

5. Operational experience

Long term Structural Health Monitoring (SHM) is an important tool for reducing risks and costs in development and management of offshore wind farms. Due to the amount of installations in a wind farm, systematic flaws or problems can be very expensive. Consequently, potential savings are big if the design can be improved and optimized based on observed response to environmental loads in the field; see Figure 33.

Figure 33. In-situ observations of structural Health and Response.

An example of a systematic fault with large consequences was the problems with the grouted connections between the transition piece and the monopile detected in 2010. Cracks and severe deterioration of the grout was discovered on a large amount (hundreds) of monopile foundations in Europe. The problem was solved by a re-designed conical joint, however the offshore repair of the old joints has costed enormous sums.

The in-situ dynamic response, for example lateral stiffness and dampening of the monopiles, is important to monitor for design optimization. With respect to the long-term behavior and operational life of the foundations, the degradation due to corrosion is probably the most critical parameter to observe in the field [9]. The amount of SHM data recorded in-situ is sparse, presently the most comprehensive field monitoring campaigns have been conducted by Ørsted in conjunction with their prototype SBJ foundations installed at BKR01 and 02 windfarms; see Figure 34.

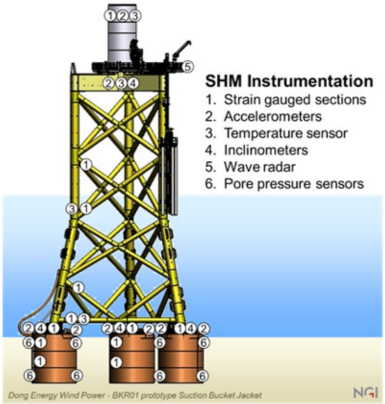


Figure 34. Example of integrated SHM system with 141 sensors implemented on Ørsteds prototype Suction Bucket Jacket BKR01 installed in 2014. (SHM system provider: NGI).

Initial interpretation of data from BKR 01 Suction bucket jacket [10] revealed that undrained conditions are present for cyclic load periods less than 2.5 minutes and drained conditions appears for periods longer than 46 minutes. The nonlinear stiffness anticipated in the design was confirmed and the eigen-frequency is higher (foundation is stiffer) than conservatively assessed in design.

6. Future trends

Due to the cost efficiency, the limiting depth and maximum turbine size for monopile foundations will be pushed as far as possible. Major operators such as Ørsted consider monopiles with up 12 MW turbines at water depths down to 70m as feasible in the near future. 12 MW offshore wind turbines are already being developed such as General Electrics Haliade-X turbine; see Figure 35.

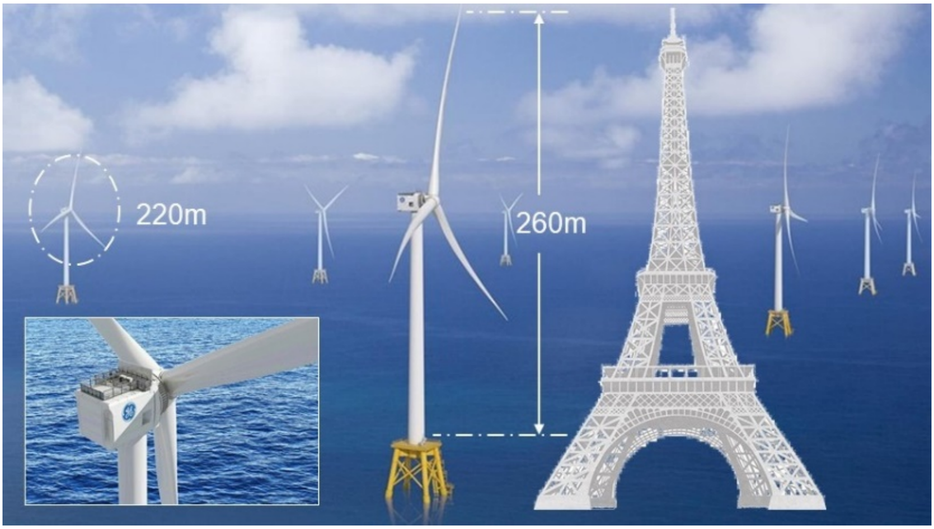


Figure 35. The 12 MW Haliade-X turbine presently being developed by General Electrics.

Due to the dominating place in the market, fabrication and installation costs for monopiles have been optimized over the years, the cost gap may be reduced when alternative solutions mature. Due to increasing turbine size and/or water depth, tripod jackets with buckets or piles (if required due to the soil conditions) may be the preferred bottom fixed foundation in the future, however the fabrication costs must be decreased. Development of new installation methods and vessels (for example with regard to lifting capacity and pile driving noise) are also important factors affecting the optimal foundation concept in the future. Local soil conditions, infrastructure, resources and regulations are also important. Crane free gravity base solutions may be attractive at some locations but not in other places.

Figure 36. Floating deep-water foundations with Vertical Axis Wind Turbines (VAWT's), Image: InFLOW.

Although the opinion among the operators is diversified, the general approach is that the water depth must exceed ~70m before floating wind farms are considered as competitive with bottom fixed structures. New technology may however change this opinion. Significant development work is ongoing for Vertical Axis Wind Turbines (VAWT's). These types of turbines imply a low Centre of gravity and significant less moment loads on the foundation. VAWT solutions are especially attractive for floating foundations see Figure 36, but mechanical problems with bearings etc. remain to be solved.

Power generating kites can harvest the strong winds at very high altitude, up to 3 km; see Figure 37. The technology is being developed by several actors in the market. Due to air traffic and other hazards they are difficult to operate on land, but may be suitable for floaters far out in the sea.

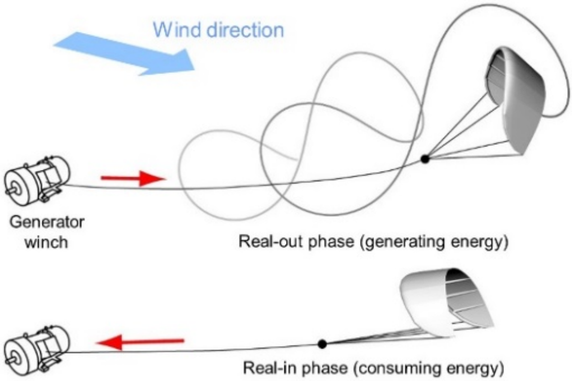


Figure 37. Example showing the operation principles of a power generating wind kite (illustration: Xsens).

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