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OFFSHORE WIND FARMS – FROM DETAILED STRUCTURAL DESIGN TO CONSTRUCTION

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ABSTRACT: Offshore wind farms are located in various different locations each with their own unique conditions. Notwithstanding, the processes and methodology employed in their structural design are typically similar. The paper therefore presents a generic introductory overview of the process involved in the structural design of the support structure for offshore wind turbine structures. This is done by considering the methodology employed for a monopile type support structure, since this is the most common form of foundation to date. Finally, a brief description of the manufacturing process, transport and installation stages is also provided.

Keywords: Offshore wind farms, detailed design, structural design, monopile support structure

1 INTRODUCTION

Offshore wind turbines and their supporting foundation structures are invariably required to withstand a variety of conditions throughout their operational life. They are therefore subjected to various different loading scenarios resulting from the meteorological, oceanographic and geological environment which they are located in. This paper briefly outlines the factors that need to be considered in the structural design of typical offshore wind turbine foundation structures and introduces the ensuing design process. Furthermore, an overview of a typical construction process is also broached. This is done with special reference to wind farm foundations built using monopile foundations, given that to date these are by far the most prevalent foundation types adopted.

An offshore wind farm consists of a number of wind turbine generators that are used to produce electric power and which are located somewhere out at sea. The individual wind turbine generators are positioned in an array, where the generators are spaced nearly equidistantly in one direction and at a similar (though not necessarily identical distance) in the orthogonal direction. Presently the size of offshore wind farms varies from a couple of hundred turbines to those that contain less than a dozen. However, there are currently plans for constructing offshore wind farms which are to contain several hundred turbine generators extending over an area of hundreds of square kilometres and are a couple of hundred kilometres out to sea.

Consequently the specific conditions and ensuing loads, and hence the structural design of specific wind turbines can vary considerably. Notwithstanding, the factors, processes and methodology necessary for their design, by and large remains the same, irrespective of their exact location.

Figure 1: Offshore wind turbine structures are similar in scale to landmarks such as the London Eye

From a construction point of view, the wind turbine generator can be broadly broken down into two main subsets of components. The first set includes the actual generator itself, which comprises the nacelle, blades and the actual tower amongst other items. These in turn require a support structure, whose main function is to keep the wind turbine generator in place, and for a fixed support (as opposed to a floating concept), to transfer all the loads from the turbine to the seabed. This subdivision stems from current industry practice, whereby the first set of components is generally provided directly by the turbine manufacturer, whereas the second set is provided by the wind farm developer. It is this latter set that is further discussed in this paper.

2 SUPPORT STRUCTURE

The support structure needs to carry the wind turbine generator and is therefore subjected to the environmental loading from the generators' components and their self weight. However, invariably the presence of the support structure itself attracts loading which include hydrodynamic and aerodynamic loads which need to be transferred to the seabed.

The support structure is itself subdivided into two main subsets. The first of these is known as the primary part, i.e. that portion of the structure which is primarily intended to transfer the loads to the seabed. The other subset includes the secondary items. The latter are required because the support structure also has the function of allowing access to the wind turbine for operation and maintenance purposes, and also to provide the means for exporting the power generated by the turbine.

2.1 Primary Support Structure

The specific form of the primary support structure can take many forms. The most common types are the following :

- Monopile structure
- Tripod structure
- Jacket structure
- Gravity structure
- Suction caissons
- Floating structure

The choice of foundation structure for a particular wind farm, or even portion of wind farm will depend on many factors, primarily economic ones and the corresponding geotechnical conditions. A detailed discussion of the various foundation types for these structures can be found in several references[1,2]. Suffice to say that to date the monopile has been the most prevalently used.

The monopile foundation is essentially a continuation of the wind turbine generator tower structure. It consists of a hollow steel tube, a pile, which is driven or drilled into location and into the seabed, (Fig. 1). The vertical loads are then transferred to the soil through friction and tip resistance. On the other hand the much larger lateral loads are transmitted to the foundation in bending and laterally to the soil. To provide enough stiffness the diameter of the monopile foundation has to be large enough, this in turn attracts large hydrodynamic loads. With the constraints of current technology, it is expected that this type of foundation will face limitations on its applicability towards the 30-35 metres of water depth. This is due to the requirement that the diameters become ever larger, with consequent limitations of steel plate sizes and difficulties in sourcing suitable sizes of pile driving equipment.

A transition piece is required to be placed over the monopile. This is done for various reasons. The transition piece in fact takes up any tolerance for out of verticality and rotational adjustment. It has been common practice in recent wind farms to have the transition piece grouted over the pile with an annulus of high strength concrete gout. Problems which have plagued this type of connection have only come to light in recent years and has resulted in slippage of the transition piece structure over the monopile, and therefore it is becoming increasingly common to weld shear keys on the monopile and to have a conical section at the juncture. But various other concepts abound, such as bolted flange plates which do require greater tolerances in manufacture. Moreover, in order to safeguard the monopile against driving fatigue, most attachments are placed on the transition piece.

Figure 2: Transition pieces awaiting transport

2.2 Secondary Support Structure

Attached to the primary support structure there are numerous components which serve various functions. These are known as the secondary support structure components, often termed as the secondary steel. Typically these will include some or all of the following items :

- Boat landing
- Ladders
- Platforms
- J-Tubes
- Brackets and attachments for ancillary items such as navigation aids, davit cranes etc.
- Anodes

The boat landing is the assembly to which a maintenance vessel is moored temporarily to transfer personnel and small scale equipment. Depending on the operational requirements of the system there may be more than one boat landing usually aligned to a particular direction depending on operational requirements which are dependent on prevalent wave and wind directions at the site.

Ladders in offshore wind turbine structures become complex systems in their own right. They are required to allow personnel to access all parts of the structure. The ladder assembly may be caged and have fall arrester systems as safety devices.

Platforms are required to provide safe working areas for personnel to perform the respective tasks and also to allow access to various parts of the structure. Different platforms are located at various levels depending on their intended function. The main platform is usually located at the base of the wind turbine generator tower. Internally within the support structure itself more than one platform might be required depending on the particular design of the generator. Moreover, service platforms might be required to allow construction activities to occur.

Figure 3: Attachments are welded to the transition piece and the welds are tested using non destructive methods

J-tubes are needed to protect and guide the cables which exit from the support structure and which allow the export of the power generated. The J-tube can be either internal or external depending on the particular design. However, some of the latest wind farms also have J-tubeless designs.

Anodes are needed to provide cathodic protection against corrosion, These typically take the form of aluminium blocks that may be installed as sacrificial elements. The substructure must include the necessary attachments for these members.

3 SUPPORT STRUCTURE DESIGN

3.1 Background

The first step in the design process is to establish the external conditions which will enable the necessary loading on the structure to be derived. Therefore, for modelling of the support structure and for load calculation purposes, the environmental parameters affecting the support structure must be defined early on. The data needed includes the following[3] :

- Water level data
- Wave data
- Current data
- Wind data
- Soil data

3.2 Water Level Data

The variation due to tides and storm surges all need to be accounted for. This is done by defining the highest astronomical tide (HAT) and lowest astronomical tide (LAT) and also the Mean Sea Level (MSL). Water levels within an offshore wind farm will typically be different for each location. Moreover, for a particular location the seabed level will vary accordingly with time. Surveys of the expected seabed level changes with time are therefore also typically required.

3.3 Wave Data

Wave height, wave period and direction are the characteristics necessary to describe the wave data. The wave conditions are then synthesised in sea state data sets, which are characterised by the significant wave height and a corresponding period. Typically a sea state can be considered stationary for a certain amount of time. Within this time window, the maximum expected wave height is generally calculated as 1.86 times the significant wave height. Extreme events are established from the wave data with corresponding extreme wave heights.

3.4 Sea Currents

Data on the sea current at the site is needed in order to allow a part of the hydrodynamic loading on the structure to be calculated. This is typically characterised by current velocity, direction and profile.

3.5 Wind Data

The wind data is required to determine the loading on the turbine and the tower. Typically one year and 50 year values of the wind speeds, as a function of the return period are needed, for calculation of the extreme aerodynamic loads. This data is often collected from wind masts located somewhere within the offshore wind site maybe at more than one location within the development.

From this wind data the foundation designer is issued with the loads imparted at the interface flange level from the turbine manufacturer.

3.6 Soil Data

Given the typically large area of an offshore wind farm the soil characteristics at each turbine location can be expected to vary from its neighbours, sometimes insignificantly and at others substantially. Therefore tests are conducted ideally at each turbine location to characterise the soil at each turbine position. This will then allow a ground model to be constructed and the necessary soil parameters to be extracted for eventual use in the mathematical model.

3.7 Natural Frequency Analysis

Establishing the correct stiffness of the support structure is of key importance in the design process[4], especially for monopile structures. Indeed tuning the natural frequencies of the support structure is a key stage in the design process because it determines the whole dynamic behaviour of the offshore wind turbine generator. For a three bladed rotor, it has been established that peaks in excitation at frequencies of 1P and 3P are created throughout its operation, where P represents the rotor blade frequency. The peaks are used to determine the lower and upper boundaries respectively, for the natural frequency of the structure and are set by the wind turbine generator supplier based on the specifications of the particular turbine. To avoid resonance, the structure is ideally tuned such that its first natural frequency does not coincide with either of these frequencies.

Moreover, for an offshore wind turbine structure dynamic excitation also results due to the hydrodynamic loading. Sea states with a high frequency of occurrence, such as those composed of short waves with a significant wave height of up to 1.5 metres and a period of around 5s, usually have significant effect on the fatigue lives of the support structures.

During the natural frequency analysis the dimensions of the monopile support structure are determined by varying the main parameters such as pile diameter, can thickness and penetration depth amongst the more noteworthy ones. From a materials point of view the design with the lowest mass is considered to be the most economic one.

3.8 Extreme Event Analysis

The combined loading on the integrated structure (foundation and wind turbine + tower) is determined by simulations for combined wind/wave action. These simulations are typically performed by the turbine manufacturer, following some form of initial input from the foundation designer. The latter then applies equivalent extreme event loads to the foundation structure by assuming equal or larger forces than those supplied from the manufacturer. Material strength and stability checks are then performed to ensure that the structure performs within the necessary parameters as defined by the appropriate design codes. The check is extended to make sure that the supporting soil also behaves satisfactorily. This analysis is termed the ultimate limit state.

3.9 Fatigue Analysis

As in any offshore structure the fatigue calculations are central to confirming that the structure performs safely throughout its operational life span. The latter is normally established by the developer and might typically be expected to be around 25 years in modern developments.

The structure is then analysed according to the loading issued by the turbine manufacturer for this load case. For monopile type structures it is not uncommon to find that the minimum fatigue lives are generally found in circumferential welds with a change in wall thickness and for the transition pieces the minimum fatigue lives might typically be located at the attachments. In calculating the fatigue lives consideration of pile driving damages should be accounted for as also the necessity or otherwise of a lifetime inspection regime.

3.10 Grouted Connection Analysis

Where present, a finite element analysis of the grouted connection needs to be carried out and should include representation of the transition piece, grout and the monopile. The analysis conducted should be a non-linear analyses of the interaction between the grout and steel. The model, (Fig. 4) should also cover the entire range of corrosion allowance. Checks for both the extreme event analysis and the fatigue state need to be carried out. This analysis is key for this type of structure, though as recent events have shown it is not without its pitfalls[5]. Indeed wherever friction mechanisms are relied upon by the tools of numerical modelling caution and rigour should always prevail.

3.11 Ship Impact Analysis

An accidental limit state also needs to be designed for and this usually takes the form of a design ship impact of a maintenance vessel of suitable size, in the design of the secondary steel structure.

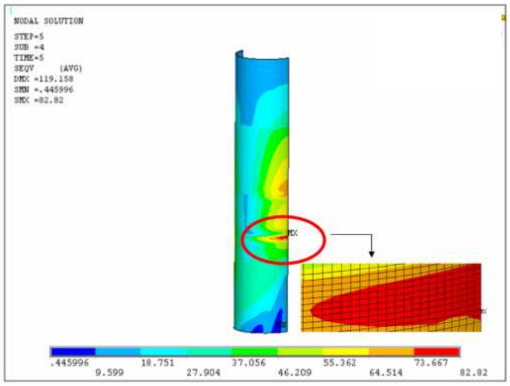

Figure 4: Typical grouted joint detailed finite element model

3.12 Sea-bed Level Scour

In the design of the primary steel it might be necessary, given the local site characteristics, to assume the development of scour. This needs to be calculated and accounted for accordingly. If the depth to the bottom of the scour hole is found to be approaching the design values a scour protection system might be installed to protect the foundations against further erosion.

3.13 Corrosion and Corrosion Protection

Given the harsh environment that the turbines and the support structures operate in, the design is carried out with certain assumptions on corrosion and corrosion protection. These might typically take the form of ensuring that the transition piece is coated, whilst allowing for a certain value of corrosion allowance to be applied in the splash zone for the ultimate limit state and maybe a smaller allowance in the fatigue analysis over the wind farm’s lifetime. A varying corrosion allowance should be used within the natural frequency analysis. Moreover, the support structures are typically supplied with anodes for cathodic protection.

4 FABRICATION

The production process for a monopile type support structure starts by creating the tubular steel primary elements. The manufacturing yard receives sheets of steels cut to predetermined sizes and of the required thicknesses. The edges are bevelled as a preparation for welding. Next the sheets are rolled to form the individual cans of the support structure. The resulting seam is then welded to form a tubular section, a single can (Fig. 5). Depending on the design, the welds may be ground in order to reduce the possibility of stress concentrations and provide the required fatigue lives.

During all stages it is most important to adhere to a rigorous quality control procedure in order to ensure that the cans respect the specified dimensional tolerances. Furthermore, the welds are investigated to monitor their quality by means of non-destructive testing methods.

Figure 5: Individual steel cans prior to welding

The sections thus produced are then aligned and welded together according to a pre-determined sequence which is a direct result of the structural design process. Following any preheating the individual cans are welded together to form the monopile, (Fig. 6). Grinding is also carried out to any welds as per the design requirements and weld testing ensues. Depending on the particular design any holes and attachments are also introduced as may be required.

Figure 6: The individual cans are aligned and welded to form the monopiles

The transition piece is manufactured in a similar manner. However, in this case several items still need to be attached. One of the key items on the transition piece is the flange at the transition piece top to which the actual tower of the turbine generator is bolted to. This key element is welded to the top of the transition piece whilst ensuring strict tolerances are adhered to. As a matter of fact care must be taken to ensure that the transition piece is perfectly round when the flange is attached, as there is always the danger in ending up with ovalised elements for large diameter tubular structures, which occurs under their own weight.

All the stubs to which the secondary steel items are attached are subsequently welded to the transition piece. These might include brackets for ladders and anodes. A grout skirt at the bottom of the transition piece is also attached, together with any supports for the platforms. The surface of the support structure is then shot blasted after which the required coating is applied.

The internal platforms are then installed together with the ancillary items that can be attached in shop. These normally exclude the full length of the J-tube since these depend on the particular height to the sea bed and specific coordination with each location is necessary. A certain amount of flexibility is therefore needed for these elements and rails are frequently employed to achieve this. Finally the platforms are installed together with the boatlandings and any other secondary steel items, including the rubber grout seals at the base of the transition piece. This process ensures that once on location the minimal amount of operations are required to commission the whole structure.

Figure 7: Transition piece at the fabrication yard ready for upending

5 TRANSPORT AND INSTALLATION

The exact installation process naturally depends on the type of support structure adopted and its location. Typically monopile foundations are transported to the site in one of three main ways. They are either floated to the site by tug boats after having their ends sealed, they can also be delivered to the site using a barge or they could actually be delivered on location on the installation vessel itself, say a jack up vessel.

Prior to commencing certain activities weather forecasts will need to be reviewed in order to establish that safe working windows can be adhered to. Once on location the pile is upended, using an upending tool, lifted into the correct position, aligned and then inserted into the seabed, (Fig. 8). The latter is normally done using large offshore hammers to drive the pile into the seabed, however there are instances, depending on the geotechnical conditions, where drilling will have to be resorted to, in order to ensure that the pile is at the correct penetration.

Of particular importance during this stage is to monitor the actual blow counts versus the estimated ones and also the blows per metre relative to the depth in order, to confirm adherence with the driving fatigue calculations. In fact it is at this point that if the refusal criteria are exceeded drilling will be resorted to. Occasionally scour protection is installed at this juncture.

Figure 8: The monopile being hammered into place

The next step is to install the transition piece onto the in place foundation pile. Whenever a grouted connection is used, the transition piece installation should be preceded by the cleaning of the pile head which will be in contact with the transition piece. This is done in order to remove any marine growth that has occurred and will ensure that the best conditions possible for friction to develop between the concrete and steel surfaces once grouting has occurred. Prior to grouting the transition piece is levelled and oriented correctly.

The turbine tower is then installed, typically this is done in two separate pieces and bolted together. Finally the rotor-nacelle assembly is installed, occasionally with only two blades at first (Fig. 9).

Figure 9: The wind turbine generator being assembled at sea.

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