Challenges in the Design and Construction of Offshore Wind Turbine Foundations Including Sites in Seismic Areas

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1 Climate Change and Wind Power

The United Nations recently declared that we are facing a grave climate emergency and this one of the grand technological challenges in our times. Continuous ocean and atmospheric warming, heat waves and rising sea levels are some of the most common manifestations of climate change. The recent floods in Venice (Italy) and the ongoing forest fires in Australia are attributed to the effects of climate change. It is not an understatement that island and coastal cities and towns will be disproportionately affected. Developed nations are taking decisive actions, and in this context, it is important to highlight that the UK Committee on Climate Change has set an ambitious target to reduce greenhouse emission to net-zero by 2050. This must involve decarbonising the economy, the backbone of which is energy. A practical way to achieve net-zero target is to run the country mostly on electricity produced from renewable sources without burning much fossil fuel.

Offshore wind power is one the major renewable energy technologies and can tackle many of the current technological and societal challenges by providing green energy and thus reducing the air pollution and improving life-long health. Wind power has an established track record in the sense that it has been used for centuries for sailing ships, sawing wood, grinding grains and many more.

It is one of the oldest sources of '*machine*' power which fits the definition of machine as laid out in Cambridge Dictionary, i.e., a piece of equipment with several moving parts, that uses wind power to carry out a particular type of work such, i.e., sawing a wood. The invention of wind-powered sawmills by Dutchman Cornelis Corneliszoon van Uitgeest in the late sixteenth century helped Holland increase ship

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Fig. 1 Wind mill in Zaanse Schans (the Netherlands) where the sawing of wood can be seen. *Photo* Prof. Bhattacharya

production through automated wood cutting, outcompeting their European rivals who were relying on slow manual processes. It can also be said that offshore wind turbine machines are also the largest moving machine. A typical 10 MW turbine will have three 80 m long blades and each weighing circa 35 tonnes turning at average of 8–10 RPM.

Figure 1 shows a wind mill for sawing wood still conserved in the Netherlands and is a tourist attraction. The readers are referred to various aspects of climate change in relation to offshore wind in Nikitas et al. (2018, 2020) in the edited books on Managing Climate Change: Human intervention and Future Energy.

1.1 Offshore Wind Energy

Modern-day wind power is harvested through wind farms, either onshore or offshore. As compared to onshore, an offshore wind farm is scalable and relatively easy (not necessarily cheaper) to construct due to the sea routes and vessels available to transport parts from manufacturing sites to turbine locations. Further details of comparison between offshore and onshore turbines can be found in Chap. 1 of Bhattacharya (2019).

A typical offshore wind farm can generate 1 GW of power, approximately equivalent to two standard nuclear power plants. A typical turbine can produce 8–10 MW of power, and therefore, 1 GW of offshore wind farm power involves 100–125 offshore turbines.

Figure 2 illustrates a typical layout of an offshore wind farm, annotating all the different components (turbine generator through the electricity cables to the offshore substation and finally to the onshore power grid). The design of an offshore wind farm requires extensive and comprehensive input from geotechnical engineers. Figure 3 shows an aerial view of the Dudgeon wind farm, with a capacity 400 MW, located off the coast of Norfolk showing the turbines and a substation.

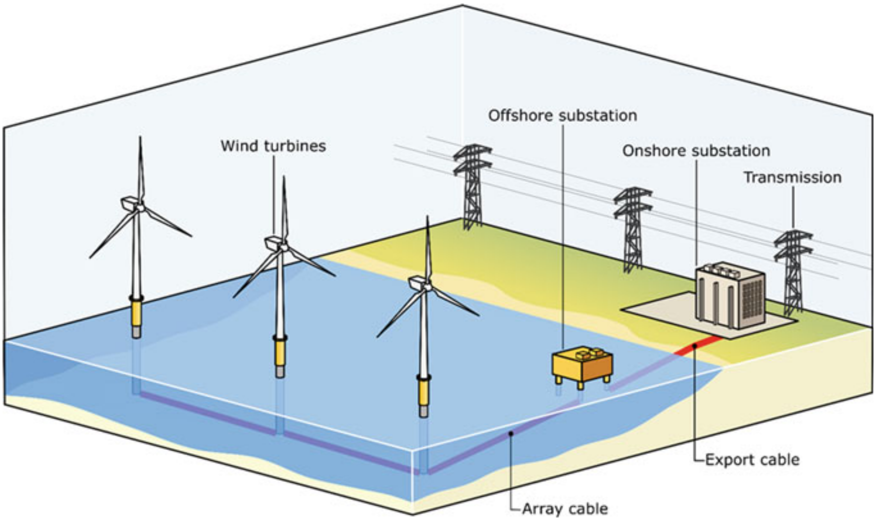

Fig. 2 Layout of an offshore wind turbine

Fig. 3 Aerial view of Dudgeon wind farm. *Photo* Jan Arne Wold, Equinor

1.2 Sustainability of Wind Farm and Tackling Intermittency of Wind Power

In a nutshell, wind will blow as long as the sun is shining. The sun is the ultimate source of energy and responsible for wind. Due to the radiation of the sun reaching the earth, a continuous warming of the earth's surface is caused. Out of this radiation, the largest amount is sent back to space, and only a small amount is transformed into heat. Due to the surface characteristics of the earth and having different materials (water and land), its surface is not heated evenly resulting in the equator getting more energy than the poles. As a result, there is a continuous heat transfer from the equator to the poles.

The atmospheric air consists of nitrogen and oxygen, and they expand when heated and contract when cooled. The solar radiation causes the air to get warmer and lighter and less dense than cold air. This also results in the rise of warm air in higher altitudes and the creation of areas of lower atmospheric pressure, where the air is warmer. Due to the variance in pressure, the air will move from a high pressure to a lower pressure area, in an attempt to reach equilibrium.

Wind is essentially atmospheric air in motion and is very complex, see Fig. 4. At 30° and 60° latitude, there is a major change in atmospheric pressure creating zones of high and low pressure, respectively. The air circulation within these zones is known as cells and the major winds created as trade winds. Due to the diurnal motion of the earth, the wind deflects to the right in the Northern Hemisphere and to the left in the Southern one, leading to a spiral movement of the air mass, and this phenomenon is known as Coriolis effect. Figure 4 describes the mechanism of

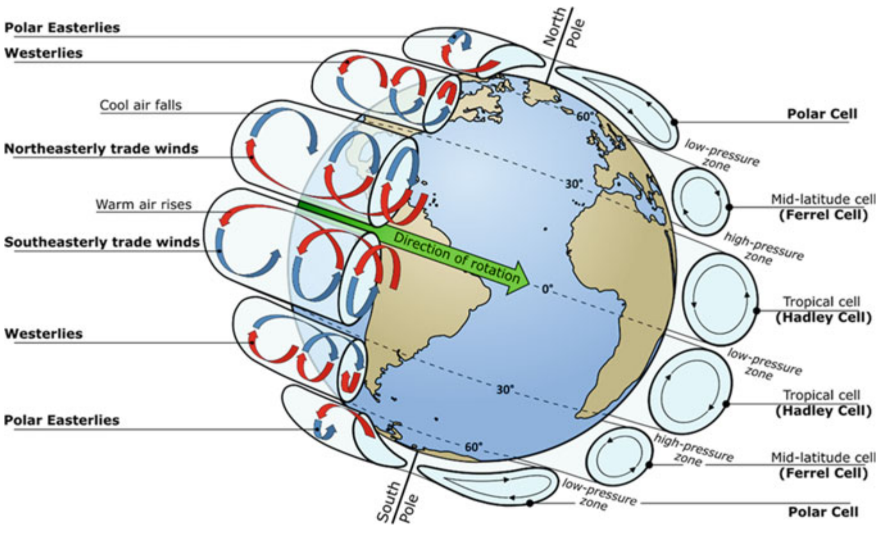

Fig. 4 Global circulation of wind

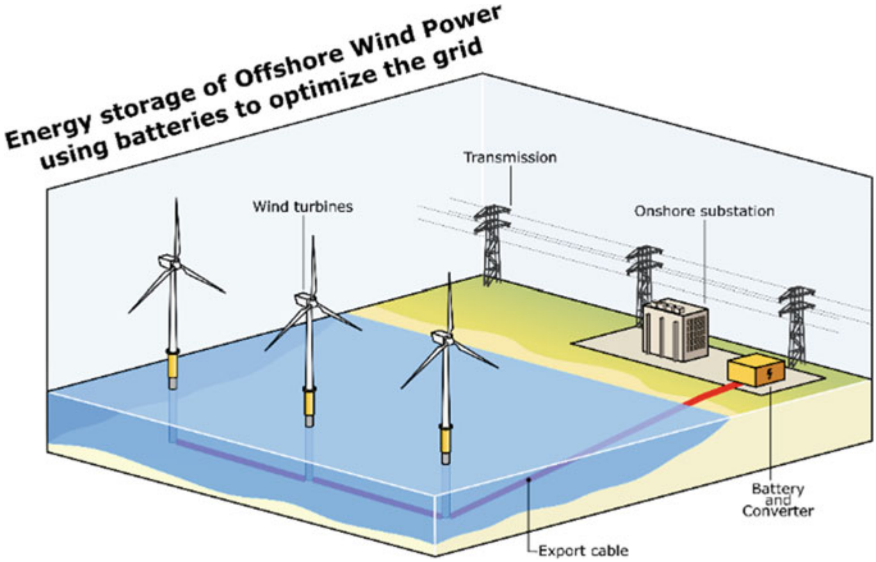

Fig. 5 Combining offshore wind with battery storage

the global wind system. In addition to the global wind system, there are localised influences as well and are mostly related to the terrain of an area and its proximity to water bodies. Further details of wind energy engineering can be found in the edited book by Letcher (2017).

A power curve from a typical turbine will show that a turbine can generate power from a wind speed starting from as low as 3 m/s and reach the rated power at about 12 m/s. It is believed by many that wind does not blow constantly, and therefore, when you need power, it will not be available or when the wind is blowing there may not be the need for the power. To face these problems, technologists have manufactured systems that can store the energy generated by wind in batteries and thus optimising the grid. The synergy of offshore wind along with storage technologies such as batteries will become necessary in order to secure grid's stability. However, such technologies often need rare earth metals for battery production which needs extensive mining and the effects of commodity trading (similar to oil and gas trading). The next section shows another technology that may avoid some of the above effects (Fig. 5).

1.3 Hydrogen Production Using Offshore Wind—The Japanese 'Jidai' Concept

The 2011 Fukushima Daiichi Nuclear Power Plant (NPP) disaster was a devastating moment in the history of mankind, see Bhattacharya et al. (2019). Following the disaster, many countries such as Germany and Japan reduced their reliance on nuclear power and compensated with fossil fuels and renewables. Within the framework of global warming, and amongst others such as energy security, Japan aims to become a carbon-free country through a 'hydrogen society'. The main idea is to generate hydrogen from water through renewable energy sources such as wind, solar and hydroelectricity. Japan named it as the Jidai concept. Similar attempts are also ongoing in major European economies. These attempts have been boosted by other technology developments, i.e., the invention of hydrogen-powered cars, trains, ships and even aircrafts (Fig. 6).

The Jidai concept is a four-step process: (a) seawater is desalinated; (b) electrolysis is used to produce hydrogen and oxygen from water; (c) hydrogen gas is compressed to 700 bar to reduce storage volume; (d) high-pressure hydrogen gas is stored in a module-based tank system (Fig. 7).

The potential of hydrogen is huge: through the existing offshore infrastructure of pipe networks, hydrogen can be transported for distribution. With the advent of hydrogen cars and trains, the economy can be transformed without the need for expensive metals that are needed for battery production. For example, lithium and nickel, unlike hydrogen, can be seen as a trading commodity like oil and gas.

Studies are being conducted to demonstrate that a 100% hydrogen gas network is equally as safe as the existing natural gas. It is worth noting that burning natural gas to heat homes and businesses accounts for approximately a third of the UK's

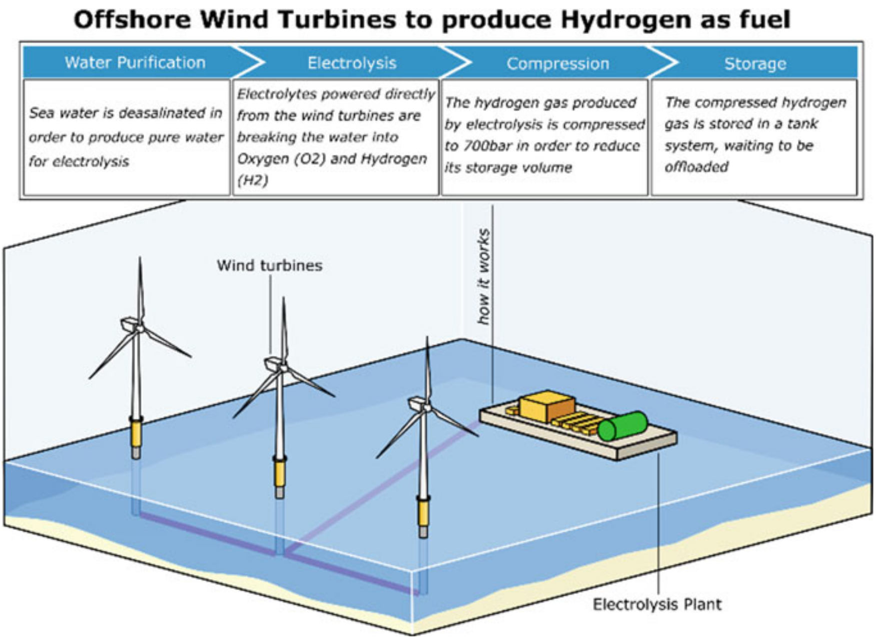

Fig. 6 Use of offshore wind to produce hydrogen

Fig. 7 Hydrogen-powered buses in Tokyo (photo taken in September 2019)

carbon emissions. Hydrogen-powered commuter trains are available, and it has been reported in New Civil Engineer that 30% of the UK rail fleet could be suitable for running hydrogen-powered trains. In summary, wind power has the potential to carry the transition to low carbon energy, transforming the fossil fuel energy landscape to a more sustainable energy future.

1.4 Opportunity for Increasing Resilience of Nuclear Power Plant Through the Use of Offshore Wind Turbines

Following the 2011 Fukushima Nuclear Power Plant disaster, one of the main technological challenges is the seismic resilience of existing nuclear power plant, so that similar incidents may not happen. Table 1 shows the summary of the main three nuclear accidents, and it appears that cooling power for the reactor is vital for safety.

Table 1 Case studies of major global NPP disasters

Name of NPP	Cause of failure
Three-mile island (USA)	Damage to reactor core due to cooling loss
Chernobyl (Russia)	Overheating, steam explosion and meltdown
Fukushima (Japan)	Failure of emergency cooling caused an explosion after the shutdown of reactor during the cascading events of Tohoku earthquake

Bhattacharya (2009), Bhattacharya and Goda (2016) and Bhattacharya et al. (2018) described the Fukushima NPP incident, and it was inferred that seismic resilience of NPP is directly linked to resilience of the cooling power.

In the context of offshore wind, it is of interest to describe the performance of near-shore offshore wind turbines in Japan during the 2011 Tohoku earthquake.

1.4.1 Case Study: Performance of Near-Shore Wind Farm During 2011 Tohoku Earthquake

A devastating earthquake of moment magnitude 9.0 struck the Tohoku and Kanto regions of Japan on 11th March at 2:46 p.m. which also triggered a tsunami, see Fig. 8 for the location of the earthquake and the operating wind farms. The earthquake and the tsunami caused effects such as: liquefaction, economic loss, loss of life, damage to national infrastructures but very little damage to the wind farms. Extensive damage was also caused by the massive tsunami in many cities and towns along the coast. Figure 9 shows photographs of a wind farm at Kamisu (Hasaki) after the earthquake, and Fig. 10 shows the collapse of a pile-supported building at Onagawa where for the first time the world saw complete uprooting of piled foundations. At many locations (e.g., Natori, Oofunato and Onagawa), tsunami heights exceeded 10 m, and sea walls and other coastal defence systems failed to prevent the disaster.

The earthquake and its associated effects (i.e., tsunami) also initiated the crisis of the Fukushima Daiichi nuclear power plants (NPP). The tsunami, which arrived

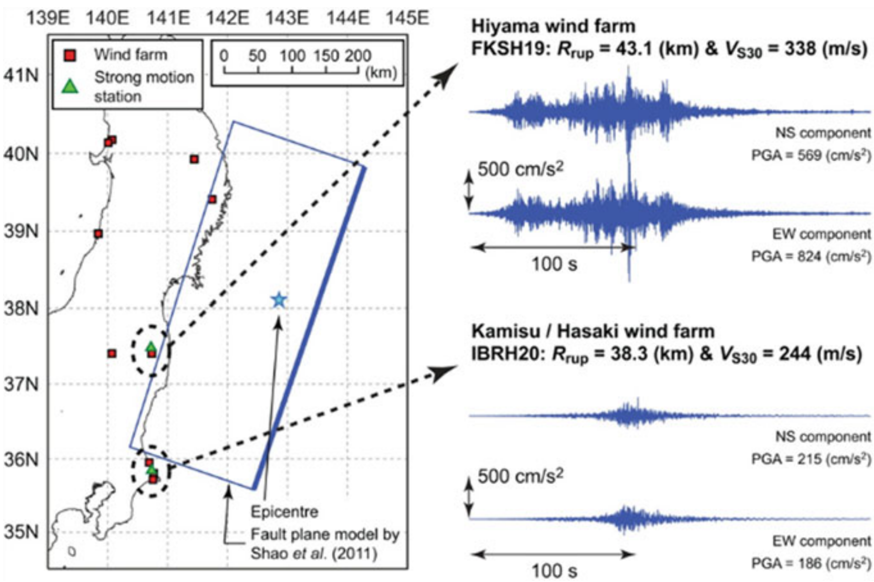

Fig. 8 Details of the 2012 Tohoku earthquake and locations of the wind farms

Fig. 9 Photograph of the Kamisu (Hasaki) wind farm following the 2012 Tohoku earthquake

Fig. 10 Collapse of the pile-supported building following the same earthquake

around 50 min following the initial earthquake, was 14 m high which overwhelmed the 10 m high sea walls, flooding the emergency generator rooms and causing a power failure to the active cooling system.

Limited emergency battery power ran out and subsequently led to the reactor heating up and the subsequent meltdown leading to the release of harmful radioactive material to the atmosphere. Power failure also meant that many of the safety control systems were not operational. The release of radioactive materials caused a large-scale evacuation of over 300,000 people, and the clean-up costs are expected to be of the order of tens of billions of dollars. On the other hand, following/during the earthquake, the wind turbines were automatically shut down (like all escalators or lifts), and following an inspection, they were restarted.

1.4.2 Why Did the Wind Farm Stand Up?

Recorded ground acceleration time-series data in two directions [North–South (NS) and East–West (EW)] at Kamisu and Hiyama wind farms [FKSH19 and IBRH20] are presented in Fig. 11 in frequency domain. The dominant period ranges, of the recorded ground motions at the wind farm sites, were around 0.07–1 s, and on the other hand, the periods of the offshore wind turbine systems are in the range of 3 s. Due to non-overlapping of the vibration periods, these structures will not get tuned in, and as a result, there are relatively insensitive to earthquake shaking. However, earthquake-induced effects such as liquefaction may cause some damages. Further details of the dynamics of wind turbine structures together with the effects of foundation can be found in Bhattacharya (2019).

Forward Outlook: One may argue, had there been few offshore wind turbines operating, the disaster may have been averted or the scale of damages could have certainly been reduced. The wind turbines could have run the emergency cooling system and prevented the reactor meltdown. In this context, it is interesting to note that there are plans to replace the Fukushima NPP by a floating wind farm.

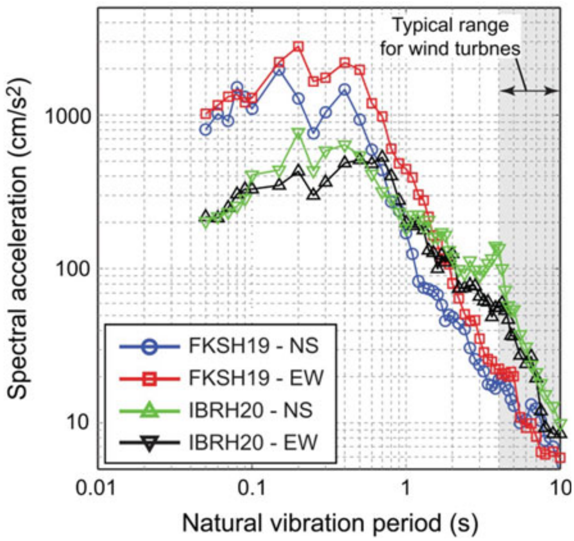

Fig. 11 Power spectra of the earthquake and natural frequency of wind turbines

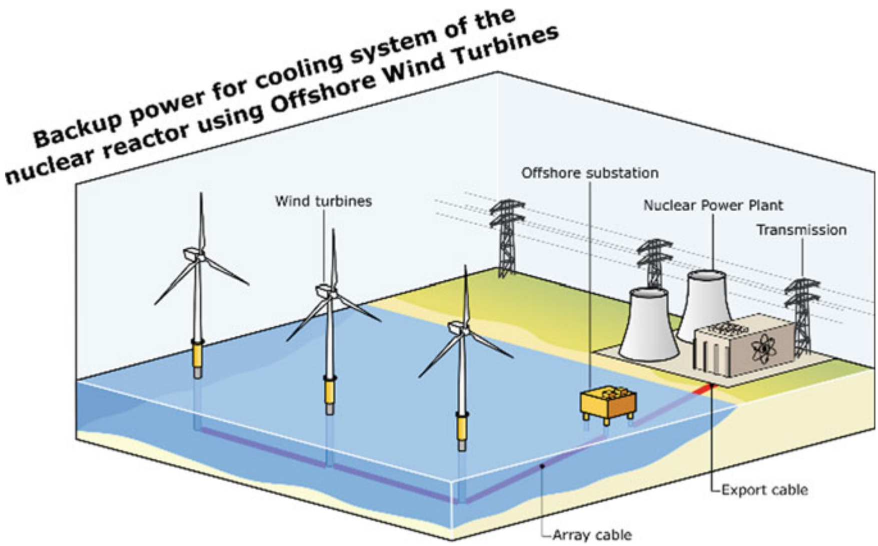

Fig. 12 Proposition of additional backup power for resilience of NPP

The proposition is therefore to have few offshore wind turbines in seismic locations close to the existing NPP so as to have an additional cooling system backup, see Fig. 12 for schematic. To summarise, the primary system of cooling is the grid (external source), and backup systems are offshore wind turbines and diesel generator as well as battery power. Figure 13 shows locations of NPP (either planned or operating) in four countries (India, China, UK and Japan), and it is interesting to note that many of these are near the coastline. One of the risks are therefore Tsunami effects where seismically-qualified OWT's can be easily installed to add resilience. An alternative way to increase resilience against Tsunami is by developing a very long robust sea-wall (along the external boundary) based on the prediction of tsunami wave height, which can be very expensive (Fig. 14). Furthermore, if due to local variation if one part of the sea-wall fails, the whole resiliency is lost. Use of offshore wind turbines may provide a viable, economic and equally (if not higher) robust alternative. Figure 15 shows the aerial view of Fukushima Daiichi NPP sea-defence before the disaster, taken from National Land Information Division.

Installation of wind turbines are therefore crucial even in seismic zones, and for this to happen, design methodology must be developed. This paper also highlights such issues. Figure 16 shows the expansion of offshore wind farms in seismic zones, further details can be found in De Risi et al. (2018).

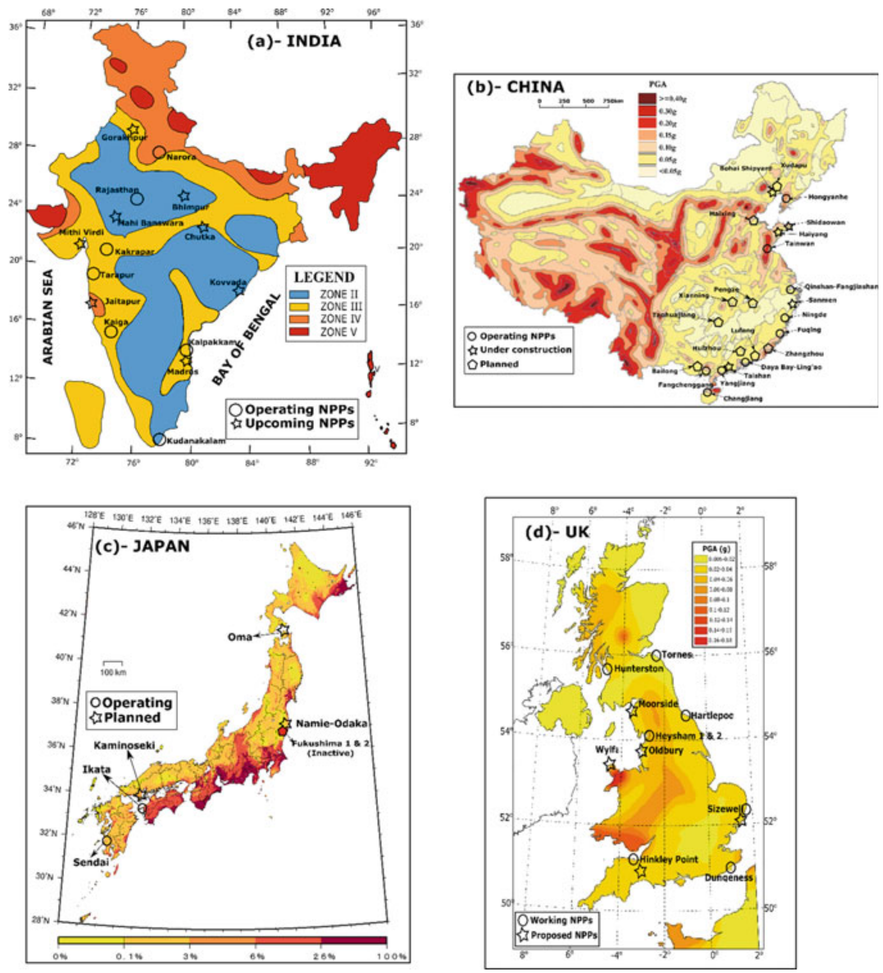

Fig. 13 Locations of offshore wind turbines for four countries together with seismic hazard

1.5 Research Needs in Offshore Wind Turbines

The aim of this lecture is to highlight some of the challenges related to design and construction of offshore wind farms. The paper is structured in the following way:

1. Section 2 discusses the uniqueness of offshore wind turbine structure together with loading complexities.
2. Considerations for analysis and design in different seas around the world.
3. Issues with long-term performance prediction.
4. Additional considerations for construction and maintenance.
5. Emphasis is given for seismic considerations.

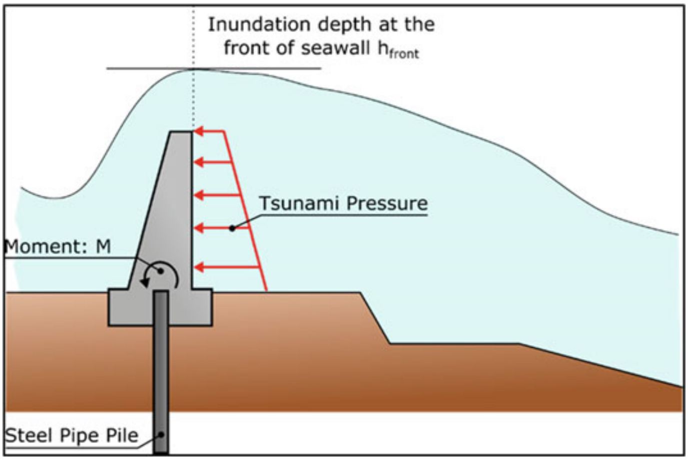

Fig. 14 Robustness concept of resiliency of sea-wall for safe-guarding NPP

2 Uniqueness of Offshore Wind Turbine Structure

Figure 17 shows a schematic diagram showing the loads on the structure which must ultimately be carried by the foundations. There are four main loads apart from the self-weight of the whole system: wind, wave, 1P (rotor frequency) and 2P/3P (blade-passing frequency) loads. Figure 17 shows a schematic representation of the time history (wave form) of the main loads. The salient points of the loads are discussed here:

1. Each of these loads has unique characteristics in terms of magnitude, frequency and number of cycles applied to the foundation. Figure 18 shows a plot where the various frequencies of the loads are shown. The example of 3 MW turbine is taken together with the fundamental frequency of the wind turbines in two wind farms.
2. The loads imposed by the wind and the wave are random in both space (spatial) and time (temporal), and therefore, they are better described statistically.
3. Apart from the random nature, these two loads may also act in two different directions (often termed as wind-wave misalignment) to have a steady power output.
4. 1P loading is caused by mass and aerodynamic imbalances of the rotor, and the forcing frequency equals the rotational frequency of the rotor.
5. On the other hand, 2P/3P loading is caused by the blade shadowing effect, wind shear (i.e., the change in wind speed with height above the ground) and rotational sampling of turbulence. Its frequency is simply two or three times the 1P frequency. Further details on the loading can be found in Arany et al. (2015a, b, 2017) and Chap. 2 of Bhattacharya (2019).

Fig. 15 Sea-defence system for Fukushima NPP

Figure 18 presents a schematic diagram of the main frequencies of these four types of loads, so that the dynamic design constraints can be visualised where three design space may be noted: soft-soft, soft-stiff and stiff-stiff. These terms are essentially concerned based on relative flexibility of the tower with respect to the foundation. Figure 19 shows a schematic view of the definition.

Few points may be noted from the design choices available:

1. In the 'soft-stiff' design, the natural frequency or the resonant frequency is very close to the upper end of 1P (i.e., frequency corresponding to the rated power of

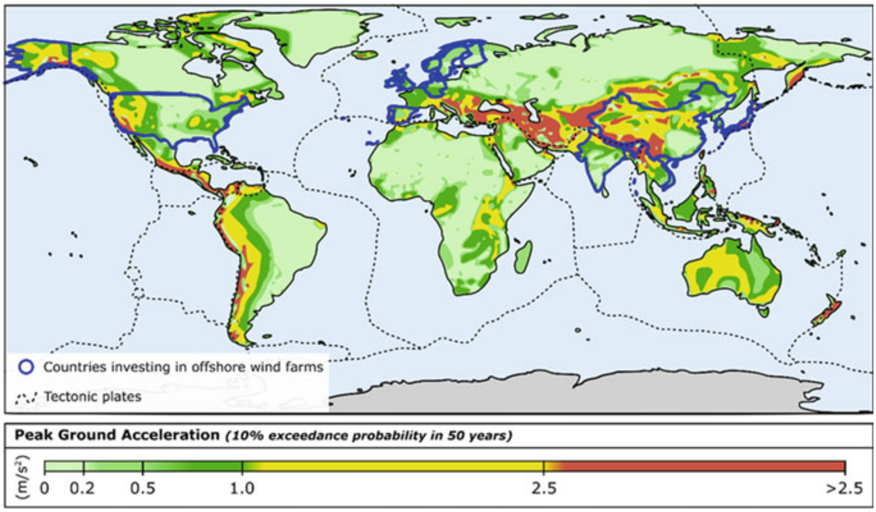

Fig. 16 Expansion of offshore wind is seismic locations

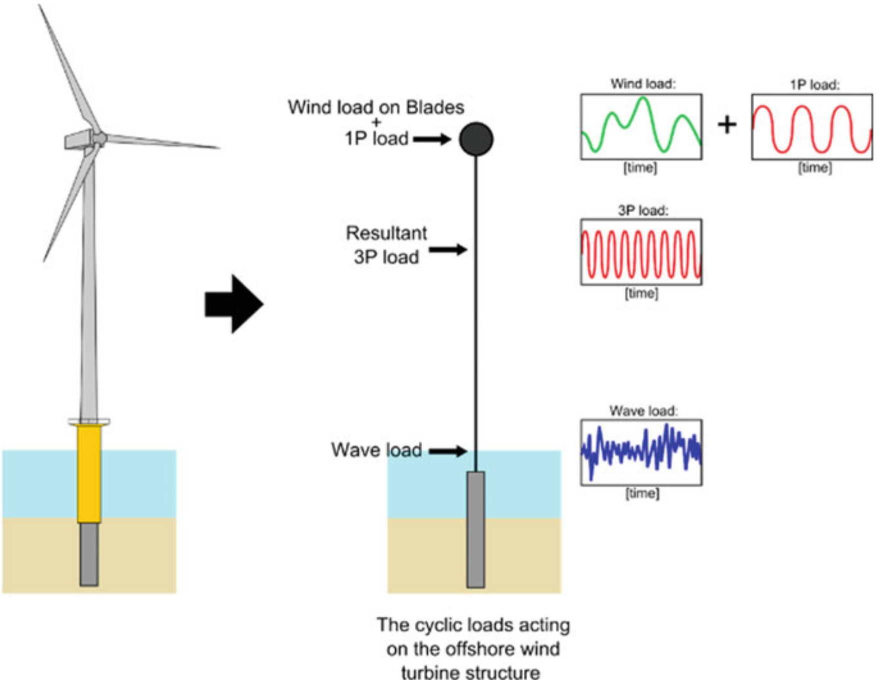

Fig. 17 Loads on offshore wind turbine foundations

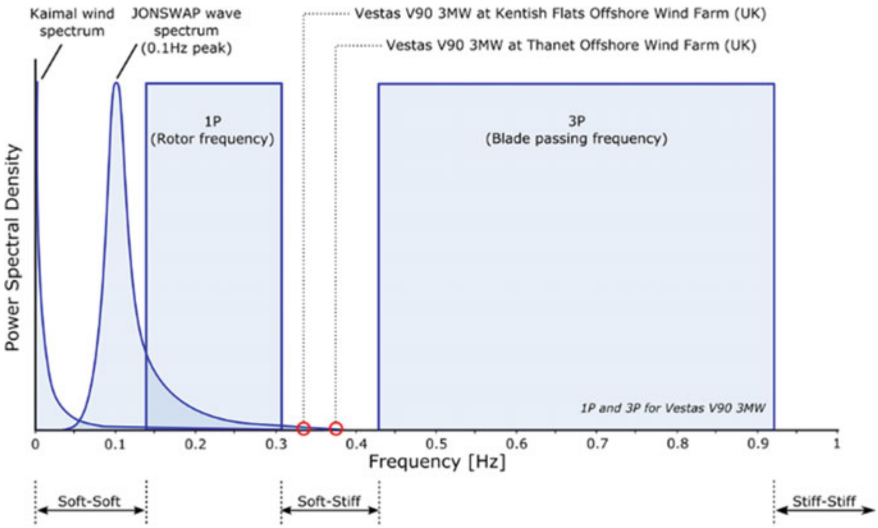

Fig. 18 Frequency range of the loads along with natural frequency of the turbines for 3 MW turbines

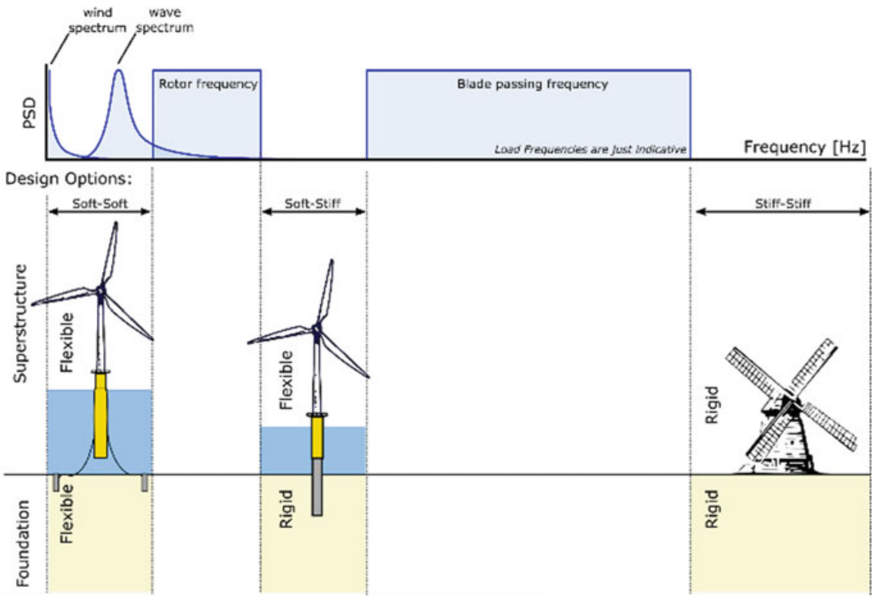

Fig. 19 Schematic shows the different structural systems

the turbine) and lower bound of the 3P (i.e., cut-in speed of the turbine). This will inevitably cause vibration of the whole system as the ratio of forcing to natural frequency is very close to 1. It is worth noting that resonance under operational condition has been reported in the German North Sea projects, see Hu et al. (2014).

2. For a soft-stiff 3 MW WTG system, 1P and 3P loading can be considered as dynamic (i.e., ratio of the loading frequency to the system frequency very close to 1). Most of the energy in wind turbulence is in lower frequency variations (typically around 100 s peak period), which can be considered as cyclic. On the other hand, 1P and 3P dynamic loads change quickly in comparison with the natural frequency of the WTG system, and therefore, the ability of the WTG to respond depends on the characteristics, and dynamic analysis is therefore required.
3. As a rule of thumb, if the natural frequency of the WTG structure is more than five times the forcing frequency, the loading can be considered cyclic, and inertia of the system may be ignored. For example, for a 3 MW wind turbine having a natural frequency of 0.3 Hz, any load having frequency more than 0.06 Hz is dynamic. Therefore, wave loading of 0.1 Hz is dynamic.

Current design aims to place the natural frequency of the whole system in between 1P and 3P in the so-called 'soft-stiff' design. In the plot in Fig. 18, the natural frequency of two Vestas V90 3 MW wind turbines from two wind farms (Kentish Flats and Thanet) are also plotted. Though the turbines are same, the variation in the natural frequency is due to the different ground and site conditions.

2.1 Can the Foundations Design Code for Oil and Gas Platforms Be Directly Used for Design of Offshore Wind Foundations?

Often to explain the problem of foundation design of wind turbines to school children, an analogy may be used. It is effectively a large washing machine on the top of a flagpole, see Fig. 20. The flagpole is supported on a fence post. The whole challenge is how to design the fence post. Figure 20 also shows a typical offshore oil and gas structure. There are, however, obvious differences between those two types of foundations, see Chap. 1 of Bhattacharya (2019), and they are listed below:

1. Offshore oil and gas platforms are supported on many small diameter piles. Piles for offshore platform structures are typically 60–110 m long and 1.8–2.7 m in diameter, and monopiles for offshore wind turbines are commonly 30–40 m long and 3.5–9 m in diameter.
2. The fixity or the boundary condition of oil and gas platform piles is very different than from that of the monopiles. The oil and gas platform piles can under lateral loads translate laterally but cannot rotate. Therefore, degradation in the upper

Fig. 20 Analogy of OWT and offshore oil and gas structure

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. Free-headed piles allows more deformation and, as a result, high strain levels in the soil.

3. Beam on nonlinear Winkler springs (known as 'p-y' method in American Petroleum Institute, API code or Det Norske Veritas, DNV code) is used to obtain pile-head deflection under cyclic loading for offshore oil and gas piles, but its use is limited for wind turbines application because for two reasons: (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, foundation stiffness for monopiles in sandy soil will actually increase as a result of densification of the soil next to the pile.

Foundation choice is very important as it affects in many ways including economics. Figure 21 shows a typical guidance in this regard based on water depth. Further details on the different design considerations can be found in Bhattacharya (2019). Typically for water depths more than 60 m, floating foundations are likely to be used. The first floating wind farm is located in Scotland and is known as Hywind concept which is essentially is floating spar. The type of foundation dictates the loads on it—see Figs. 22 and 23. As may be observed, for a monopile (or a single foundation type such as gravity base, suction caisson), the foundation (H). For a jacket type of structure (or Tripod on piles), the loads are push-pull action, i.e., mainly axial load on the foundation. For floating and anchor type, the load on the foundation is pull, i.e., snatch type of load, see Fig. 23, and acts when one mooring line is broken.

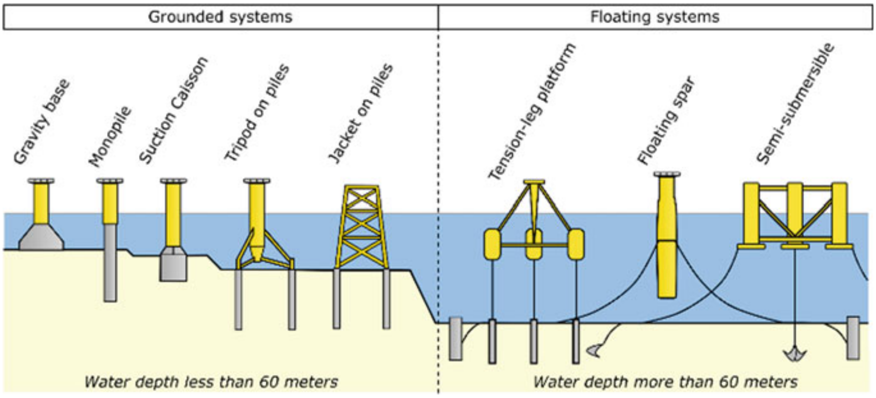

Fig. 21 Foundation choices based on water depth

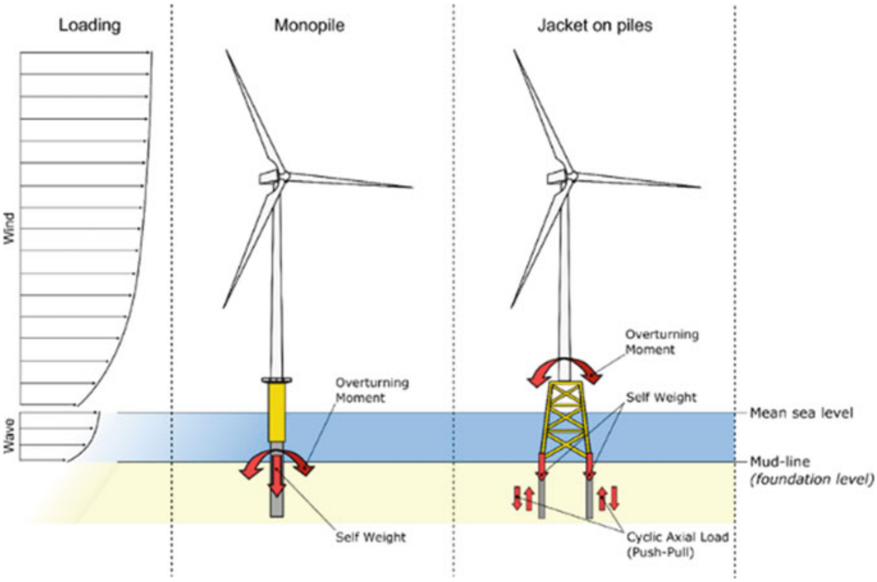

Fig. 22 Loads on foundation for grounded systems

3 Known Challenges in Design

This section of the paper highlights some of the known engineering challenges in design which are identified so far.

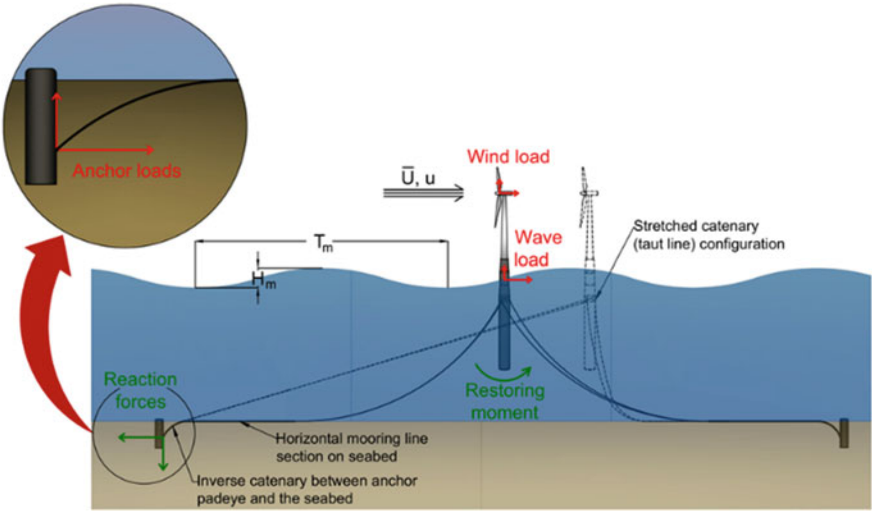

Fig. 23 Loads on foundation for a floating system

3.1 Load Complexities in Monopile Type of Foundation

Figure 24 shows the four main loads on foundations in a simplified model which can be estimated based on closed form solution, see Arany et al. (2016, 2017) and

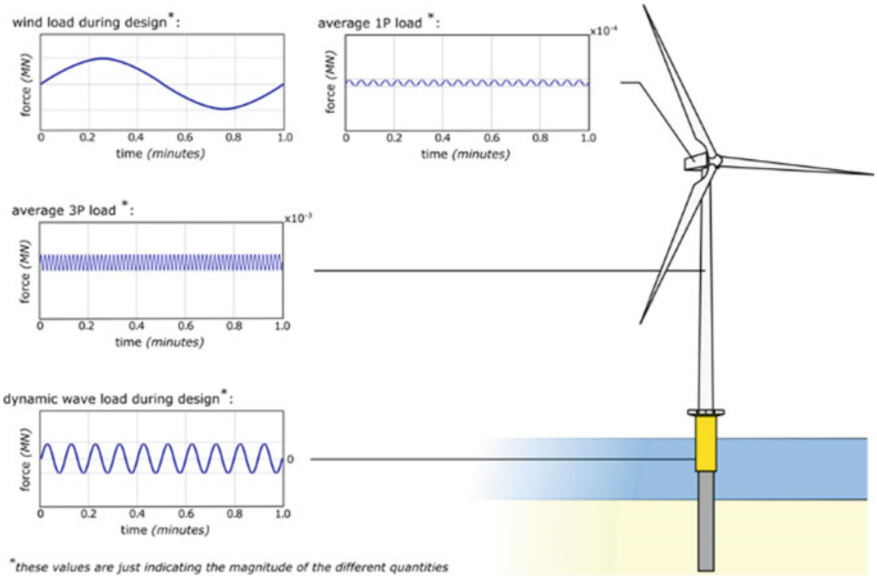

Fig. 24 Instantaneous description of load on a foundation

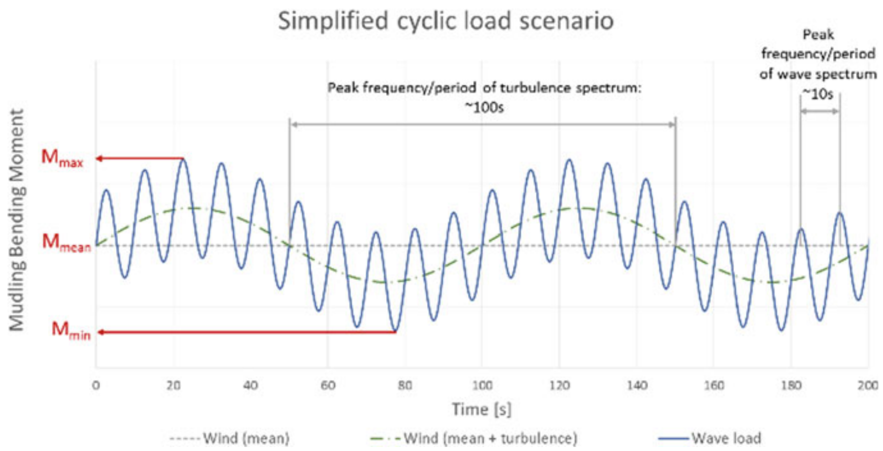

Fig. 25 Simplified load on monopile foundations

Chap. 6 of Bhattacharya (2019) without needing to recourse to expensive aero-servo-hydro-dynamic-soil-structure-interaction (ASH-DSSI) Code. For obtaining preliminary sizes of foundations for economic viability and tender document preparation, these methods are adequate. Figure 25 shows a simplified version of the load scenario which can be estimated for different design load cases (known as DLC's). The method is explained in Jalbi et al. (2019) from where minimum and maximum over-turning moment can be obtained. These values depend not only on the turbine size (3.6 or 10 MW), water depth (10 m water or 21.5 m water) but also on the wind and wave climate (wind turbulence and sea states), i.e., extreme turbulence model (ETM), normal turbulence model (NTM) and extreme wave height (EWH), see Figs. 26 and 27 for two examples. It is clear that there may be a bias in the foundation load and one of the challenges is to predict the long-term tilt due to this type of loading for the entire design life time of 25–30 years. The problem is schematically shown by Fig. 28 and is a highly nonlinear soil-structure interaction (SSI) problem. Theoretical understanding of the problem based on discrete element method (DEM) where each sand particle is modelled has been carried out by Cui and Bhattacharya (2016) and Cui et al. (2017, 2019).

3.2 Impact of Technological Advancements (i.e., Long Blades, Large Turbines) and Deeper Water Installations

Figure 29 shows technological progress since 1980s, where it may be noted that the turbine capacity increased from 0.01 to 20 MW with 9.5 MW currently available commercially. Figure 30 shows the top rotor-nacelle assembly (RNA) mass and the tower height. With both RNA mass and turbine height increasing, the natural

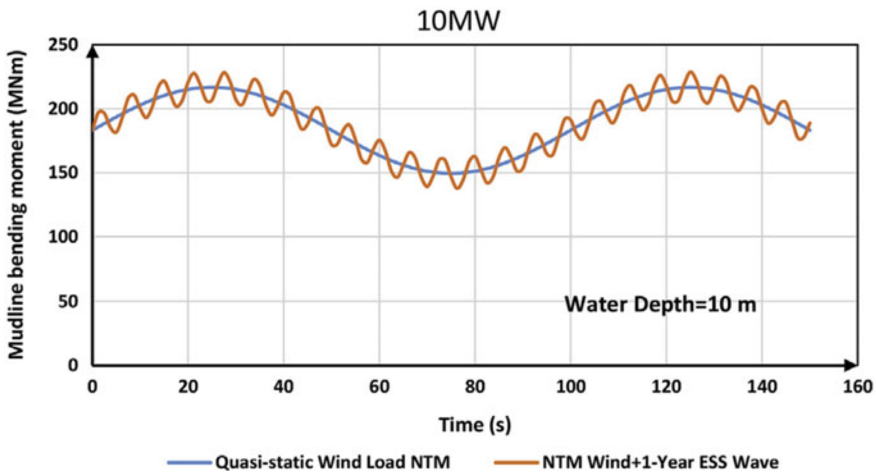

Fig. 26 Loading scenario for a typical 10 MW turbine in 10 m water depths

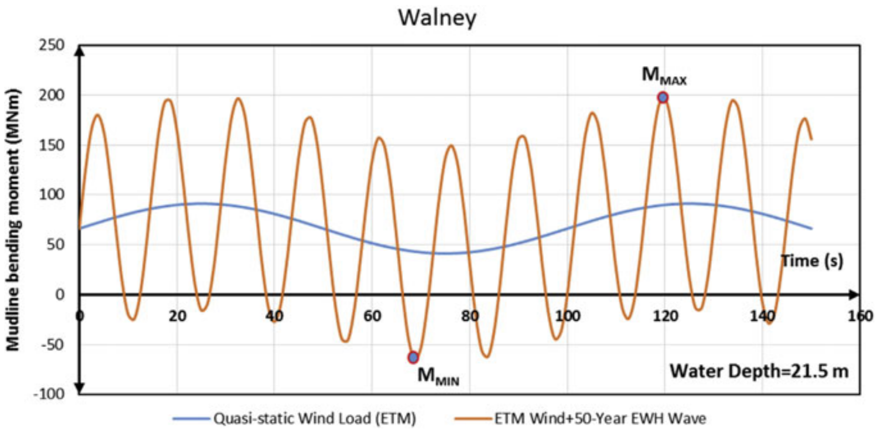

Fig. 27 Loading scenario for 3.6 MW turbine in 21.5 m water depths

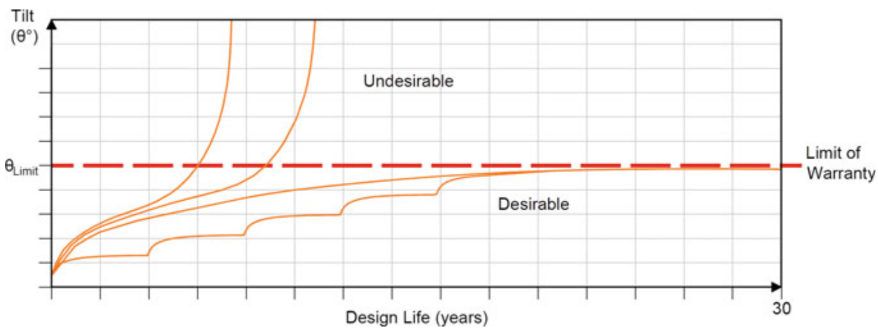

Fig. 28 Prediction of long-term tilt over 30 years life time for a complex load scenario

frequency is reducing due to increased flexibility of the system. For example, the target frequency (which is provided by the turbine manufacturer) of a typical 3.6 MW is circa 0.33 Hz and that of 8 MW is 0.22 Hz. As the target frequency reduces, it may come close to wave frequencies causing higher fatigue damages. Figure 31 shows the impact of turbine sizes on the target natural frequency.

Table 2 shows the wave frequencies for different Chinese seas, and it is clear that some of the predominant wave period is very close to the target frequencies of large turbines which poses significant design challenges from the point of view of fatigue and long-term tilting.

3.3 Modes of Vibrations of the Wind Turbine System

Vibration characteristics play a significant role in choosing a particular structural system to support wind-turbine-generator (WTG), i.e., four-legged suction caisson or three-legged pile (Tri-pile) Bhattacharya and Adhikari (2012). There are mainly two types of vibrations for grounded wind turbines: (a) Sway-bending; (b) Rocking. Readers are referred to Bhattacharya (2019) for the modes of vibration. Due to lack

Year	1980	1985	1990	1995	2000	2005	2010	2015	2020
Rotor Diameter (m)	15	20	40	50	112	126	150	178	252
Rated Power (MW)	0.01	0.10	0.50	0.60	2.40	5.00	7.50	10.00	20.00
Top Mass (tonnes)				80	250	340	360	550	880

Fig. 29 Technological progress of turbines

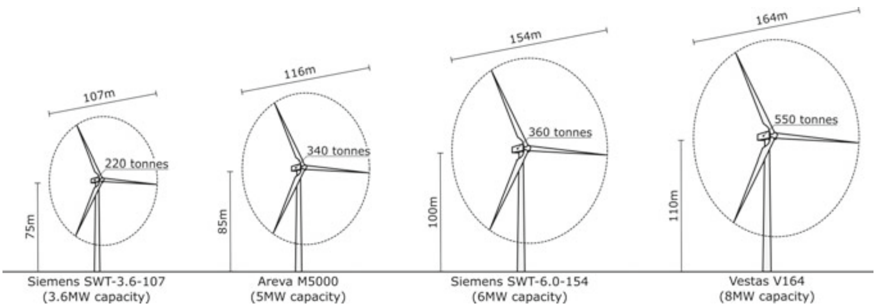

Fig. 30 Future of turbines showing the top mass and tower height

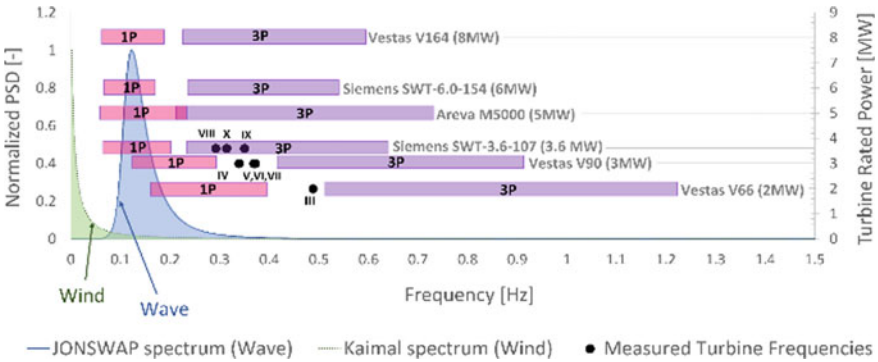

Fig. 31 Target frequencies for a range of turbines

Table 2 Typical wave period for various Chinese seas

China Sea	Region	Wave height (m)	Wave period (s)
Bohai Sea	Bohai Strait	1.2	4.8
	Others	<1	<4.5
Yellow Sea	North	1.2	5
	Centre	1.4	5
	South	1.6	6
East China Sea	Shanghai coastline	1.6	6
	Zhejiang coastline	1.8	7
	Taiwan Strait	2.4	9
South China Sea	Luzon Strait	2.8	10
	Indo-China Peninsula	2.6	8
	Others	<2	6

of space, the non-trivial case is discussed here: If the foundation is rigid compared to the flexibility of the tower, sway-bending mode is expected. On the other hand, if the foundation is not sufficiently rigid, rocking modes combined with flexible modes of tower may occur (Fig. 32). Bhattacharya (2019) and Jalbi et al. (2019) showed that rocking modes must be avoided at any cost for offshore wind turbine structures as low-frequency rocking mode may interact with the rotor frequency. There is therefore a requirement of minimum vertical stiffness of suction caissons as is described in Jalbi et al. (2019). Often, surprising type of vibration modes may be encountered, either in field records or scaled testing. Figure 33 shows one such case, a '*beating*' modes of vibration observed in a scaled model testing of a symmetric tripod on shallow foundation. Theoretical studies revealed that this is typical of two

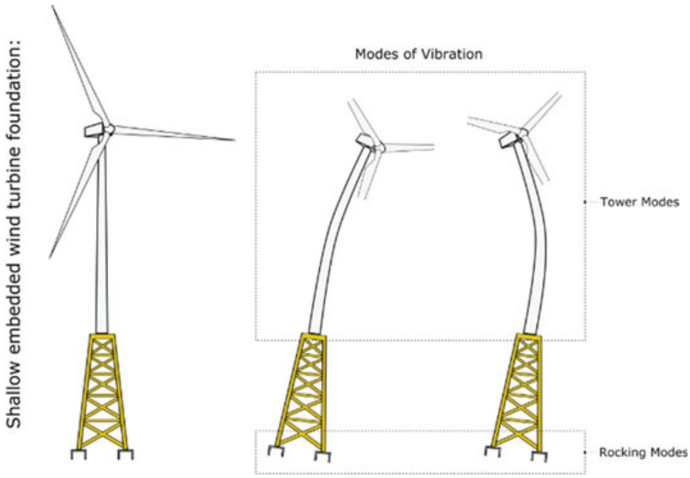

Fig. 32 Rocking modes of vibration

closely spaced vibration modes with low damping. The main point to highlight is the importance of damping for performance prediction.

3.4 Scour

Figure 34 shows the observed scour in few turbines of Robin Rigg Offshore Wind farm leading to early decommissioning. The observation was a rapid change in

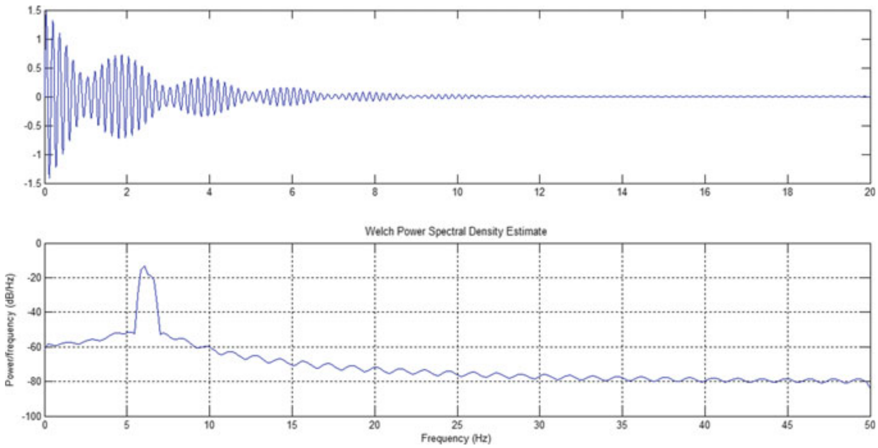

Fig. 33 'Beating' type modes of vibration

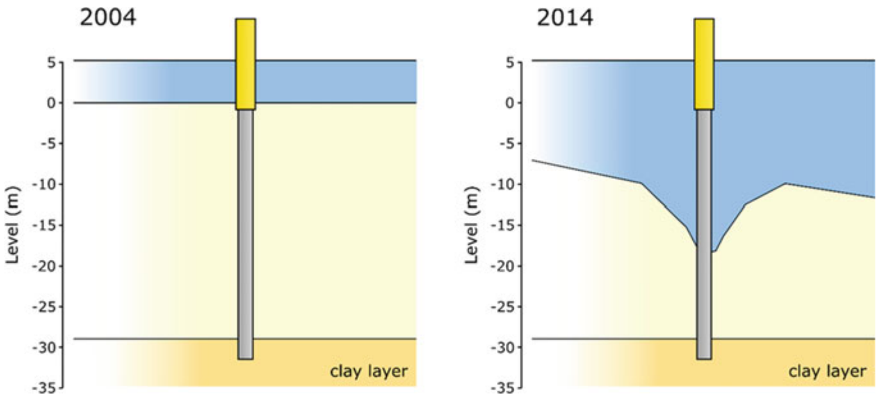

Fig. 34 Observed scour of wind turbine foundations

frequency leading to investigation and then shut down. Further details can be found in Cassie (2017). This highlights the importance of site investigation.

3.5 Soft Soil and Typhoon Challenges for Chinese Offshore Wind Development

One of the challenges in Chinese offshore wind development is that the soft soils are encountered in the seas together with typhoon. Figure 35 shows the ambition of offshore wind development in China, and Fig. 36 shows a typical profile in Fujian sea. It is therefore not surprising that unconventional (from the point of view of European offshore win development) innovative type of foundations are being used in Chinese developments. Some details are provided in the next section.

3.6 Specific Challenges Due to Seismic Actions

Design of OWT structures in seismic regions required additional considerations and detailed discussions are carried out in Chap. 2 of Bhattacharya (2019). This section is relevant to the ongoing developments in Taiwan and some parts of China and Korea, India and USA. The steps in the design process are summarised as follows:

1. **Seismic hazard analysis (SHA):** This is carried out to assess the seismic risk in the lifetime of the offshore wind turbines. The work can be carried out in deterministic framework. The required outcome of the analysis that will be sensitive to the design choices are: types of faults, expected peak ground acceleration (PGA) and earthquake moment magnitude. Another aspect is the identification

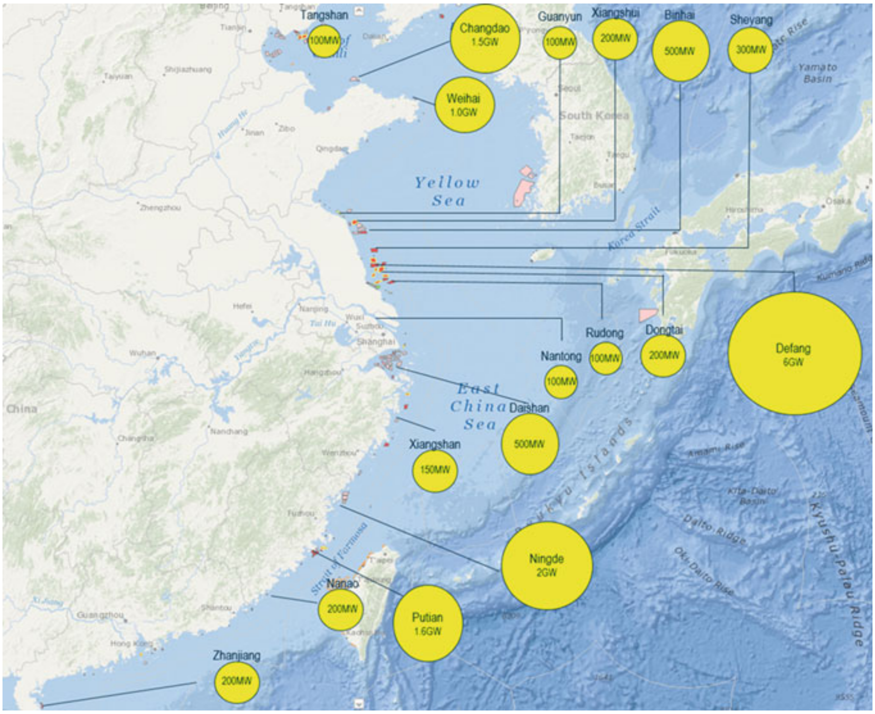

Fig. 35 Development of offshore wind in Chinese seas

of potential seismic hazards at the site and must also include potential cascading events. Some examples are:

(a) Impact of large fault movements and specially on the inter-array cables and export cables.
(b) Effect of strong shaking on the structure. One needs to also consider shaking without the effects of liquefaction of the subsurface. Therefore, inertial effects on the structure and inertial bending moment on the foundation piles.
(c) Effect of shaking coupled with effects of subsurface liquefaction. Liquefaction may lead to a rather long unsupported length of the pile and elongate the natural vibration period of the whole structure. The ground may liquefy very quickly or may take time (and is a function of ground profile and type of input motion). In such scenarios, the transient effects of liquefaction need to be considered, as it will affect the bending moment in the piles.
(d) The combined effects of shaking followed by liquefaction and subsequently tsunami.
(e) Effects of shaking and submarine landslides.
(f) The effects of earthquake sequence and suitable combinations of foreshock, mainshock and aftershock.

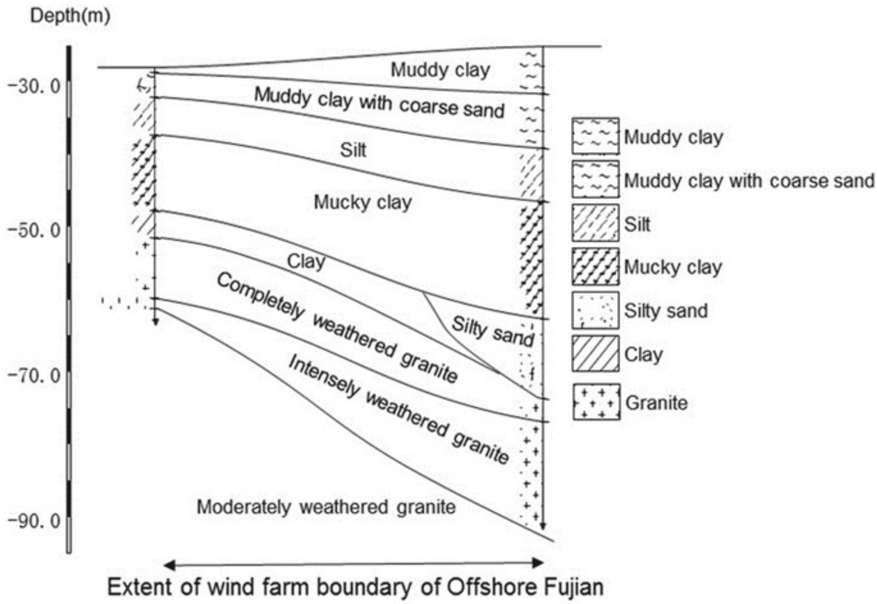

Fig. 36 Example from ground profile in Fujian Sea

2. Generation of site-specific input motion for the site and further details can be found in Chap. 3 of Bhattacharya et al. (2019). The input motion depends on the seismo-tectonics of the faulting region area. Some of the factors are: faulting pattern, distance of the site from earthquake source, wave travelling path, and the geology of the area. Strong motions generated can be either synthetic (artificially generated through spectrum compatibility) or recorded ground motion from previous earthquakes in that area.
3. Site-specific response analysis will predict how the ground will behave under the action of the input motion. This requires site-specific soil testing.
4. Dynamic SSI analysis incorporates the knowledge of the site response into the calculations.

Figure 37 shows a mechanical model of the problem where the foundation is replaced by a set of springs (K_L, K_R and K_{LR}) (Bhattacharya, 2014). During earthquake liquefaction, these springs will degrade substantially. Figure 38 shows p-y model for ULS and SLS calculations. Methods to calculate p-y springs for liquefied soils can be found in Lombardi et al. (2017a), Bhattacharya et al. (2019) and Dash et al. (2017).

Often new challenges are encountered while designing and constructing these structures. In many cases, standard foundations such as monopile or caissons are not suitable, and some form of hybrid foundations are necessary. In other cases, different structural systems are adopted. For example, in one of the Chinese developments, a group of eight piles were used, and it is named as high-rise pile cap (HRPC) as

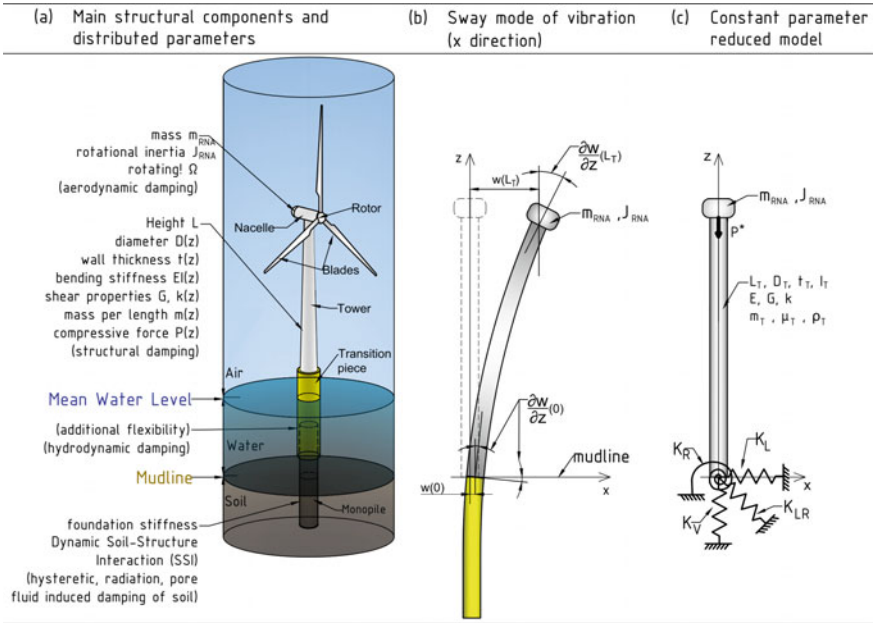

Fig. 37 Mechanical model of the structure

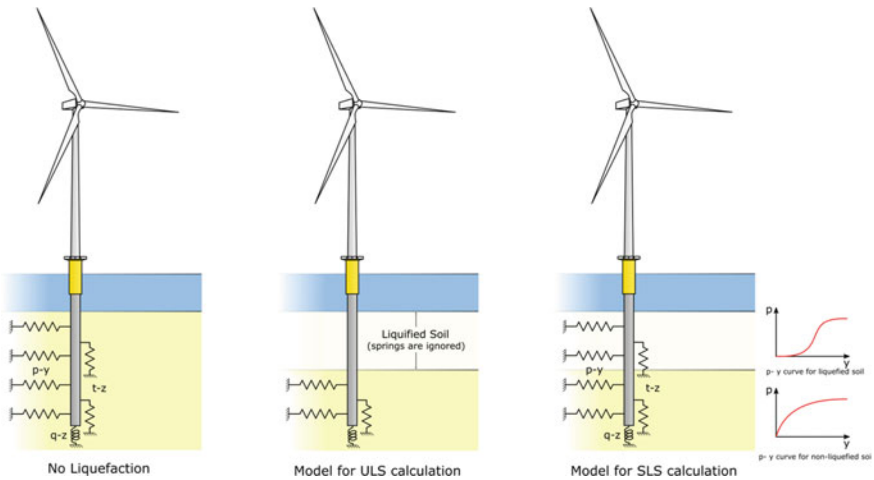

Fig. 38 p-y model for ULS and SLS calculations

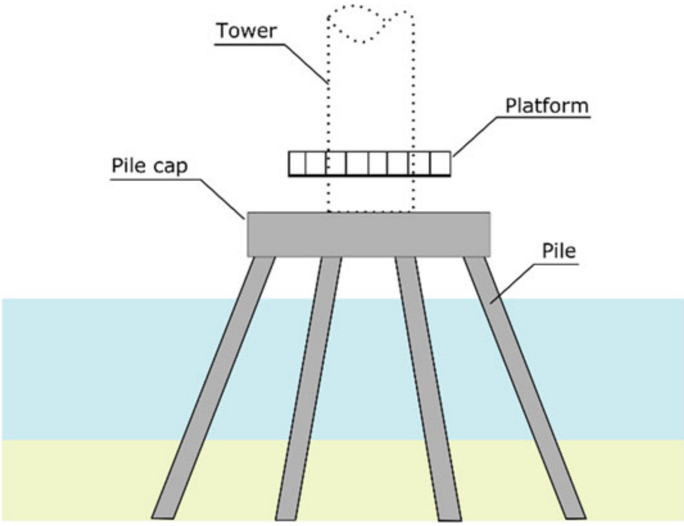

Fig. 39 HRPC type of foundation used in a Chinese offshore development project

shown in Fig. 39. As in many of the innovative cases, there will be no codes of practice or best-practice guide, and therefore, model tests (physical modelling) are often carried to verify the various design assumptions and establish reliability of the chosen method. The next section of the paper discusses various aspects of physical modelling highlighting the subtleties.

4 Physical Modelling of Offshore Wind Turbine Foundations

Foundations typically cost 25–35% of an overall offshore wind farm project, and in order to reduce the levelised cost of energy (LCOE), new innovative foundations are being proposed. However, before any new type of foundation can actually be used in a project, a thorough technology review is often carried out to de-risk it.

European Commission defines this through technology readiness level (TRL) numbering starting from 1 to 9, see Table 3 for different stages of the process together with the meanings.

One of the early studies that needs to be carried out is technology validation in the laboratory environment (TRL and 4), and in this context of foundations, it would mean carrying out tests to verify the failure mechanism, modes of vibration and long-term performance under the action of cyclic loads.

It must be realised that it is very expensive and operationally challenging to validate in a relevant environment, and therefore, laboratory-based evaluation has to

Table 3 Technology readiness level (TRL)

TRL level as European Commission	Interpretation of the terminology and remarks
TRL-1: Basic principles verified	In this step, the requirement is to show that mechanics principles are obeyed. For example, in the case of foundation, it must be checked whether the whole system is in equilibrium under the action of environmental loads
TRL-2: Technology concept formulated	In this step, it is necessary to think about the whole technology starting from fabrication to methods of installation and finally operation, maintenance (O&M) and decommissioning. In this step, it is expected that method statements will be developed
TRL-3: Experimental proof of concept	In this step, small-scale models will be developed to verify steps in TRL-1 and TRL-2. In terms of foundation, this would correspond to checking the modes of failure in ultimate limit state (ULS) and identifying the modes of vibration
TRL-4: Technology validated in laboratory	Once TRL-3 is satisfied and business decision is taken to go ahead with the development/design, it is necessary to check the technology for further details. This may correspond to long-term performance under millions of cycles of loading and checking the dynamic performance over the lifetime in relation to fatigue limit state (FLS)
TRL-5: Technology validated in relevant environment	Relevant environment may mean numerical simulation whereby close to reality analysis can be carried out. In the context of foundation, this step may use advanced soil constitutive models to verify the performance under extreme loading
TRL-6: Technology demonstrated in relevant environment	In this step, a prototype foundation is constructed and tested in an offshore environment. Critical aspects are verified
TRL-7: System prototype demonstration in operational environment	In this step, the foundation is subjected to operational loads, and the performance are monitored
TRL-8: System completed and qualified	Based on the results in TRL-7, the system can be classified as qualified or not-qualified or changes are required
TRL-9: Actual system proven in operational environment	Technology may be used in energy generation with contingency plans

be robust so as to justify the next stages of investment. From the point of view of assessment, the main issues are:

1. Verification of safe load transfer from the superstructure to the supporting ground,
2. Modes of vibration of the structural system adopted.
3. Long-term change in dynamic characteristics, i.e., change in natural frequency and damping.
4. Long-term deformation so that SLS requirements are not violated.

4.1 Suitability on Different Methods of Testing

Behaviour of offshore wind turbines involves complex dynamic-wind–wave–foundation–structure interaction, and the control system onboard the RNA hub adds further interaction. There are different established methodology, see Table 4 for carrying out testing for some part of the problem to a scientifically acceptable level:

1. Wind Tunnel can model the aerodynamics and aeroelasticity of the problem.
2. Wave tank can model the hydrodynamics part.
3. Geotechnical Centrifuge testing can identify soil-structure interaction problem.
4. Shaking table at 1-g or in a centrifuge can model the seismic soil-structure interaction (SSI).

In wind tunnel tests, aerodynamic effects are modelled efficiently and correctly (as far as practicable), and as a result, the loads on the blade and towers can be simulated. On the other hand, in the wave tank, the hydrodynamic loads on the sub-structure and scouring on the foundation can be modelled. In a geotechnical centrifuge, one

Table 4 Different forms of testing for offshore wind turbines

Types of testing	Remarks on the understanding
Wind tunnel testing	Example: Blades can be tested to show the importance of profile
Wave tank testing	Wave tank of different forms can be used to study scour, hydrodynamic loading, tsunami. In this type of testing, the wave loads on the foundations can be understood
Geotechnical centrifuge	In a geotechnical centrifuge, the stress levels in a soil can be modelled accurately (as far as practicable). However, the whole model is spun at a high rate which creates unwanted small vibrations. Therefore, the subtle dynamics of the problem is difficult to study as filtering of signals are inevitable during processing of data
Whole system modelling	Small-scale whole system modelling which can be considered as a very scale prototype pioneered by Bhattacharya et al. (2011) is one of the ways to study the overall system. This type of modelling was used to carry out TRL of self-installing wind turbine (SIWT), asymmetric tripod and details are provided in Bhattacharya et al. (2013a, b). As the system is tested in a stable floor, dynamics of the problem can be studied very well

can model the stress level in the soil, but the model package is spun at a high RPM which will bring in unwanted vibrations in the small-scale model. Ideally, a tiny wind tunnel together with a tiny wave tank onboard a geotechnical centrifuge may serve the purpose, but this is not viable and will add more uncertainty to the models than it tries to unearth. Each of the techniques has its own limitations, and these aspects must be taken into consideration while scaling the observations. Therefore, the focus of the experiments needs to be on the governing laws or mechanics or process.

A model need not be more complex, and often simple experiments can unearth the governing laws. In every type of experiments, there will be cases where the scaling laws/similitude relationships will not be satisfied (rather violated), and these must be recognised while analysing the test results. Therefore, results of scaled model tests for offshore wind turbine problems involving so many interactions (examples include: aerodynamics, hydrodynamics, damping from three different mediums: air, water and soil, control system intervention affecting misalignment of wind and wave) should not be extrapolated for prototype prediction through scaling factors (N^a where N is typically geometrical scale ratio and a is the scaling factor) (Lombardi et al. 2017b). The tests must be carried out to identify trends and behaviours and upscaling must be carried out through laws of physics through numerically or analytically or through soil-element tests (Nikitas et al. 2017). Figure 40 shows a method laid out in Bhattacharya (2019) for such purpose and also shows the usefulness of small-scale tests and its application in developing design methods.

Based on the literature of physical modelling and in the context of predicting foundation behaviour, the experimental test setup can be classified as follows:

1. '*Foundation only modelling*' referred to as Type 1 as shown schematically in Fig. 41. In this modelling, cyclic loads (symmetric or asymmetric or a combination) can be applied. The limitation of this method is that the effects of vibration of the whole system, i.e., the effects of inertia is not modelled. In other words, using the analogy (from Fig. 20), the vibration of the washing machine is not considered. If we were to translate in the context and bring the understanding of soil mechanics, the small strain vibration is ignored. For sandy soil, this phenomenon will definitely densify the soil around the foundation.
2. '*Whole system modelling with an actuator (attached with the model with rigid link)*' referred to as Type 2 as shown in Fig. 42. In this case, actuator provides lateral stiffness to the overall system, and the effect is distorting the modes of vibration.
3. '*Whole system modelling with eccentric mass actuator*' referred to as Type 3 as shown in Fig. 43. This is currently the most appropriate physical modelling technique, and details can be found in Nikitas et al. (2016). Type 3 modelling technique is scalable, can model wind-wave misalignment, can be used in field testing and can also study fatigue-related issues. Examples of testing using Type 3 technique can be found in Yu et al. (2015) and Guo et al. (2015) where long-term performance of monopiles have been studied. Xu et al. (2019) using the apparatus studied the fatigue problem.

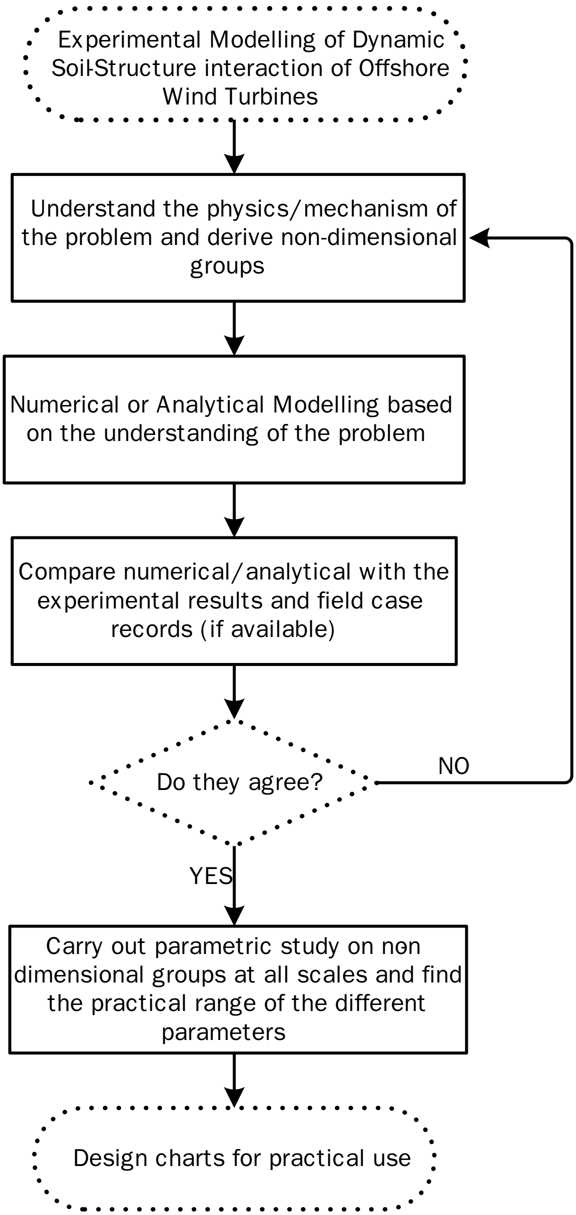

Fig. 40 Flowchart showing the usefulness of scaled laboratory testing

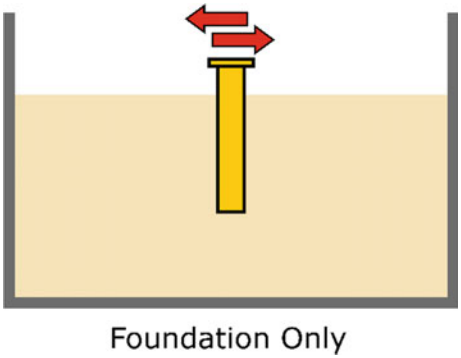

Fig. 41 'Foundation only modelling'—Type 1 technique

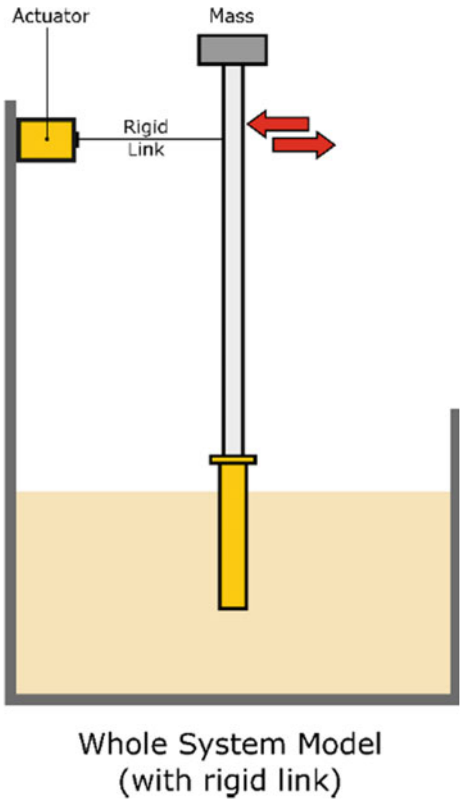

Fig. 42 Whole system model with an actuator connected to the model through a rigid link (Type 2 technique)

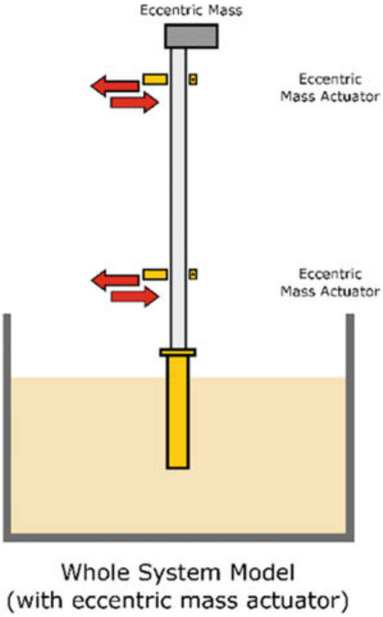

Fig. 43 Whole system modelling with eccentric mass actuator (Type 3 technique)

4.1.1 Example Application of Study of Failure Mechanisms Using Physical Modelling

One example of usefulness of physical modelling is taken here in relation to spar type floating wind turbine (see Fig. 23). Physical modelling was conducted to understand the optimum location of the padaye, i.e., where the chain will be attached to the anchor piles and what failure mechanism may be invoked, see Figs. 44 and 45. A second purpose was to see the deformation mechanism of soil around the foundation. Figure 46 notes the observed modes of failure. Knowledge from this understanding was used (without scaling any numbers) to develop a design method and can be found in Arany and Bhattacharya (2018). The method was calibrated and compared with Hywind Wind Farm project.

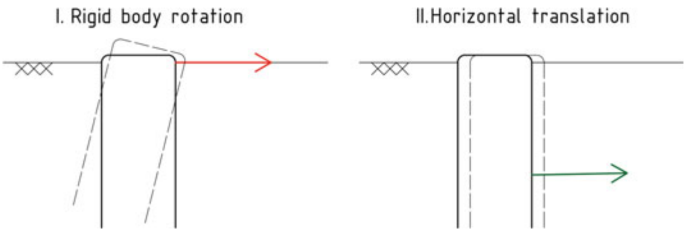

Fig. 44 To verify the above hypothesis of failure mechanism

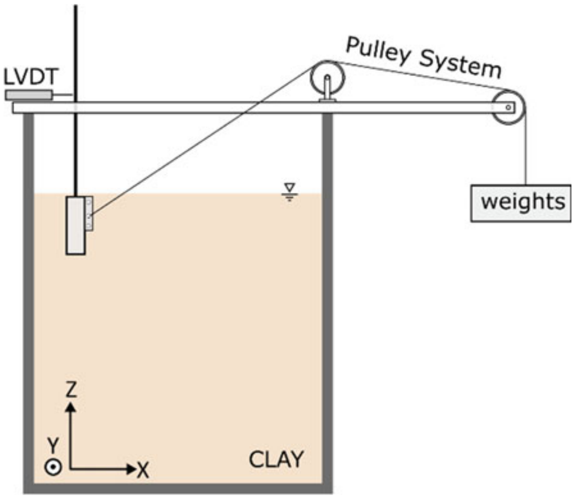

Fig. 45 Schematic of the test setup

5 Concluding Remarks

The paper provides a summary of the outlook of offshore wind in relation to tackling the grave climate change crisis. The paper summarises the challenges faced in design and construction together with potential way forward.

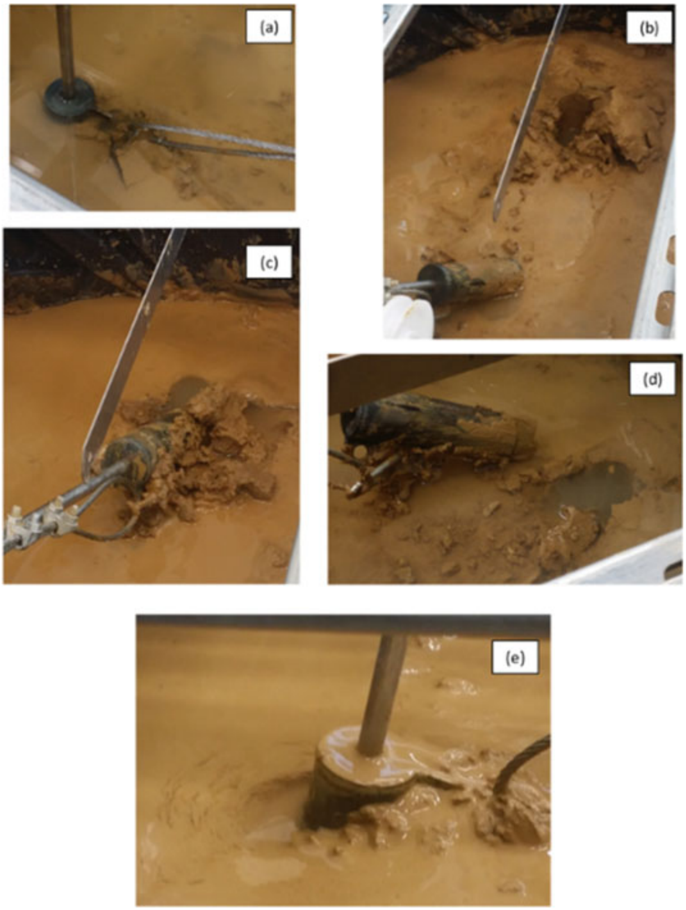

Fig. 46 Example of understanding failure mechanism of anchor for different location of padaye

References

Arany L, Bhattacharya S (2018) Simplified load estimation and sizing of suction anchors for spar buoy type floating offshore wind turbines. Ocean Eng 159:348–357

Arany L, Bhattacharya S, Adhikari S, Hogan SJ, Macdonald JHG (2015a) An analytical model to predict the natural frequency of offshore wind turbines on three-spring flexible foundations using two different beam models. Soil Dyn Earthq Eng 74:40–45. https://doi.org/10.1016/j.soildyn.2015.03.007

Arany L, Bhattacharya S, Macdonald J, Hogan SJ (2015b) Simplified critical mudline bending moment spectra of offshore wind turbine support structures. Wind Energy 18:2171–2197

Arany L, Bhattacharya S, Macdonald JHG, Hogan SJ (2016) Closed form solution of eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI. Soil Dyn Earthq Eng 83:18–32. https://doi.org/10.1016/j.soildyn.2015.12.01

Arany L, Bhattacharya S, Macdonald J, Hogan SJ (2017) Design of monopiles for offshore wind turbines in 10 steps. Soil Dyn Earthq Eng 92:126–152
Bhattacharya S (2014) Challenges in the design of offshore wind turbine foundations. Engineering and Technology Reference, IET
Bhattacharya S (2019) Design of foundations for offshore wind turbines. Wiley
Bhattacharya S, Adhikari S (2012) Experimental validation of soil–structure interaction of offshore wind turbines. Soil Dyn Earthq Eng 31(5–6):805–816
Bhattacharya S, Goda K (2016) Use of offshore wind farms to increase seismic resilience of nuclear power plants. Soil Dyn Earthq Eng 80:65–68. https://doi.org/10.1016/j.soildyn.2015.10.001
Bhattacharya S, Lombardi D, Wood DM (2011) Similitude relationships for physical modelling of monopile-supported offshore wind turbines. Int J Phys Model Geotech 11(2):58–68
Bhattacharya S, Orense RP, Lombardi D (2019) Seismic design of foundations: concepts and applications. Text book. ICE Publications
Bhattacharya S, Cox J, Lombardi D, Muir Wood D (2013a) Dynamics of offshore wind turbines supported on two foundations. Geotech Eng Proc ICE 166(2):159–169
Bhattacharya S, Nikitas N, Garnsey J, Alexander NA, Cox J, Lombardi D, Muir Wood D, Nash DFT (2013b) Observed dynamic soil–structure interaction in scale testing of offshore wind turbine foundations. Soil Dyn Earthq Eng 54:47–60
Cassie P (2017) Robin Rigg-WTG decommissioning project: decommissioning project review and lessons learnt. Presentation on 25/01/2017. Renewables UK
Cui L, Bhattacharya S (2016) Soil–monopile interactions for offshore wind turbines. Proc Inst Civ Eng Eng Comput Mech 169(4):171–182
Cui L, Bhattacharya S, O'Kelly BC (2017) Discussion: soil–monopile interactions for offshore wind turbines. Proc Inst Civ Eng Eng Comput Mech 170(4):174–176
Cui L, Bhattacharya S, Nikitas G, Bhat A (2019) Macro- and micro-mechanics of granular soil in asymmetric cyclic loadings encountered by offshore wind turbine foundations. Granul Matter 21(3):73
Dash S, Rouholamin M, Lombardi D, Bhattacharya S (2017) A practical method for construction of p-y curves for liquefiable soils. Soil Dyn Earthq Eng 97:478–481
De Risi R, Bhattacharya S, Goda K (2018) Seismic performance assessment of monopile-supported offshore wind turbines using unscaled natural earthquake records. Soil Dyn Earthq Eng 109:154–172
Guo Z, Yu L, Wang L, Bhattacharya S, Nikitas G, Xing Y (2015) Model tests on the long-term dynamic performance of offshore wind turbines founded on monopiles in sand. ASME J Offshore Mech Arct Eng 137(4). https://doi.org/10.1115/1.4030682
Hu W-H, Thöns S, Said S, Rücker W (2014) Resonance phenomenon in a wind turbine system under operational conditions. In: Proceedings of the 9th international conference on structural dynamics, EURODYN 2014 Porto, Portugal, 30 June–2 July 2014, pp 3619–3626
Jalbi S, Nikitas G, Bhattacharya S, Alexander N (2019) Dynamic design considerations for offshore wind turbine jackets supported on multiple foundations. Marine Structures 67:102631
Jalbi S, Arany L, Salem A, Cui L, Bhattacharya S (2019) A method to predict the cyclic loading profiles (one-way or two-way) for monopile supported offshore wind turbines. Marine Structures 63:65–83
Lombardi D, Dash SR, Bhattacharya S, Ibraim E, Muir Wood D, Taylor CA (2017a) Construction of simplified design—curves for liquefied soils. Géotechn 67(3):216–227
Lombardi D, Bhattacharya S, Nikitas G (2017b) Physical modelling of offshore wind turbine model for prediction of prototype response, Chap 17. In: wind energy engineering: a handbook for onshore and offshore wind turbines. Academic Press. ISBN 9780128094518
Letcher T (2017) Why wind energy?, Chap 1. In: Wind energy engineering: a handbook for onshore and offshore wind turbines. Hardcover. Elsevier. ISBN: 9780128094518
Nikitas G, Vimalan NJ, Bhattacharya S (2016) An innovative cyclic loading device to study long term performance of offshore wind turbines. Soil Dyn Earthq Eng 82:154–160

Nikitas G, Arany L, Aingaran S, Vimalan J, Bhattacharya S (2017) Predicting long term performance of offshore wind turbines using cyclic simple shear apparatus. Soil Dyn Earthq Eng 92:678–683
Nikitas G, Bhattacharya S, Vimalan N, Demirci HE, Nikitas N, Kumar P (2018) Wind power: a sustainable way to limit climate change, Chap 10. In: Managing global warming. Academic Press. ISBN 9780128141045
Nikitas G, Bhattacharya S, Vimalan N (2020) Wind Energy, Chap 16. In: Future energy (3rd Edition): Improved, sustainable and clean options for our planet. Academic Press. ISBN 9780081028865
Xu Y, Nikitas G, Zhang T, Han Q, Chryssanthopoulos M, Bhattacharya S, Wang Y (2019) Support condition monitoring of offshore wind turbines using model updating techniques. In: Structural health monitoring
Yu L, Wang L, Guo Z, Bhattacharya S, Nikitas G, Li L, Xing Y (2015) Long-term dynamic behavior of monopile supported offshore wind turbines in sand. Theor Appl Mech Lett 5(2):80–84