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Corrosion issues and monitoring techniques for offshore wind turbine foundations

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Summary
About 16 years ago, the first large-scale offshore wind farms were put into operation. Corrosion experiences and connected issues collected from the various foundation designs are summarised and discussed as to prevalence and general mechanism. A range of different direct and indirect corrosion monitoring techniques are presented and explained. Results of specific experimental assessments are demonstrated.

Key words
Wind turbine foundation, marine corrosion, corrosion monitoring, corrosion inspection.

Introduction
The world's first major offshore wind farm was installed around 2002-2003 in Denmark. Having no former experience with these specific monopile-based wind turbine constructions for offshore usage, the construction and corrosion protection scheme for the wind turbine foundations and towers were, at the time, to a large extent inspired by the offshore oil & gas constructions, specifically the platforms. However, differences in construction details between monopile-based wind turbines and multiple legged platforms as well as the necessary choice of non-proven protection technology have since given rise to different corrosion related issues inside and outside the foundations. Based on the knowledge obtained from the first offshore wind farms, various new design details as well as protective schemes were introduced for the design of the next generation of wind farms and, ever since then, wind turbine foundations' corrosion design has been improved continuously, from project to project.

State of The Art
Now, some 16 years later, the construction of offshore wind foundations and towers has ripened, and new types of foundations have entered the market to supplement the monopile-based foundations. Nevertheless, the monopile-based foundation is presently the most frequently used foundation type, and corrosion issues, along with other more structural issues, are occasionally disclosed, often after years of operation. Also, reasoned suspicions concerning whether special types of corrosion like microbially influenced corrosion (MIC), corrosion as a consequence of change of pH inside the foundation and other potential issues could occur, are still not fully settled.
As compared to the very first offshore wind turbine projects, later projects have had significantly more focus on the total cost of energy, i.e. "for how little can we produce a kilowatt hour of electricity"? As cost of energy (CoE) includes calculations from both the capital expenditures (CAPEX) as well as the operational expenditures (OPEX), the CoE is a result of production price, quality of the construction (durability), installation costs, cost of maintenance and cost of unexpected repairs. This economic driver has inevitably had impact on the construction details, including the anti-corrosion design that have become much optimised to avoid a too conservative (and unnecessarily expensive) design. But

moving closer to the durability boundaries increases the risk of undesirable corrosion issues, which again calls for risk-reducing measures like surveillance or monitoring techniques. After years of collecting experiences of the deterioration mechanisms we are presently in a better position to understand how to mitigate the issues, or how to establish a proper surveillance system to avoid rampant and expensive issues, or even catastrophic failures.

Monopile-based foundations

The monopile foundation is a combination of a monopile (MP) to be rammed into the seabed and a transition piece (TP) that is mounted on the MP to act as support and alignment for the tower. The two parts are fixed to each other via a grouted connection or a bolted flange. The monopile is fully submerged in the water whereas the TP is only partially submerged. This type of foundation is presently used for water depths up to around 35 m. For deeper waters, other types of foundation will often be considered.

Figure 1: A principle sketch of a monopile-based design. The grey part is the monopile, the yellow part is the transition piece.

The TP is usually fully coated by protective paint, both inside and outside, while the MP is left uncoated in most projects. However, recently, some operators have considered or have already implemented a full coating of both the outside and the inside of the MP to mitigate some of the uncertainties regarding corrosion issues. Galvanic anodes (GACP) for externally protecting the submerged parts of both MP and TP are installed on the TP. In some projects, impressed current (ICCP) is used instead of GACP.

The early design of the monopile included an airtight deck at the top. In this way it was expected that the closed compartment formed inside of the monopile would rapidly be oxygen-depleted and hence no corrosion control on the inside would be necessary. Unfortunately, the operational context has proven it differently. The reason for oxygen or oxygenated water to enter the internal compartment has been found to be the result of various potential leaking areas. The driver for ingress of oxygenated water is tidal variations of which the penetration of the MP for the power cable (the “J-tube”) is known to play a major role. Other suspected contributors to ingress of oxygenated water is through the seabed and to some extent also ingress through cracks in the grouted connection between the TP and the MP.

Consequently, ingress of oxygen or oxygenated seawater could facilitate continuous corrosion in an area that was not designed to be subject to corrosion.

Latent deterioration mechanisms in the foundation

Although later attempts have been made to preserve an airtight compartment through various design solutions, it seems to be generally accepted that, in practice, it is very difficult to ensure oxygen-depleted conditions internally in the MP. For that reason, discussions about the best practice for protecting the internal compartment are still ongoing.

Today, different approaches based on GACP, ICCP and/or coating are being applied to protect the internal compartment. Forced exchange of water through vent holes is also applied in some projects to avoid the build-up of an aggressive acidic environment originating from the internal cathodic protection.

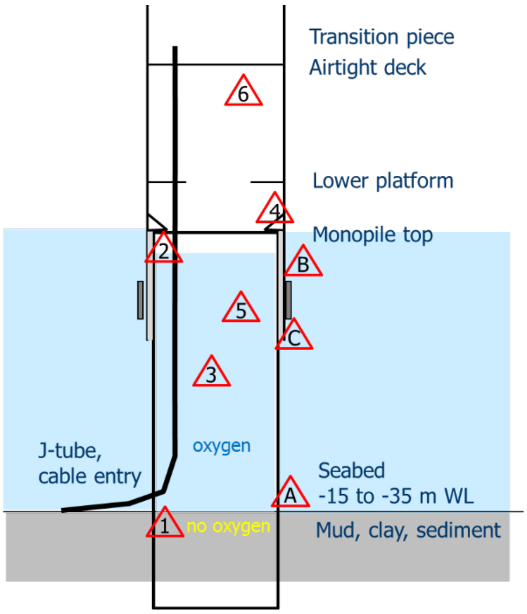

Figure 2: An overview of potential corrosion issues in connection with the monopile-based foundation.

To define a good strategy for inspecting and monitoring corrosion, the potential "hot-spots" must be identified. Figure 2 depicts such areas of concern for the internal and external side with reference to the two lists below.

Internal side:

1. Mud zone, risk of macro galvanic element (differential aeration), microbiologically influenced corrosion (MIC) and hydrogen induced stress cracking (HISC)
2. Waterline, risk of localised corrosion due to macro galvanic element (differential aeration)
3. Large stagnant water volume, large environmental variations
4. Weld defects, hardness, quality vs stress corrosion cracking and corrosion fatigue thresholds at critical details such as brackets, stoppers, cable entry etc.
5. Acidifying, especially if galvanic aluminium anodes are installed
6. Accumulation of gasses: H_2S, H_2 and CH_4

External side:

A. Insufficient CP due to distance from anodes and high current demand

B. Splash zone, requirement for 20 years (25+ years in recent projects) lifetime of coatings

C. Grouted connection, possible ingress of oxygen or aerated seawater

As an example, the waterline in the closed compartment could cause highly localised corrosion in the circumference of the monopile, especially if the water level remains constant and ingress of oxygen occurs. In case of tidal variations, this area could also be vulnerable to accelerated low water corrosion (ALWC). Similar corrosion mechanisms can be expected at the mud line, where the presence of sulphate-reducing bacteria (SRB) may promote localised corrosion additionally by MIC.
In combination with other weakening factors, e.g. as mentioned in item 4 above, a potential risk of the structural integrity has led to special considerations, which shows it necessary to establish periodic or continuous inspection or surveillance systems during the operational period.

Monitoring options

Whereas the wind turbine "power plant" placed on top of the tower has always had a comprehensive system for monitoring almost all power generation functions in detail, the internal parts of the foundation has, from the beginning of offshore wind power generations, not been subject to any particular monitoring or inspection programmes. Not until after about 5 years of operation, it became clear that the inside of the foundation could not be disregarded with respect to surveillance. As offshore inspections are costly, up to around 100 times more expensive than that of an onshore inspection, monitoring systems became an obvious choice for long-term surveillance.
Hence, retrofitted sensor systems were subsequently installed in the first monopile foundations to ensure control with the most significant deterioration mechanisms, including corrosion. This experience, in combination with a better understanding of the potential corrosion propensity, has presently led to a more systematic monitoring approach for the foundations. For new projects, monitoring of a segment of the foundations in a wind farm is often an integrated part of the design and includes regular monitoring of structural behaviour, environmental conditions and corrosion related factors.

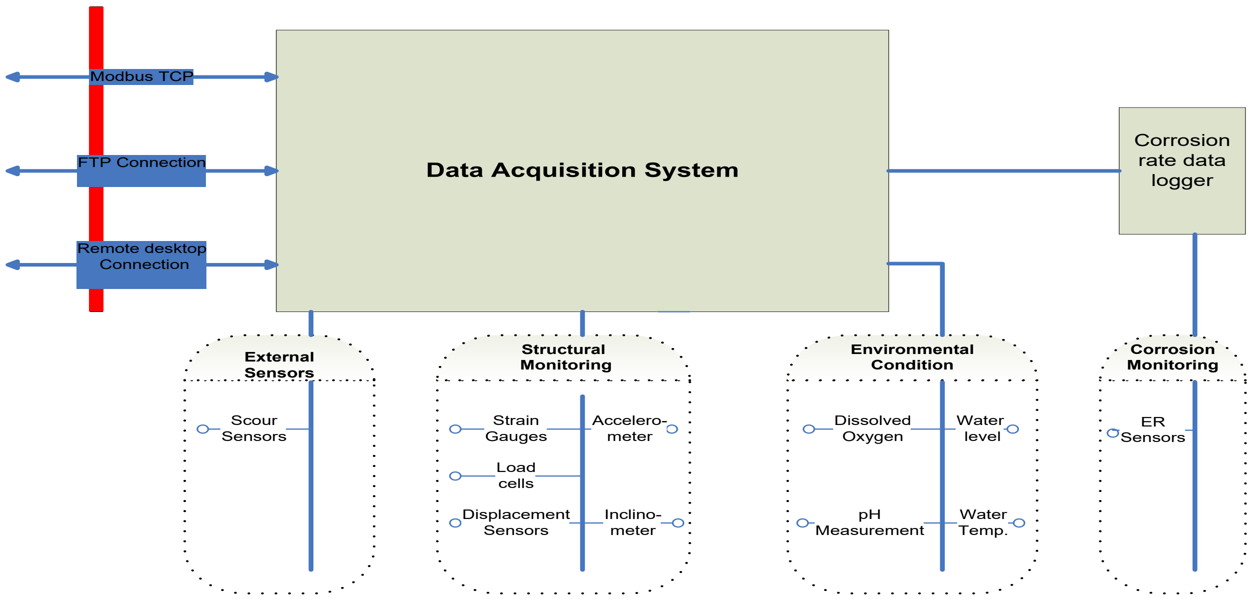

Figure 3: An example of a connected monitoring system for surveillance of an offshore monopile foundation.

In the following, some of the monitoring techniques for direct or indirect monitoring corrosion related issues are presented [1].

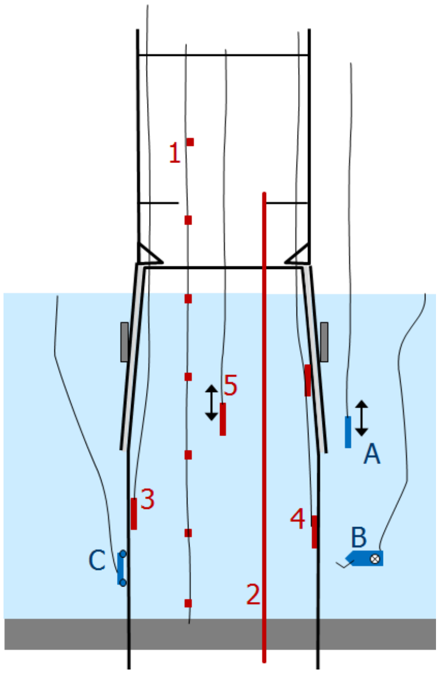

Figure 4: Overview of techniques for evaluating corrosion in- and outside monopile foundations

Techniques used on the internal side:

1. Corrosion coupons for visual evaluation and weight loss determination
2. Full-length corrosion coupon that includes macro galvanic elements and mud zone
3. Electrical resistance (ER) probe for real-time measurement of the corrosion rate
4. Magnet-mounted reference electrodes measuring the protection potential in projects with CP
5. Lowerable rack of sensors including potential, pH, dissolved oxygen, temperature and resistivity

Techniques used on the external side:

A. Drop-cell (reference cell) measuring protection potential of CP
B. Stabber (contact reference cell) mounted on ROV for measuring the protection potential of CP or high-resolution field gradient sensor (FIGs)
C. UT crawler (ultrasonic testing) for measuring wall thickness

In some cases, surveys rather than fixed probes have been applied, using drop-cells or probes for CP evaluation and environmental profiling.

Corrosion coupons

Coupons (weight loss) are the direct technique providing reliable data of corrosion rate including the option of examining deposits and corrosion attacks. The drawbacks are the need for retrieval to obtain data, slow response rate and that only historical data are obtained, not real-time data. Figure 5 shows an example of exposed coupons covering three different corrosion zones inside a monopile. Corrosion is most pronounced in the region at the waterline, where wet/dry cycles occur due to tidal variations.

Figure 5: Corrosion coupons exposed inside monopile in three different corrosion zones.

Since the mud zone area is not accessible for inspection or NDT, the risk of highly localised corrosion has been of concern in some projects. Corrosion in the mud zone could be promoted by differential aeration and/or microbiologically influenced corrosion. A basic device concept has been developed [2] for wind foundations comprising a full-length cylindrical corrosion coupon covering the height from the service platform to 0.5 m deep into the mud zone.
Figure 6 shows close-up photos of an unexposed and an exposed coupon after 1 year of exposure. At this site, only superficial corrosion was observed.

Figure 6: Cleaned surface of full-length coupon showing only minor corrosion after 1 year of exposure.

Real-time corrosion measurements
As indicated earlier, the environment inside the foundation is not static and several parameters (e.g. O_2, pH etc.) have been found to be changing as a function of the depth [3,4].

These special conditions occurring in the closed compartment have in some cases required installation of fixed probes for real-time monitoring. A similar need for such detailed monitoring of the corrosion protection is usually not found for the external side.
The ER probe is a fixed sensor type for real-time corrosion rate measurement. It measures the change in electrical resistance (ER) over a steel element with temperature compensation by a non-exposed reference element. Any corrosion in the sensors' steel element leads to decreased thickness of the element and hence increased resistance which, compiled with time, is converted to a corrosion rate. Apart from the corrosion rate, the ER probe also provides the current density in structures protected by CP.

Figure 7: An ER probe installed on the monopile wall.

Surveys inside the foundation
The inside of a monopile has in most wind farms a volume of moderately stagnant water that ranges from about 300 to 1000 m3. The tall, slender structure creates the possibility of large variations in the seawater conditions with depth, despite recent projects contain vent holes to promote water exchange. This special circumstance represents a main challenge in corrosion protection, regardless of whether it is based on CP or a completely sealed compartment.
For that reason, measuring different parameters would provide valuable information about the risk of corrosion. Selected parameters to be measured are represented here:

- *Protection potential.* The protection potential could be measured by the use of a drop-cell. The potential provides information of the CP's efficiency in a specific area.
- *Conductivity.* A reasonable constant conductivity is expected within the water column. However, the water temperature strongly influences this parameter.
- *Dissolved oxygen* (DO) has a strong influence on corrosion or the current demand when applying CP. Large variations have also been observed for this parameter.
- *pH.* The pH of fresh seawater is usually fairly constant at a level of approximately 8.0. In foundations without CP, an inspection has shown that the pH remains at this level throughout the entire water column. However, the pH may be affected in foundations with CP where installation of aluminium anodes may cause acidification down to pH 4.5-5.0 [5,6].

Surveys on the external side
The use of galvanic anodes generally provides a safe solution in terms of corrosion protection. However, the efficiency and service lifetime of the CP system may be affected by several undesirable events that define the need for inspection or monitoring.
As for the inside of the foundation, drop-cell measurements have also been used on the external side for assessing the CP system protecting the external side of monopile foundations.

When performing drop cell measurements, the error due to distance of the reference cell from the structure that is caused by strong sea currents must always be considered. In case of any doubt, verification must be performed by contact/stab measurements, which represents a safer but more costly method than drop-cell surveys.
For complicated CP designs or challenging regions with low conductivity, a high-resolution field gradient sensor (FIGs) has been used to verify CP performance [7,8]. This sensor produces a detailed 3D picture of the current flux around the structure, which gives additional certainty to the readings of the protection potentials. By using this technique on monopile foundations in brackish water, it was possible to calculate the anode output and the remaining anode lifetime, which turned out to be 70-85 years, and thus, by far on the safe side.

Conclusion

Having designed and operated offshore wind turbines for more than 16 years, the offshore wind business is presently to a large extent in a position to either design the way out of threats to the structural integrity or alternatively to establish control or mitigating actions that lowers the risk of structural deterioration. However, some potentially critical corrosion issues are still not fully mapped and understood for the monopile-based foundation, and new designs often solve some problems but introduces new issues.
For that reason, it is important to develop and install a proper surveillance system that can provide real-time specific knowledge or a more long-term based source of information about the foundation's condition.

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