Challenges in Design of Foundations for Offshore Wind Turbines

Professor Subhamoy Bhattacharya Chair in Geomechanics, University of Surrey, UK

Abstract
Designing foundations for offshore wind turbines (OWTs) are challenging as these are dynamically sensitive structures in the sense that natural frequencies of these structures are very close to the forcing frequencies of the wind, wave and 1P (rotor frequency) and 2P/3P (blade shadowing frequency) loading. Typically for the widely used soft-stiff design (target frequency of the overall wind turbine is between 1P and 2P/3P), the ratio of forcing frequency to natural frequency is very close to 1 and as a result is prone to dynamic amplification of responses such as deflection/rotation which may enhance the fatigue damage, thereby reducing the intended design life. Therefore, a designer apart from accurately predicting the natural frequency of the structure, must also ensure that the overall natural frequency because of dynamic-soil-structure-interaction does not shift towards the forcing frequencies making the value of $f_f/f_n$ even closer to 1. Therefore, foundations are one of critical components of OWTs not only because of the overall stability of the structure but also because of financial viability of the project. The article highlights technical challenges associated with foundation design for offshore wind farm.

Importance of Foundation Design
Foundation selection plays an important role in the overall concept design for offshore wind farms as there are large financial implications attached to the choices made. Typically, foundation costs 25 to 34% of the overall costs. For the North Hoyle project the cost of foundation was 34%, [1] and it has been reported that the development of the Atlantic Array wind farm did not go ahead and one of the main reasons is the expensive foundation. Foundations for wind turbines can be classified into two main types: fixed (or grounded to the seabed) and floating. Although most of the currently installed or operating turbines are supported on fixed/grounded foundation system, research and development of floating foundations are underway. Fig. 1 shows the different types of grounded system (fixed to the seabed) foundation system either in use or proposed and will constitute the main part of this article.

Types and Nature of the Loads Acting on the Foundations
Offshore wind turbines (OWTs), because of their shape and form (i.e. a long slender column with a heavy mass as well as a rotating mass at the top) are dynamically sensitive because the natural frequency of these slender structures are very close to the excitation frequencies imposed by the environmental and mechanical loads. Fig. 2 shows a simple mechanical model of the whole system showing the different components and the design variables. In the model, the foundation is replaced by four springs: $K_L$ (lateral spring), $K_R$ (rocking spring), $K_V$ (vertical spring) and $K_{LR}$ (cross-coupling spring). It is therefore clear that the stability and deformation of the system is very much dependent on these four springs. A few things may be noted regarding these springs:

(a) The properties and shape of the springs (load-deformation characteristics) should be such that the whole structure should not collapse under the action of extreme loads and the deformation is acceptable under the working loads.

(b) The values of the spring (stiffness of the foundation) is necessary to compute the natural period of the whole structure as this is linear eigenvalue analysis. Further details on the analysis required can be found in [2, 3].

(c) The values of the springs will also dictate the overall dynamic stability of the system because of its non-linear nature. It must be mentioned that these springs are not only frequency dependent but also change with cycles of loading because of dynamic soil structure interaction. Further details on the dynamic interaction can be found in [4, 5].
Loads acting on the foundations
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 selfweight of the components and the dynamic loads (or in some instances this can be cyclic). However, the challenging part is the dynamic loads acting on the wind turbine which are discussed below:

(a) The lateral load acting at the hub level (top of the tower) from the rotating blades produced by the turbulence in the wind. The magnitude of dynamic component depends on the turbulent wind speed.
(b) The load caused by waves crashing against the substructure very close to the foundation. The magnitude of this load depends on the wave height and wave period.
(c) 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 (referred to as 1P loading in the literature). Since most of the industrial wind turbines are variable speed machines, 1P is not a single
frequency but a frequency band between the frequencies associated with the lowest and the highest rpm (revolutions per minute).

(d) Loads in the tower because of the vibrations caused by blade shadowing effects (referred to as 2P/3P in the literature). The blades of the wind turbine passing in front of the tower cause a shadowing effect and produce a loss of wind load on the tower and is shown in Fig. 3. This is a dynamic load having frequency equal to three times the rotational frequency of the turbine (3P) for three bladed wind turbines and two times (2P) the rotational frequency of the turbine for a two bladed turbine. The 2P/3P loading is also a frequency band such as 1P and is simply obtained by multiplying the limits of the 1P band by the number of the turbine blades.

The turbulent wind velocity and the wave height on sea are both variables and are best treated statistically using power spectral density functions. In other words, instead of time domain analysis the produced loads are more effectively analysed in the frequency domain whereby the contribution of each frequency to the total power in wind turbulence and in ocean waves is described. Representative wave and wind (turbulence) spectra can be constructed by a discrete Fourier transform from site specific data. However, in absence of such data, theoretical spectra can also be used. The DNV standard specifies the Kaimal spectrum for wind and the Joint North Sea Wave Project spectrum for waves in offshore wind turbine applications.

Fig. 4 shows the main frequencies for a three-bladed National Renewable Energy Laboratory standard 5 MW wind turbine with an operational interval of 6.9 to 12.1 rpm. The rotor frequency (often termed 1P) lies in the range 0.115–0.2 Hz and the corresponding ‘blade passing frequency’ for a three-bladed turbine lies in the range 0.345–0.6 Hz. The figure also shows typical frequency distributions for wind and wave loading. The peak frequency of typical North Sea offshore waves is about 0.1 Hz. Further details on loading can be found in [12].

Design options

It is clear from the frequency content of the applied loads (see Fig. 4) that the designer has to select a system frequency (the global frequency of the overall wind turbine including the foundation) which lies outside these frequencies to avoid resonance and ultimately increased fatigue damage. From the point of view of the first natural frequency ($f_0$) of the structure, three types of designs are possible (see Fig. 4)

(1) **Soft-Soft** design where $f_0$ is placed below the 1P frequency range which is a very flexible structure and almost impossible to design for a grounded system.
(2) **Soft-Stiff** design where $f_0$ is between 1P and 3P frequency ranges and this is the most common in the current offshore development.
(3) **Stiff-Stiff** designs where $f_0$ have a higher natural frequency than the upper limit of the 3P band which will need a very stiff support structure.

It is of interest to review the codes of practice in this regard. DNV [11] code suggests that first natural
frequency should not be within 10% of the 1P and 3P ranges as indicated in Fig. 4. It is apparent from Fig. 4 that for soft-stiff design, the first natural frequency of the wind turbine needs to be fitted in a very narrow band (in some cases the 1P and 3P ranges may even coincide leaving no gap).

A few points to be noted:

(1) From the point of view of dynamics, OWT designs are only conservative if the prediction of the first natural frequency is accurate. Unlike in the case of some other offshore structures (such as the ones used in the oil and gas industry), under-prediction of $f_0$ is unconservative.

(2) The safest solution would seem to be to place the natural frequency of the wind turbine well above the 3P range. However, stiffer designs with higher natural frequency require massive support structures and foundations involving higher costs of materials, transportation and installation. Thus from an economic point of view, softer structures are desirable and it is not surprising that almost all of the installed wind turbines are 'soft-stiff' designs and this type is expected to be used in the future as well.

(3) It is clear from the above discussion that designing soft-stiff wind turbine systems demands the consideration of dynamic amplification and also any potential change in system frequency because of the effects of cyclic/dynamic loading on the system, that is, dynamic-structure-foundation-soil-interaction. Typically, the first modal frequency of the wind turbine system lies in the range of 75 to 120% of the excitation frequencies and as a result, dynamic amplifications of responses are expected.

(4) Clearly, for soft-stiff design, any change in natural frequency over the design/operation period of the turbine will enhance the dynamic amplifications which will increase the vibration amplitudes and thus the stresses and fatigue damage on the structure. Therefore, fatigue is one of the design drivers for these structures. Predicting fatigue damage is undoubtedly a formidable task because of the complexity associated with the uncertainty in the dynamic amplification (owing to changes in system characteristics over time and number of cycles), randomness of the environmental loading and last but not the least, the impact of climate change.

**Design Considerations for Foundations**

One of the main aims of the foundations is to transfer all the loads from the wind turbine structure to the ground within the allowable deformations. Guided by limit state design philosophy, the design considerations are to satisfy:

1. **Ultimate Limit State (ULS):** This would require the computation of capacity of the foundation. For
monopiles type of foundation, this would require computation of ultimate moment, lateral and axial load carrying capacity.

2. Serviceability Limit State (SLS): This would require the prediction of tilt at the hub level over the life time of the wind turbine.

3. Fatigue Limit State: This would require predicting the fatigue life.

4. Robustness and ease of installation: Can the foundation be installed and are there adequate redundancy in the system?

A note on SLS design criteria

Serviceability criteria will be defined based on the tolerance requirements for the operation of the wind turbine and is often described as ‘turbine manufacturer requirements’. Ideally, these should be turbine specific, that is, size and the hub height, gear boxed or direct drive. Typically, these tolerances are specified in some codes of practice (e.g. DnV) or a design specification supplied by the client which may be dictated by the turbine manufacturer. Some of the specific requirements are:

(a) Maximum allowable rotation at pile head after installation. DnV code specifies 0.25 degree limit on ‘Tilt’ at the nacelle level.

(b) Maximum accumulated permanent rotation resulting from cyclic and dynamic loading over the design life.

Example methodology to predict the foundation stiffness required: For Walney farm (in the Irish Sea having Siemens SWT-3.6–10 type turbine having an operating wind speed range of 4 to 25 m/s), it has been estimated that for 9 m/s wind speed, the maximum moment at the mudline level is about 60 MN and for 20 m/s wind speed, the maximum value is 125 MNm. Assuming design over turning moment is 125 MNm and if the allowable tilt is 0.25° at the foundation level, one can therefore estimate the Rotational Foundation stiffness required and is given by (1)

\[ K_R = \frac{125 \text{ MNm}}{4.36 \times 10^{-3} \text{ rad}} = 28.6 \text{ GNm/rad} \]  

This is a very large number and would require large diameter monopile or equally alternative foundation multiple pod foundations may be used.

In this context it may be mentioned that SLS criteria impacts the foundation design and thereby costs. It has been reported that floating wind turbines are allowed to tilt by up to ± 5° in the worst sea states. Therefore, it is necessary to understand the stringent criteria of 0.25° for grounded wind turbine system. A value of 0.25° represents a horizontal deflection of 450 mm for a typical 80 m tower. Clearly, a less stringent tilt criterion will save on the foundation costs and installation time and make wind energy cheaper.

Challenges in Analysis of Dynamic Soil-Structure Interaction

OWTs are new types of offshore structures and are unique in their features. The most important difference with respect to oil and gas installation structures is that they are dynamically sensitive (as explained in Section 2) and moment-resisting. Fig. 5 shows a typical monopile supported wind turbine and a pile supported fixed offshore jacket structure. There are, however, obvious differences between those two types of foundations. Piles for offshore structures are typically 60–110 m long and 1.8–2.7 m diameter and monopiles for OWTs commonly 30–40 m long and 3.5–6 m diameter. Degradation in the upper soil layers resulting from cyclic loading is less severe for offshore piles which are significantly restrained from pile head rotation, whereas monopiles are free-headed. The commonly used design method using a beam on non-linear Winkler springs (‘p-y’ method in API code or DNV code) may be used to obtain pile head deflection under cyclic loading, but its use is limited for wind turbines because:

(a) the widely used API model is calibrated against response to a small number of cycles (maximum 200 cycles) for offshore fixed platform applications. In contrast, for a real offshore wind turbine \(10^7–10^8\) cycles of loading are expected over a lifetime of 20–25 years.

(b) under cyclic loading, the API or DNV model always predicts degradation of foundation stiffness in sandy
soil. However, recent work by [4, 6, 7, 10] suggested that the foundation stiffness for a monopile in sandy soil will actually increase as a result of densification of the soil next to the pile.

(c) The ratio of horizontal load (P) to vertical load (V) is very high in OWTs when compared with fixed jacket structures.

Although, offshore wind turbine structures are designed for an intended life of 25 to 30 years, but little is known about their long term dynamic behaviour under million of cycles of loading. Although monitoring of existing offshore wind turbine installation is a possibility and can be achieved at a reasonable cost, full scale testing is very expensive. An alternative method is to carry out a carefully planned scaled dynamic testing to understand the scaling/similitude relationships which can be later used for interpretation of the experimental data and also for scaling up the results to real prototypes. There are mainly two approaches to scale up the model test results to prototype consequences: first is to use standard tables for scaling and multiply the model observations by the scale factor to predict the prototype response and the alternative is to study the underlying mechanics/physics of the problem based on the model tests recognising that not all the interaction can be scaled accurately in a particular test. Once the mechanics/physics of the problem are understood, the prototype response can be predicted through analytical and/or numerical modelling in which the physics/mechanics discovered will be implemented in a suitable way. The second approach is particularly useful to study the dynamics of OWTs as it involves complex dynamic wind-wave-foundation-structure interaction and none of the physical modelling techniques can simultaneously satisfy all the interactions to the appropriate scale. Ideally, a wind tunnel combined with a wave tank on a geotechnical centrifuge would serve the purpose but this is unfortunately not feasible. It is recognised that not all physical mechanisms can be modelled adequately and therefore those need special consideration while interpreting the test results. As dynamic soil structure interaction of wind turbines are being studied, stiffness of the system is a top priority. [4, 5, 8] carried out experimental testing of a 1:100 scaled wind turbine to characterise the free dynamics of the system and to study the long term behaviour under the action of the dynamic loading.

The following conclusions could be reached from the study

(a) The change in natural frequencies of the wind turbine system may be affected by the choice of foundation system, that is, deep foundation or multiple pods (symmetric or asymmetric) on shallow foundations. Deep foundations such as monopiles will exhibit sway-bending mode, that is, the first two vibration modes are widely spaced – typical ratio is 4 to 5. However multiple pod foundations supported on shallow foundations (such as tetrapod or tripod on suction caisson) will exhibit rocking modes in two principle planes (which are of course orthogonal). Fig. 6 shows the dynamic response of monopile supported wind turbine and tetrapod foundation plotted in the loading spectrum diagram.

(b) The natural frequencies of wind turbine systems change with repeated cyclic/dynamic loading. In the case of strain-hardening site (such as loose to medium dense sandy site) the natural frequency is expected to increase and for strain-softening site (such as normally consolidated clay) the natural frequency will decrease.

(c) The results showed that the multipod foundations (symmetric or asymmetric) exhibit two closely spaced natural frequencies corresponding to the rocking modes of vibration in two principle axes. Furthermore, the corresponding two spectral peaks change with repeated cycles of loading and they converge for symmetric tetrapods but not for asymmetric tripods. From the fatigue design point of view, the two spectral peaks for multipod foundations broaden the range of frequencies that can be excited by the broadband nature of the environmental loading (wind and wave) thereby impacting the extent of motions. Thus the system lifespan (number of cycles to failure) may effectively increase for symmetric foundations as the two peaks will tend to converge. However, for asymmetric foundations the system life may continue to be affected adversely as the two peaks will not converge. In this sense, designers should prefer symmetric foundations to asymmetric foundations.

Foundation Design

Although design guidelines are available for offshore oil and gas installation foundations, its direct extrapolation/interpolation to offshore wind turbine foundation design is not always possible, the reasons of which is explored in the earlier section. There are two reasons: (a) The foundations of these structures are moment resisting, that is, large overturning moments at the foundation which are disproportionately higher that the vertical load; (b) The structure is dynamically sensitive and therefore fatigue is a design driver. This section of the article therefore explores a simplified foundation design methodology.
which may be used during option engineering or preliminary design.

1. Compute the maximum mudline bending moment, considering the different load combinations. The overturning moments because of 1P (misalignment) and 3P (blade shadowing) may be neglected in this step.
2. Based on the allowable tilt criteria for the particular project-determine the foundation stiffness required as shown in Equation 1. This is the minimum stiffness that is required to satisfy the SLS.
3. It is then required to check the ULS criteria, that is, the foundation capacity. If the foundation is not adequate, the size must be increased.
4. The soil surrounding the foundations will be subjected to tens of millions of cycles of cyclic and dynamic loading of varying strain as well as varying frequency. It must be ensured that the soil remains in the linear elastic range so as not to alter the dynamic stiffness of the foundation. For detailed design, Resonant Column testing is recommended to find the threshold strains for the ground and further details on the use of threshold strain concept in monopile design can be found in [9].
5. Beam on non-linear Winkler model or finite element analysis can be carried out and it must be ensured that the p-y curves in soil are within the linear elastic section at all depths. However, 3D Finite Element Analyses are recommended to understand the strains around the foundation.
6. It is now required to obtain stiffness of the foundation to calculate natural frequency of the whole system to check where the overall system is placed: soft-soft, soft-stiff or stiff-stiff (see Fig. 4). If the natural frequency is not acceptable, the design parameters such as foundation stiffness, tower stiffness and mass may be altered so that the desired frequency is obtained. This is an iterative process.
7. The foundation stiffness may change over the life time of the wind turbine because of soil-structure interaction which will have an impact on the natural frequency of the system and tilt. If the ground is sandy site (shown as strain-hardening site in Fig. 4), the natural frequency to expected to increase and if it is a clay site (shown as strain-softening site in Fig. 4), the natural frequency may decrease. If the site is layered, the change in natural frequency cannot be ascertained a priory and depends on various factors including the geometry of layering. This is termed as uncertain site in Fig. 4. Engineers need to carry out calculations to predict the change in frequency which is also necessary to compute the fatigue loading.

**Challenges in monopile foundation design and installation**

Monopiles have been predominantly used to support wind turbine generators in water depths up to 30 m. However, there are discussions with regard to the
use of monopiles in deeper water depths termed as ‘XL’ monopile. Preliminary calculations suggests that 10 m diameter monopiles weighing 1200 tonnes may be suitable for 45 m water depth and of course dependent of ground conditions. However, the use is uncertain because of the following: (a) no codified cyclic design to predict long term tilt; (b) lack of redundancy in foundation system and therefore chance of single-point failure; (c) installation costs and lack of adequate specialised vessels; (d) connection between foundation, transition piece and the tower. Some of these aspects are described below in further details:

1. Lack of redundancy: Monopiles are ‘overturning moment’ resisting structures and there are two main components: (a) overturning moment arising from the thrust acting at the hub level; (b) overturning moment because of the wave loading. Also these two moments can act in two different planes and will vary constantly depending on the time of the day and time of the year. Monopiles are rigid piles and the foundation collapse can occur if the soil around the pile fails, that is, there would be rigid body movement. If the foundation starts to tilt, it is very expensive to rectify.

2. Cyclic (rather dynamic) design of monopile: The response of monopiles under cyclic/dynamic load is not well understood and there is a lack of guidance in codes of practice. If cyclic design is incorrect, monopile can tilt in the long term. If the tilt is more than the allowable limit, the turbine may need a shutdown. Monopile design is usually (also wrongly) carried out using API design procedure calibrated for flexible pile design where the pile is expected to fail by plastic hinges.

3. Issues related to installation of monopiles: Large monopile installations require suitable vessel availability as well as specialised heavy lifting equipments. Other issues are noise refusals, buckling of the pile tip, drilling out, grouted connections. If the site contains weak rock (siltstone/sandstone/mudstone) and where the local geology shows bedrock or hard glacial soils at shallow depths, drive-drill-drive techniques may be required, with subsequent increases in cost and schedule. It must be mentioned here that driving reduces the fatigue life.

Jacket on flexible piles

There has been considerable interest in jacket type structures for deeper water applications, but it is perceived as being expensive because of the amount of steel required. However jackets supported on piles can be considered as a safe solution because of excellent track record of good performance in the offshore oil and gas industry. The offshore oil and gas industry have been using long flexible piles (diameters upto 2.4 m) which are easy to drive, the necessary vessels are readily available (relatively as opposed to vessels to install monopiles). This aspect will drive down the time in construction costs regarding piling and also large vessels are not required for pile installation. However there are costs associated with jacket installation. One of the requirements is the optimisation of the jacket so as to consume minimum steel. There are two types of jacket – normal jacket or twisted jacket. The advantage of twisted jacket over normal jacket is fewer number of joints and therefore less of a fatigue issue.

Conclusion

OWTs are new types of offshore structure characterised by low stiffness (as a result flexible and having low natural frequency) and therefore sensitive to the dynamic loading imposed upon them. The article discusses the complexity involved in designing the foundation of these structures. It has been shown that design guidelines available for offshore oil and gas installation foundations cannot be direct extrapolated/interpolated to offshore wind turbine foundation design.

REFERENCES


© The Institution of Engineering and Technology 2014


