Presented at NACE Corrosion 2016, Paper C2016-7702
Vancouver, BC, March 2016.

Monitoring and Inspection Options for Evaluating Corrosion in Offshore Wind Foundations

Troels Mathiesen, Anders Black, Frits Grønvold
FORCE Technology
Park Alle 345
2605 Brøndby
Denmark

ABSTRACT

The design of offshore wind foundations is still evolving as large projects are being commissioned or planned for the northern part of Europe. Monopile foundations represent the most common design, but other structure types are also being installed, such as jackets, tripods and gravity foundations. In comparison with offshore structures for oil and gas production, wind foundations present some new challenges for corrosion protection. As the structures are unmanned, the requirements for operation and maintenance must be kept at a minimum. At the same time, the huge water volume in the closed compartment of monopiles raises some concerns about MIC at seabed. The cathodic protection (CP) being applied both outside and inside also involves certain challenges. In this respect, several new approaches for inspection and corrosion monitoring have been applied. The paper reviews specific corrosion risks, such as macro galvanic elements, MIC and insufficient CP. Experiences from evaluating such issues by using various inspection and monitoring techniques are discussed. The applied techniques include UT examination, CP surveys with drop cells and environmental depth profiling. Corrosion has been evaluated using both small coupons and full-length coupons, while real-time measurements have included ER sensors as well as potential and current measurement.

Key words: Marine corrosion, carbon steel, cathodic protection, closed compartment, MIC, inspection, NDE, corrosion monitoring

INTRODUCTION

The design of offshore wind farm foundations is still evolving in order to reduce Cost of Energy and harness energy in locations at greater depths. At the same time, there is a demand for larger turbines with an increased reliability to minimize costly offshore maintenance. This tendency creates an increasing need for customized inspecting and monitoring of the structural integrity of wind turbine foundations. While the methods applied to offshore oil and gas installations are well-established, the strategies for offshore wind structures still undergo a learning curve. Experiences from early projects are steadily growing, but simultaneously the designs in new projects change to optimize performance and costs.

Large offshore wind farms have existed for 10-15 years. Today, 80 major offshore wind farms and 2850 turbines are operating in the northern part of Europe. Most of the foundations are based on the monopile design, but other structure types are also being installed, such as jackets, tripods and gravity foundations.

The special challenges for corrosion protection of monopile structures were discussed in a previous paper.[1] Furthermore, NACE TG476[(1)] is currently addressing such topics, which will lead to the release of a standard practice soon. General requirements are also found the in DNV[(2)] and GL[(3)] standards,[2,3] but in order to define a detailed inspection and monitoring program, case-by-case evaluations are still needed due to the differences in design and corrosion protection strategy between projects. The design life is typically 20 years and offshore repair of the unmanned structures is extremely costly or even impossible. This circumstance also highlights the need for a prober corrosion protection strategy.

In Germany, the BSH[(4)] authority demands monitoring of the structural integrity in 10 % of the foundations at offshore wind farms.[4] The regulations are less strict or absent in other regions, but the owners or classifying bodies usually choose to include a certain extent of monitoring to ensure integrity of the wind farm.

The current paper presents and discusses examples of results from inspection and monitoring activities on monopile structures. A more detailed introduction to some of the concepts has previously been published.[5,6,7,8]

CORROSION CHALLENGES WITH MONOPILE FOUNDATIONS

The monopile foundation presents certain challenges in regard to corrosion control. Figure 1 shows the principle of the design that consists of a monopile (MP) driven into the seabed. On top of this, a transition piece (TP) is mounted with a grouted connection between the two structural members.

The TP is usually fully coated by protective paint, both inside and outside, while the MP is left uncoated in most projects. The TP holds the galvanic anodes for protecting the submerged part of both MP and TP externally. In some projects, impressed current (ICCP) is used instead of galvanic anodes.

In the early projects, problems with displacement at the grouted connection were observed in several cases. Although, the expected effect on corrosion by this is limited, the associated repair work raised some concerns about the general condition of the internal compartment. As an example, Figure 5 shows the visual appearance at the waterline. It turned out that the initial assumption of a completely water-tight and oxygen-depleted compartment could not be fulfilled due to leakages at the cable entry in several projects. Consequently, the exchange of aerated seawater was considerable, which facilitates continuous corrosion.

The problem with grouted connections has largely been solved by using conical or flanged connections in recent projects, but discussions about the best practice for protecting the internal compartment are still ongoing. Today, different approaches based on galvanic anodes, 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 environment.

---

(1) NACE Task Group (TG) 476 - Corrosion Protection of Offshore Wind Power Units
(2) Det Norske Veritas (DNV). Ship and offshore classification society, Veritasveien 1, Høvik, Norway. As of 12 September 2013, DNV and Germanischer Lloyd (GL) have merged to form DNV GL.
(3) Germanischer Lloyd (GL). Classification society previously based in Hamburg, Germany.
(4) The Bundesamt für Seeschifffahrt und Hydrographie (BSH), 18057 Rostock, Germany.

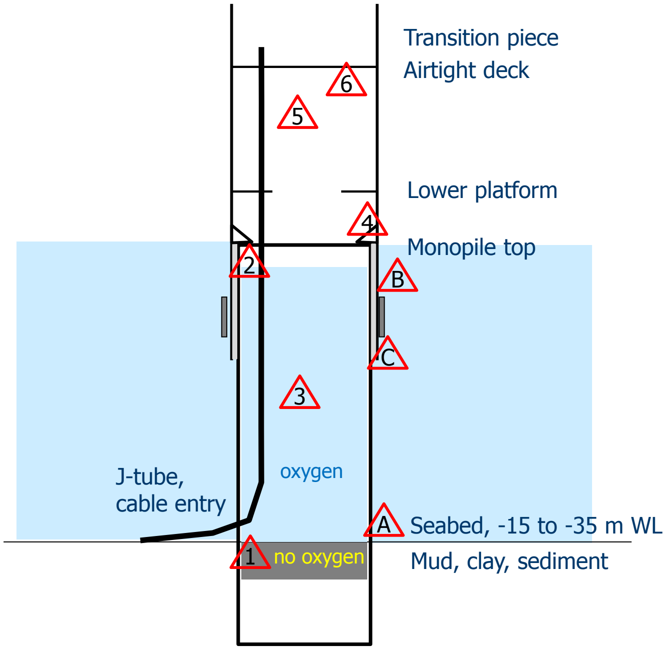

FIGURE 1: Risks related to corrosion in the monopile foundation design.

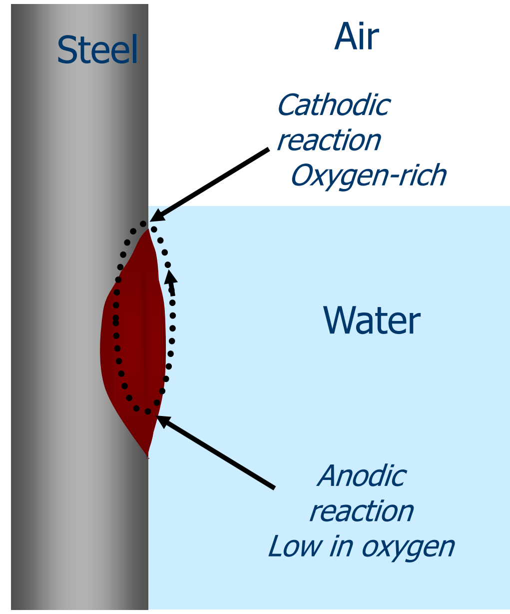

FIGURE 2: Example of localized corrosion mechanism at the waterline inside the monopile.

In order to define a good strategy for inspecting and monitoring corrosion, the potential "hot-spots" must be identified. Figure 1 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 localized 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 aluminum 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' 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 localized corrosion, especially if the water level remains constant and ingress of oxygen occurs, Figure 2. 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 sulfate reducing bacteria (SRB) may promote localized corrosion additionally by MIC.[8]

INSPECTION AND MONITORING OPTIONS

Offshore inspections are extremely expensive due to the special circumstances associated with this kind of work, Figure 3. The weather-window for embarking the foundations is small as a result of the harsh and windy environment ideal for offshore wind farms. Furthermore, working offshore implies large logistical and safety challenges. Entering the confined space, adds additional requirements for safety, backup personnel and certification. Many operators also prohibit use of divers, leaving remotely operated vehicles (ROVs) as the only option for subsea inspections.

On this basis, several attempts for monitoring have been applied to replace costly inspections. As mentioned, some authorities demand permanent monitoring in e.g. 10% of the structures.[4] Since the monopiles are mass-produced, this frequency seems reasonable with an almost identical design of the foundations at the same location. Figure 4 lists some of the techniques that have been applied for monitoring and inspection of the internal and external sides. Additional techniques have been covered in a previous paper.[5]

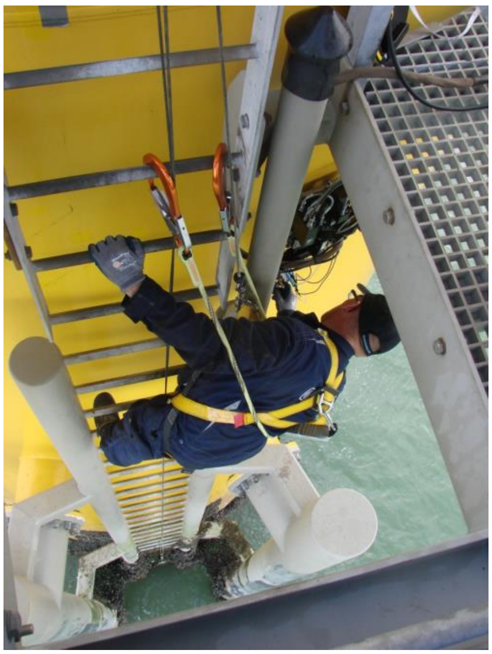

FIGURE 3: Manual inspection is complicated and presents logistical and safety challenges.

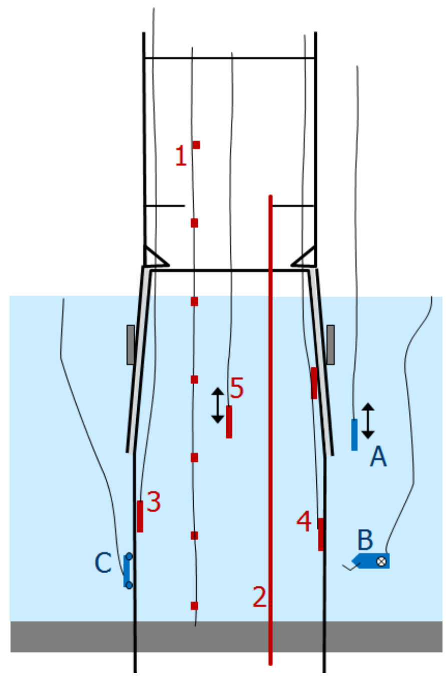

FIGURE 4: Overview of techniques for evaluating corrosion in- and outside monopile foundations.

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

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
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.

Strain gauges and other sensor types (e.g. scour, displacement, water level) are usually also part of the overall condition monitoring system, but they will not be covered in this paper.

WALL THICKNESS MEASUREMENT

Visual inspections of the closed compartment have been performed in several projects to examine corrosion at the water level. From the first impression in Figure 5, corrosion appears quite substantial. However, removal of mill scale, cleaning and closer inspection usually shows a less dramatic picture of the condition, Figure 6. Pitting may be observed, but the depth is typically not more than 2-3 mm, which equals a localized corrosion rate of 0.5 mm/yr. However, if pitting becomes too extensive it may act as stress raisers and initiate fatigue cracks if located at a critical position. It must then be investigated which degree of pitting corrosion can be tolerated in order to not compromise the structural integrity. Crack examination of critical parts may also be conducted in cleaned areas by ultrasonic testing (UT) and magnetic particle inspections (MPI).

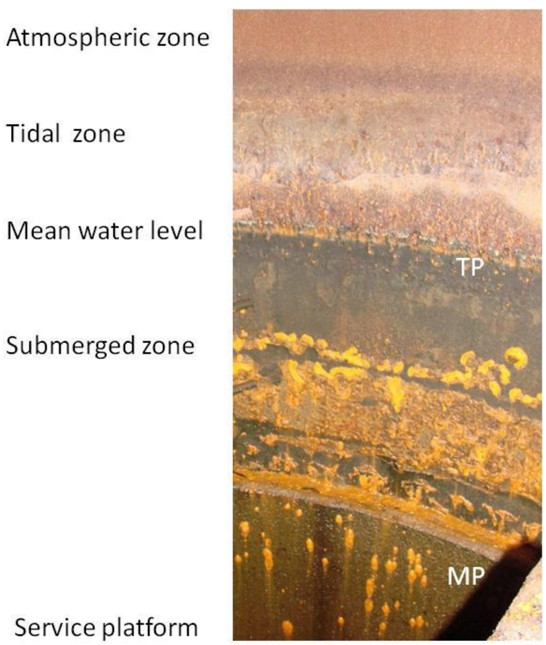

FIGURE 5: Appearance of corroded surface inside a monopile.

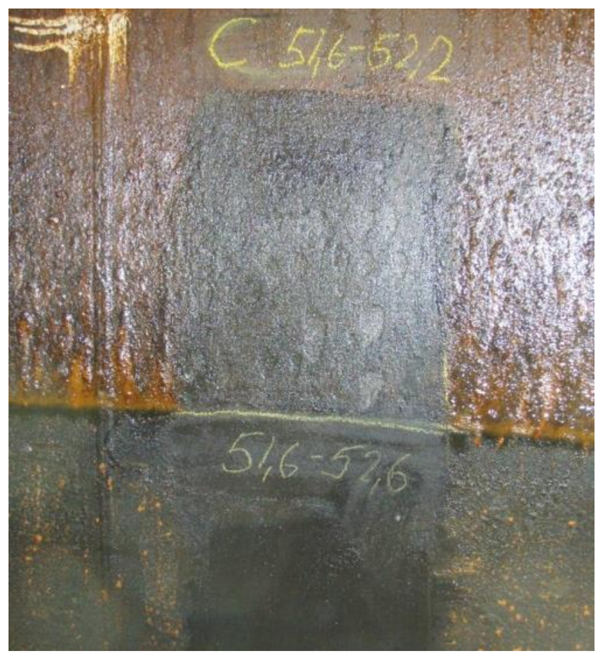

FIGURE 6: Thickness measurement of inside surfaces cleaned from scale.

Another approach is using a UT crawler for measuring wall thickness from the outside, Figure 7. The magnet-mounted UT crawler can be used for thickness measurement of the TP wall for the section above mean water level. Subsea equipment may also be applied. Figure 8 shows an example of obtained data. The scan at the left scan shows pitting at a depth up to 2.8 mm appearing just below the waterline on the internal side. However, most of the examined surfaces did not show considerable corrosion, as indicated in the scan at the right.

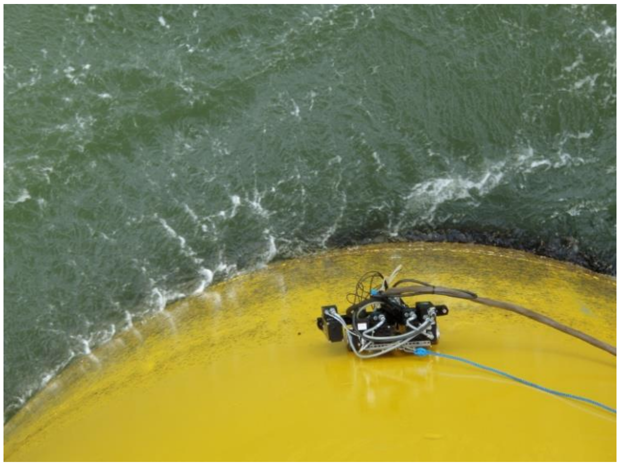

FIGURE 7: Thickness measurement by UT-crawler on the external side of transition piece by remotely controlled equipment.

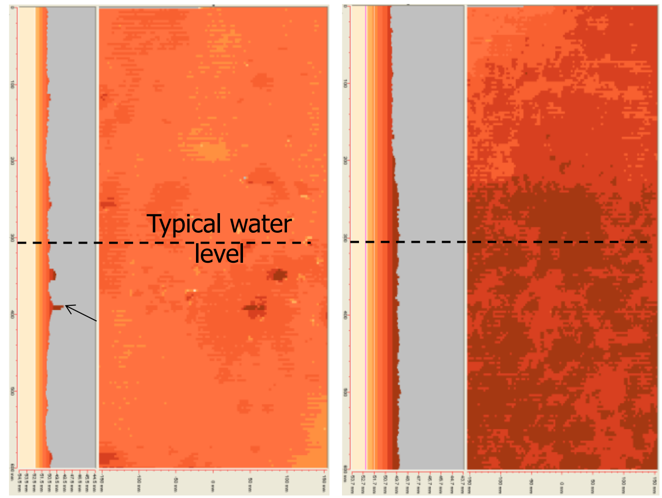

FIGURE 8: Results obtained with UT-crawler in two positions at the waterline. A maximum pit depth of 2.8 mm is observed on the inside in the left scan.

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 9 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.

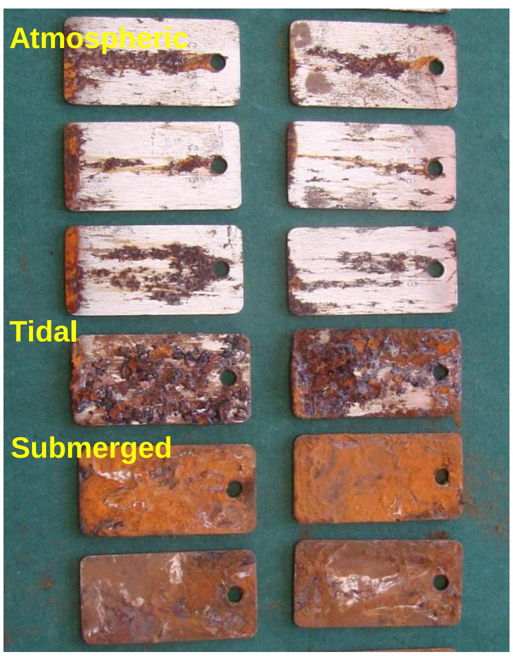

FIGURE 9: Corrosion coupons exposed inside monopile in three different corrosion zones.

FIGURE 10: Cleaned surface of full-length coupon showing only minor corrosion after 1 year' exposure.

Since the mud zone area is not accessible for inspection or NDT, the risk of highly localized 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 by the authors 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. This approach simulates the localized corrosion observed on the vertical MP wall, focusing on the risk of mud line corrosion. In contrast to conventional coupons, the full-length coupon includes macro galvanic effects and provides a more detailed picture of the corrosive conditions. The full-length coupon is supplied as a kit for easy transport and assembly on-site. Figure 10 shows close-up photos of an unexposed and an exposed coupon after 1 year's exposure. At this site, only superficial corrosion was observed.

CP SURVEYS OF EXTERNAL SIDE

The planning of surveys for verifying correct operation of the CP system should be based on the CP design report, preferably supplemented by CP modeling. This documentation will identify areas of special concern to be included in the surveys.

The use of galvanic anodes, welded or wired to the construction, generally provides a safe solution in terms of protection and self-regulating capability over time. Moreover, the monopile is a geometrically simple and symmetric structure where a decreasing correlation can be expected between the level of protection and distance from anodes. 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, such as passivation or excessive consumption of anodes, loss of electrical contact for non-welded anode connections, stray currents etc.

In accordance with DNV-OS-J101,[2] a CP survey shall be performed after minimum 30 days and maximum 180 days to confirm that the structures are adequately protected. When using ICCP, real-time monitoring of potential and current is usually part of the system, but additional inspection should still be considered.

Drop-cell measurements have frequently been used for assessing the CP system protecting the external side of monopile foundations. Figure 11 shows an example of such data obtained in a wind farm, where some of the foundations initially were under-protected near the seabed. This issue was related to inadequate CP design guidelines that account for the particularly harsh conditions, which apply to monopile foundations located in shallow waters with high tidal variation.[9,10]

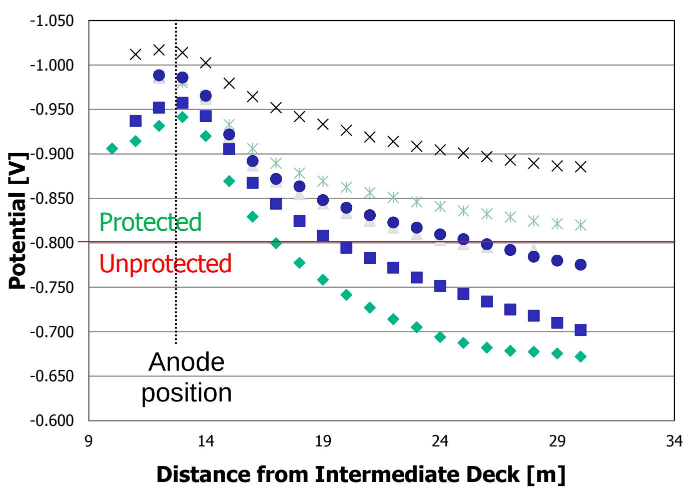

FIGURE 11: Example of drop-cell measurements obtained in a wind farm, where some of the foundations initially were under-protected.

FIGURE 12: Potential measurement using a stabber (contact reference cell) mounted on a ROV.

When performing drop cell measurements, the error due to distance of the reference cell from the structure must always be considered. Preferably this distance should not exceed 0.5 meter, but strong sea currents often interfere, necessitating a specially designed weight-load wire arrangement.

In some cases, drop-cell surveys performed by non-experienced staff have produced odd results that questioned the validity of the entire campaign. Such errors are often related to poor electrical connections. Consequently, it is advisable that a corrosion specialist either supervises or performs such surveys. 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, Figure 12.

For complicated CP designs or challenging regions with low conductivity, a high resolution field gradient sensor (FIGs) has been used to verify CP performance.[11] 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.

SURVEYS IN WATER FLOODED COMPARTMENT

The closed compartment inside a monopile foundation represents an enormous volume of fairly stagnant water. In most wind farms, the volume ranges from about 300 to 1000 m^3. At the same time, 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.

Figure 13 shows some trends observed using a lowerable rack of probes for environmental monitoring inside monopiles. When CP is installed, such surveys also include measurement of the protection potential with a drop-cell.

Seasonal variations in temperature are seen during a year in the water column, whereas the temperature just above the seabed remains fairly constant. Similar to inland lakes, such temperature variations may cause stratification (layering) or promote convection at sudden temperature shifts. It is also thinkable that slight heating from the power cables may cause local convection. Moreover, ingress of seawater through the cable entry will promote such variations depending on the water exchange rate from tidal variations.

Generally, a fairly constant conductivity is expected within the water column. However, the water temperature strongly influences this parameter. In one project, the conductivity had more than doubled in the period from winter to summer. In another project, a local high conductivity was observed in the water between the seabed and vent holes for forced exchange of seawater.

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. Without CP, the DO level is largest at the cable entry (in case of a leaking gasket) and at the waterline. For foundations having CP installed, the variations in DO are more complex.

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 aluminum anodes may cause acidification down to pH 4.5-5.0.[12,13]

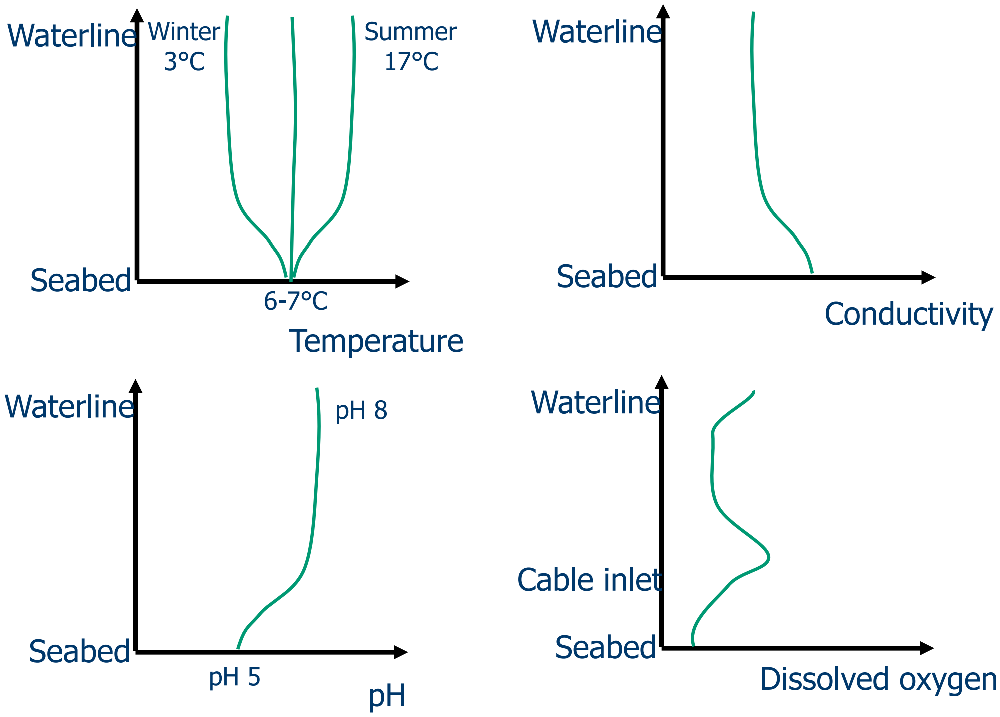

FIGURE 13: Trends observed using a drop-cell rack for environmental monitoring inside monopiles.

While not having been reported or observed yet, acidification could possibly also occur due to formation of H_2S from bacterial activity. This can take place in the de-aerated mud zone or in the water column itself, in case of complete de-aeration. Depletion of oxygen favors growth of sulfate-reducing bacteria that produce H_2S (hydrogen sulfide). Unless there is significant exchange of seawater with the outside, the nutrients for such bacteria and other organisms will be consumed with time, thereby limiting their potential effect on corrosion.

REAL-TIME CORROSION MEASUREMENTS

The special conditions occurring in the closed compartment has required installation of fixed probes for real-time monitoring in several projects. A similar need for such detailed monitoring of the corrosion protection is usually not found for the external side.

In one project, a large number of sensors were mounted with magnets at different levels in the closed compartment that is being protected with galvanic anodes, Figure 14. The recorded data included potential, pH, DO, anode current and temperature. Quite large variations were observed with depth similar to the data presented in the previous section. But most importantly, the monitoring system showed the time dependent performance of the CP system, thereby facilitating adjustments and optimization of the CP system.[14,15]

The ER probe is another type of fixed sensor 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, Figure 15. The sensitivity and resolution depend on the element dimensions and instrumentation. It may be as low as 0.006 mm/yr at daily readings with a 100 µm element. Apart from the corrosion rate, the ER probe also provides the current density in structures protected by CP.

Monitoring systems based on ER probes have been used successfully to verify correct operation of the CP system in the closed compartment. In one project, the probes were initially left freely corroding. During this period, a constant corrosion rate of 60 µm/year was measured with all probes. When the probes were connected to the CP-protected structure, the corrosion rate dropped immediately to a level below 10 µm/year.

FIGURE 14: Magnet mounted zinc reference electrode seen from the actuator used for installing the probe inside the monopile.

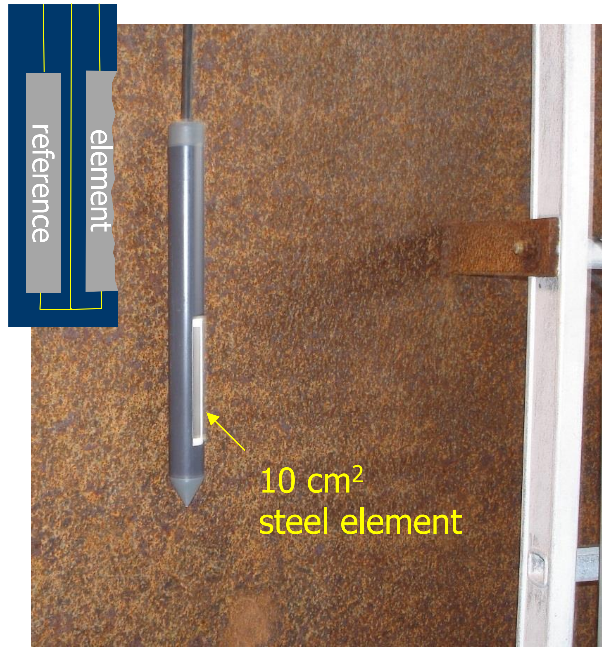

FIGURE 15: Principle and photo of ER-probe used for real-time corrosion rate measurement inside a monopile.

CONCLUSIONS

The special circumstances related to corrosion control of offshore wind foundations necessitate a customized strategy for inspecting and monitoring corrosion. Examples of the applied techniques are presented and reviewed in the paper.

Corrosion protection of the external side is fairly well-established as key technology and experience can be transferred from other marine structures such as oil and gas platforms. Paint coating in combination with CP is the typical approach for preventing corrosion. CP surveys are mandatory and may be carried out by drop-cell or stab measurement to verify protection potentials. For complicated designs or challenging regions, the Field Gradient Sensor may be considered to obtain a greater certainty about the CP performance.

Corrosion protection of the internal compartment is currently the major concern that requires the highest attention in regard to inspection and monitoring. Different approaches are being applied for protection such as galvanic anodes, ICCP and/or coating. At the same time, the large stagnant water volume creates variations in chemistry, while uncertainties about MIC in the mud zone also remain unsolved. This has justified the development and application of a range of different monitoring techniques that include UT crawler inspection, corrosion coupons, full-length coupons, environmental depth-profiling as well as application of real-time sensors measuring corrosion rate, potential, protective current, pH and dissolved oxygen. At present, there is no straight-forward way or guideline available to establishing such monitoring systems, because each system must be configured to match the particular challenges in the specific project design.

REFERENCES

1. A. R. Black, L. R. Hilbert, and T. Mathiesen, “Corrosion Protection of Offshore Wind Foundations”, CORROSION 2015, paper no. 5896 (Houston, TX: NACE, 2015).
2. DNV-OS-J101, January 2013, “Design of offshore wind turbine structures” (Høvik, Norway: DNV).
3. Germanischer Lloyd, 2012 edition, “Guideline for the certification of offshore wind turbines” (Hamburg, Germany: GL).
4. BSH Standard, 2007 edition, “Design of Offshore Wind Turbines” (Rostock, Germany: BSH).
5. L. R. Hilbert, A. R. Black, F. Andersen and T. Mathiesen, “Inspection and monitoring of corrosion inside monopile foundations of offshore wind turbines”, EUROCORR 2011, paper no. 4730 (Frankfurt am Main, Germany: DECHEMA e.V., 2011).
6. A. R. Black, P. K. Nielsen, “Corrosion protection of offshore wind farm structures – present understanding and future challenges”, EUROCORR 2011, paper no. 4586 (Frankfurt am Main, Germany: DECHEMA e.V., 2011).
7. L.R. Hilbert et al, “Corrosion control inside offshore wind farm monopile foundations”, EUROCORR 2012, paper no. 1301 (Frankfurt am Main, Germany: DECHEMA e.V., 2012).
8. L.R. Hilbert et al, “Mud zone corrosion in offshore renewable energy structures”, EUROCORR 2013, paper no. 1542 (Frankfurt am Main, Germany: DECHEMA e.V., 2013).
9. T. Mathiesen, “Cathodic corrosion protection of foundation structures – CP basics, challenges and solutions”, Offshore Wind Corrosion Protection (Esbjerg, Denmark: ATV-Semapp, 2013).
10. H. Osvoll, “Essential factors influencing cathodic protection not covered by standards and recommended practices” EUROCORR 2011, paper no. 1022 (Frankfurt am Main, Germany: DECHEMA e.V., 2011).
11. H. Osvoll, G.Ø. Lauvstad, T. Mathiesen, “CP design and retrofit for offshore wind turbine monopile foundations”, EUROCORR 2015, paper no. 801 (Frankfurt am Main, Germany: DECHEMA e.V., 2015).
12. S. Briskeby and et al, “Cathodic Protection in Closed Compartments – pH Effect and Performance of Anode Materials,” CORROSION 2015, paper no. 5657 (Houston, TX: NACE, 2015).
13. I. Tavares, P. Ernst, G, John, R. Jacob, B. Wyatt, “Internal cathodic protection of offshore wind turbine monopile foundations”, Corrosion Management (January/February 2015): pp.14-17.
14. B. B. Jensen, F. Grønvold, “Corrosive environment inside offshore monopile structures and challenges in monitoring”, EUROCORR 2014, paper no. 7365 (Frankfurt am Main, Germany: DECHEMA e.V., 2014).
15. B. B. Jensen, “Corrosion protection of offshore wind farms, protecting internal sides of foundations”, CORROSION 2015, paper no. 5762 (Houston, TX: NACE, 2015).