Chapter 5
Technical Risks of Offshore Structures

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Abstract Offshore areas are rough and high energy areas. Therefore, offshore constructions are prone to high technical risks. This chapter elaborates on the technical risks of corrosion and biofouling and technical risks through mechanical force. The expected lifetime of an offshore structure is to a great extent determined by the risk of failures through such risks. Corrosion and biofouling threaten the robustness of offshore structures. Detailed and standardized rules for protection against corrosion of offshore structures are currently lacking. There is a need for an accepted uniform specification. A major technical risk of a combined wind-mussel farm is that of a drifting aquaculture construction that strikes a wind turbine foundation. We investigate two scenarios related to this risk: (1) Can a striking aquaculture construction cause a significant damage to the foundation? (2) If a drifting aquaculture construction gets stuck around a turbine foundation and thus increases its surface area, can the foundation handle the extra (drag) forces involved? A preliminary qualitative assessment of these scenarios leads to the conclusion that a drifting mussel or seaweed farm does not pose a serious technical threat to the foundation of a wind farm. Damage to the (anticorrosive) paint of the turbine foundation is possible, but this will not lead to short term structural damage. Long term corrosion and damage risks can be prevented by taking appropriate maintenance and repair actions. Contrarily to mussel or seaweed farms, the impact/threat of a drifting fish farm on structural damage to a wind foundation depends on type, size and the way of construction of the fish cages. The risk of extra drag force due to a stuck aquaculture construction relates particularly to jacket constructions because any stuck construction may lead to (strong) increase of the

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frontal surface area of the immersed jacket structure and thereby give increased drag forces from currents or waves. To ensure an optimal lifetime and lower operational costs maintenance aspects of materials for both offshore wind and aquaculture constructions should be taken into account already in the design phase of combined infrastructure.

5.1 Introduction

For the successful operation of a wind farm and the successful combination of a wind farm with aquaculture, it is essential that the expected lifetime of the constructions used is acceptable. The expected lifetime of an offshore structure is to a great extent determined by the risk of failures. These failures can be the result of many different problems.

This chapter focuses on two technical risks, typically associated with a combination of wind farming and aquaculture: damage mechanisms of corrosion and bio-fouling, and damage risks of mechanical loads. More precisely, a major technical risk of a combined wind-mussel farm is that of a drifting aquaculture construction that strikes a wind turbine foundation. We carry out a preliminary qualitative assessment of two scenarios related to this risk: (1) Can a striking aquaculture construction cause a significant damage to the foundation? (2) If a drifting aquaculture construction gets stuck around a turbine foundation and thus increases its surface area, can the foundation handle the extra (drag) forces involved?

There are additional risks, which are not dealt with in this report. The risk of collision with ships is also there, and it may even be slightly elevated, but in terms of possible damage it does not substantially differ from the single-use situation (wind farm). Impacts of foreign (drifting) objects are also not taken into account.

The findings presented in the following sections are based on literature data. We focus on risks arising from offshore wind energy production combined with offshore mussel farming. Additionally, risks arising from seaweed culture and using fish cages are also presented here because information on technical aspects of offshore structures, available in current literature, is scarce and often does not discriminate between the different types of aquaculture. Mechanical risks are described in some more detail in Janssen and van der Putten (2013).

Chapter 3 deals specifically with corrosion aspects and biofouling of offshore structures, Chap. 4 deals with mechanical risks of wind farms in the presence of offshore aquaculture, in this chapter elaborates the two technical risk scenarios, and Chap. 6 finishes with conclusions and recommendations.

5.2 Corrosion Aspects and Biofouling

5.2.1 Corrosion Mechanisms and Corrosivity Zones for Offshore Structures

In general, the same mechanisms that can damage offshore structures like wind turbines and platforms can also damage aquaculture structures that are made of the same or similar material. Offshore structures are exposed to different and varying corrosive environmental conditions.

Based on theory and practical experience with offshore structures, in total eleven different corrosion zones of offshore wind structures can be identified. The most critical zones are the splash/tidal zone and closed compartments filled with seawater (e.g. the internal of a monopile or jacket foundation structure). Design specifications for steel structures define a corrosion allowance. In case of uniform corrosion this is an applicable design tool. However, when local corrosion mechanisms like microbial corrosion (MIC), galvanic corrosion or corrosion fatigue occur, the structural integrity of the steel structure must be evaluated. The offshore wind structure design is determined by fatigue load. Local defects like pitting attack may act as initiation sites for fatigue cracking. For this reason special attention should be given to local defects in the foundation and the tower structure.

5.2.2 Corrosion Risks in Currently Used Offshore Wind Turbines

The offshore wind energy market is young, compared to the offshore oil and gas and shipment markets; the first offshore wind farm was installed in 1991. The most important lesson learned from the first generation offshore wind turbines is: wind turbines based on onshore technology are not suitable for offshore application. The first offshore wind farm, Horns Rev (D), suffered from a major coating failure of eighty wind turbine foundations. The coating on the transition pieces broke down and resulted in unexpected repair and maintenance costs. The reason was a combination of wrong coating selection and improper application of the coating. This points out to the key issue: a lack of conformity between the manufacturer, coating applicator and coating supplier.

Other corrosion related problems reported are failing cathodic protection systems, corroding boat landings by combination of wear, impact and seawater and corroding secondary structure components like ladders and railings. The impact of corrosion damage varied from increased safety risks for maintenance personnel to re-evaluating the structural integrity of the foundation structure because of local pitting attack.

Local corrosion attack by MIC has been noticed on the internal surface of different monopile foundations on different locations in the North Sea. With grouting failure repair of several monopile foundations, local corrosion attack was detected on the internal surface area of the unprotected monopile. Until then the internal area had been a black box: the hedge was sealed to reduce and stop the internal corrosion process. Nowadays, MIC processes inside monopile foundations are still not known in very much detail and require further investigation to find optimal control measures.

Specification of corrosion protection for specific offshore wind structures is still an issue. The applied standards for European offshore wind farms vary from onshore related specifications to those deriving from offshore oil and gas specifications. Based on the experiences with coating and cathodic protection failures, there is a need for an accepted uniform specification. Up to date, such a specification is lacking.

5.2.3 Biofouling on Offshore Structures

Offshore constructions are attractive to biofouling species. Biofouling may result in increased costs due to antifouling measures that have to be taken: extensive inspection and maintenance, creation of micro-environments discouraging microbial corrosion, and heightened design criteria as a consequence of the extra hydrodynamic and weight loading (Fig. 5.1).

Generally four different process stages of bio-fouling in seawater are described (Callow & Callow 2011). These may take place in different time frames. The first

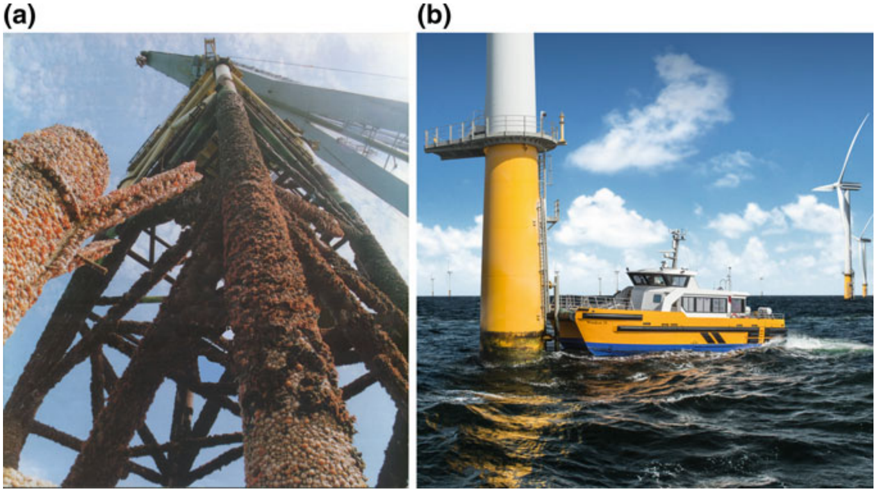

Fig. 5.1 Biofouling on an offshore jacket foundation (**a**) and access to a wind turbine foundation for maintenance (**b**): biofouling is visible in the tidal zone and on the stairs to the platform (*Source* Windcat Workboats B.V.)

stage starts almost instantly upon immersion with the formation of a conditioning layer of dissolved organic matter such as glycoproteins and polysaccharides. Subsequently a so-called biofilm can be formed with colonizing bacteria and micro-algae. Hours to days later a more complex community may form including multicellular primary producers and grazers, for instance algal spores, marine fungi and larvae of hydroids, bryozoans, and barnacles. If time and environmental conditions allow for, such communities may evolve to diverse and sometimes very thick layers with both hard fouling organisms (barnacles, mussels, tube worms, corals, etc.) and large populations of soft fouling such as ascidians, hydroids and macro algae. However, it should be explicitly mentioned that in a natural environment the biofouling process is very variable and never follows exactly this schematic representation. The process is influenced by many abiotic factors as well, such as salinity, nutrient content, sunlight intensity and duration, currents, and temperature.

In existing wind farms, no antifouling techniques are currently applied on the foundations. In this situation, the uncoated steel subsea zone and the coating system on the transition piece are both susceptible to biofouling. Especially the boat landing area (see Fig. 5.1b) is a substructure that for safety reasons may need extra attention with regard to fouling prevention.

Biofouling on floating foundations as well as the tether ropes should be taken into account when assessing the lifetime of the construction. Calculations of design loads of offshore wind turbine foundations commonly apply a maximum biofouling layer thickness of about 200 mm for extreme load conditions. A load calculation model would also take into account weight and hydrodynamic loading (current and wave load) by biofouling. At first glance, a value of 200 mm of maximum biofouling layer thickness seems sufficient. However, in order to deduce a more reliable biofouling layer thickness depending on the location, regular checks over a twenty year period must take place. Biofouling on tether ropes can additionally influence the hydrodynamic behavior by the increased diameter of these tether ropes.

Biofouling can pose a risk to offshore wind foundations in the following cases:

- **Increased drag load**. The hydrodynamic profile of a biofouling layer strongly deviates from that of the flat surface of a foundation. Extensive growth, in the form of long trail-like colonies of mussels, algae and other soft elongated macro-organisms that move along with the current, may sometimes result in unexpectedly high drag loading. Biofouling may, however not necessarily pose a risk to the mechanical load on the foundations in moderate tidal current conditions.
- **Influence on cathodic protection**. Another effect of biofouling is coverage of anodes, which affects the function of the cathodic corrosion protection system. For visual inspection on site (weld inspection, wall thickness measurements) a biofouling layer must be removed.
- **Influence on MIC**. Biofouling creates micro-environments encouraging microbial corrosion (MIC). Knowledge on MIC processes inside monopile foundations is still scarce and needs further elaboration for proper assessment of risks on failure due to pitting corrosion.

- **Safety and accessibility**. For safety reasons biofouling must be prevented on stairs and boat landing area, to ensure safe access of maintenance personnel to the foundation and wind turbine (Fig. 5.1b).

There are several techniques that can be applied to prevent or clean biofouling on surfaces: antifouling coatings, electrochemical and physical methods for fouling control, cleaning of surfaces by robots or handheld tools. It is recommended to inspect the foundation and anodes after a period of 5–10 years. Visual inspection and quantification of fouling composition and thickness can be combined with regular cleaning of the external surface.

Considering the three types of wind turbine foundations (Fig. 5.2; Table 5.1) no clear differences in biofouling settlement and/or development are expected. The basic materials used in the foundation are equally susceptible to fouling under immersion. Fouling control coatings can be applied to all types of materials. Also cleaning techniques for removal of fouling do not substantially differ between the three types of foundation structures.

5.2.4 *Potential Influence of Offshore Aquaculture on the Corrosion of Unprotected Steel Structures*

Processes in seaweed farms may influence seawater chemistry. The salinity of ambient sea water at open sea is 3.0–3.6% in most cases. The pH of seawater is relatively stable whereas temperature, dissolved oxygen and nutrients may vary strongly (Bartoli et al. 2005; Mantzavrakos et al. 2007). Seawater is generally at a pH of 7.5–8.5 due to its buffering capacity with many ions and interaction with carbon dioxide and water. Oxygen levels can range from zero to over 10 ppm in temperate waters (Valdemarsen et al. 2012).

Seaweed photosynthesis increases dissolved oxygen in the water: The oxygen concentration in seaweed tanks can vary from 7.0 to 13.0 ppm, while in ambient seawater it varies from 8.0 to 10.3 (Msuya and Neori 2008). The increased level of dissolved oxygen in the water might result in an increased corrosion rate of unprotected steel structures at sea. The corrosion rate of steel under a calcite film (deposited by seawater on cathodic areas of metal) is 250% higher in the presence

Table 5.1 Typical design properties of three different wind turbine foundations

	Monopile	Jacket	Gravity based
Weight	500 tonnes	800 tonnes	5000 tonnes
Main material	Steel	Steel	Concrete
Max. water depth	30 m	30 m	40 m
Max. wave height (H_{max})	13.7 m	16.2 m	17.5
Max overturning moment at seabed	200 MNm		450 MNm

of seaweeds than without (Buzovkina et al. 1992). Seaweeds may raise the pH of the water by 0.1–0.4 pH units (Robertson-Andersson et al. 2008). This variation may have an influence on scale formation on steel structures and thereby induce or change localized corrosion processes (Beech and Campbell 2008). Careful monitoring of scale formation and appropriate maintenance measures will help to keep corrosion risks below critical levels.

Fish farms cause metal enrichment in the bottom of the sea, e.g. extreme high concentrations of Zn, Cu and Cd in sediments and pore water (Dean et al. 2007; Kalantzi et al. 2013; Loucks et al. 2012; Nordvarg and Johansson 2002). Such high concentrations may also increase the corrosion risk of steel due to higher conductivity of the electrolyte and creation of galvanic effects. Additionally, oxygen consumption because of biodegradation may create an anoxic or anaerobic environment that stimulates MIC by microorganisms such as sulfate reducing bacteria (SRB; Kawahara et al. 2008). Increase of carbon oxides and nitric oxides can also increase the corrosion of steels (Beech and Campbell 2008). On sites with substantial water currents, however, it is not very likely that these processes will have a strong effect on corrosion of materials and constructions.

No literature data have been found on effects of mussel farms on environmental parameters that can be associated with corrosion risks. A priori such risks cannot be fully excluded, depending on type of materials used in mussel farms. If similar phenomena occur as described above for fish farms, e.g. metal enrichment and/or anoxic conditions in the near environment, then potential risks may exist but again on locations with sufficient water currents these risks are probably low.

5.3 Mechanical Risks of Wind Farms Due to the Presence of Offshore Aquaculture Constructions

Offshore wind farms are constructed and developed to withstand the forces of the oceans. Wind and waves cause the highest loads on a wind turbine (tower and foundation). The presence of an offshore aquaculture may pose an additional threat to the wind farm. The research question is: What are the effects of aquaculture constructions and activities on the (mechanical) safety of offshore wind turbines?

To grow seaweed or mussels, usually nets or ropes are used (e.g. submerged longlines, cf. Buck et al. 2010; Lagerveld et al. 2014); fish farms usually apply special cages or more or less rigid characteristics. Common materials for fish cage construction are wood, steel and plastic (Burak Cakaloz 2011).

The next section discusses likely scenarios that may occur and could lead to mechanical risks to the turbine foundation when offshore aquaculture is carried out within or in close vicinity of an offshore wind farm. Because the risks can be different depending on the type of foundation, three commonly used structures and their properties are considered: monopile, jacket and gravity based (Fig. 5.2; Table 5.1).

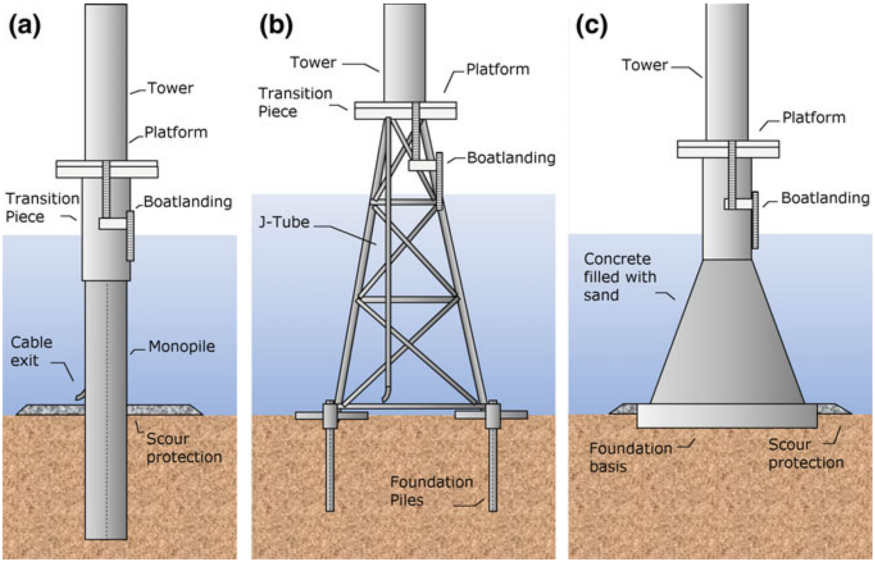

Fig. 5.2 Three types of turbine foundations: Monopile (**a**), jacket (**b**) and gravity based (**c**)

5.4 Scenario Analyses

Our analyses focus on narrative scenarios that may lead to mechanical (and corrosion) damage to the wind turbine foundation. Scenarios that could lead to damage of the aquaculture construction or the supply/maintenance vessels are not (yet) included. These risks can only be investigated at a later stage when the operational processes of maintenance and harvesting are known in detail.

Two scenarios that may occur and questions that arise are:

1. Impact. Drifting aquaculture construction **strikes** the turbine foundation.
   Is there a risk of significant damage to the foundation?
2. Extra drag force. Drifting aquaculture construction **gets stuck around** the turbine foundation, increasing its surface area.
   Can the foundation handle the extra (drag) forces involved?

The answers to these questions depend on the type of aquaculture (mussel, seaweed, fish) and corresponding constructions, and on the specific turbine foundation (i.e. monopile, jacket or gravity based). Therefore, the scenarios are presented in matrix tables. The two different scenarios and their possible risks are described below.

Scenario 1: Impact. Drifting aquaculture strikes the turbine foundation

It is possible that a drifting aquaculture (e.g. the longline construction, whether or not overgrown) strikes a turbine foundation. In such a case there are three main parameters that determine the risk of damage to the foundation:

1. the mass
2. the impact velocity
3. the deformability/robustness of the aquaculture construction

As mussel and seaweed farms mainly consist of nets and ropes, the deformability of such structures is large. In case of an accident, it is the aquaculture construction that deforms, and not the foundation. Probably this also holds for most fish cages. Elastic fish cages will not damage the foundation structure; only larger, more rigid cages have the potential to do so.

Damage to the protective coating of the foundation structures when they are hit, is possible in all cases. On a longer term, this could induce additional corrosion risks and negatively influence the safety of the construction. Inspections are required and possible repair of the coating may be necessary. Table 5.2 summarizes the effects, which do not differ for the three different foundation types.

Scenario 2: Extra drag force. Drifting aquaculture construction gets stuck around the turbine foundation, increasing its surface area

It is possible that a drifting aquaculture does not only strike, but gets stuck around a turbine foundation. In the case of a monopile or gravity based foundation, the stuck aquaculture construction will not significantly increase the frontal surface area of the structure. The frontal surface area is an important parameter in the determination of drag forces. With increasing frontal surface, drag forces due to current and surface waves increase. In the case of a jacket consisting of a lattice structure with many beams, it is possible that an aquaculture construction gets stuck around the beams and significantly increases the frontal surface area. In this case, the local force on such a beam, and the overall drag forces on the whole structure certainly increase. The effects are summarized in Table 5.3.

Possible effects of the 'worst case' scenario (grey cells in Tables 5.2 and 5.3) are preliminarily analyzed in Janssen and van der Putten (2013).

Table 5.2 Scenario 1: Drifting aquaculture strikes the turbine foundation

	Mussels	Seaweed	Fish
Monopile Jacket Gravity based	No significant structural impact damage expected	No significant structural impact damage expected	Damage depends on mass, velocity and deformability of fish cage

Grey cells indicate the worst case scenario

Table 5.3 Scenario 2: Drifting of the aquaculture

	Mussels	Seaweed	Fish
Monopile	No significant increase in loads expected		
Jacket	Increase in drag force		
Gravity based	No significant increase in loads expected		

The aquaculture is stuck around the turbine foundation. Grey cells indicate the worst case scenario

5.5 Conclusions and Recommendations

The combination of different activities offshore influences the assessment of risks arising from multi-use offshore platforms. The exact details of the processes involved in such multi-use offshore activities are still unknown and hence estimations are uncertain.

The main risk of a combined wind-mussel farm investigated here is that of a drifting aquaculture construction. Two major scenarios and related questions were investigated:

1. Is there a risk that a drifting aquaculture constructions strikes the turbine foundation and causes a significant damage to the foundation?
2. What is the risk if a drifting aquaculture construction gets stuck around the turbine foundation and thus increases its surface area? Can the foundation handle the extra (drag) forces involved?

A preliminary qualitative assessment of these scenarios yields that scenario 1 (impact between offshore aquaculture and wind turbine foundation) is not a real threat in case of mussel and seaweed farms. It is highly unlikely that aquafarm structures will be used that are heavy and rigid enough to cause significant structural damage. The (anticorrosive) paint of the turbine foundation might get damaged in case of an impact, but this will not lead to short term structural damage. In order to prevent corrosion and damage risks in the long term, appropriate actions (i.e. repair) can and should be taken. For fish farms the situation in scenario 1 may vary with the type and size of cages that are used and the way they are constructed. Potential risks of consequences of the impact should be assessed already in the design phase of such combined infrastructure.

Scenario 2 (extra drag force from currents and waves due to stuck aquaculture constructions) poses a risk especially to jacket constructions because it may lead to (strong) increase of frontal surface area of the immersed structure and thereby give increased drag forces. With monopiles and gravity based constructions the stuck aquaculture material may attach to the turbine foundation at a single point only with insignificant increase of frontal surface area and minimal increase in such drag force.

For a jacket construction, in the extreme case of a 100% coverage of its underwater surface by stuck aquaculture material during a storm, the overturning moment at the seabed could increase by 200–300 MNm (Janssen and van der Putten 2013), and eventually lead to the collapse of the wind turbine. However, this risk is merely theoretical, considering the type and construction of aquaculture materials being far less massive than the foundation itself and the unrealistic assumption of a 100% coverage. Nevertheless, appropriate methods to avoid this small risk can be investigated in the design phase of such infrastructure, for instance modular aquaculture structures that fall apart in case of drifting under severe conditions.

In severe storms with extremely high waves, an intact aquaculture structure that is physically directly connected to the turbine foundation could theoretically lead to the collapse of the turbine if the overturning moment at the seabed becomes too large. For this reason, the investigated scenarios only consider aquaculture installations that are not attached to any wind turbine foundations (Lagerveld et al. 2014). Nonetheless, if a connected wind farm-aquaculture infrastructure is considered and designed, methods to reduce and prevent high tensile forces on the turbine foundation should be taken into account. For example, use of suitable anchors to hold the aquaculture structure in place or application of so-called safety wires that break at predefined tensile forces. Although the aquaculture farm will be lost in the latter case, the turbine foundation will stay intact.

Finally, a few recommendations for the future implementation of a multi-use platform offshore, based on Noël (2015); van der Putten (2015) and Lagerveld et al. (2014):

- Appropriate measures should be taken to protect aquaculture and offshore wind constructions from corrosion attack either by selection of corrosion resistant materials or by application of suitable protective techniques or coatings.
- Type and size of aquaculture activities determine the extent of effects on water and sediment quality. In turn, water and sediment quality may affect corrosion resistance of the materials used. This aspect should be dealt with in a dedicated risk assessment for the specific location.
- Maintenance aspects of materials for both offshore wind and aquaculture constructions should be taken into account already in the design phase to ensure optimal lifetime of infrastructure.

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