Inspection and monitoring of corrosion inside monopile foundations for offshore wind turbines

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Summary

The design for corrosion inside a monopile foundation anticipates low, uniform corrosion rates in a closed compartment, but in 2-10 year old foundations sea water and thus oxygen ingress have been detected, increasing corrosion rates and localising attacks. Inspections are therefore necessary to evaluate the current corrosion state, prevailing mechanisms, cause of changed conditions, and whether areas with risk of stress concentration, e.g. at welds, are susceptible to corrosion fatigue. Monitoring campaigns increase our understanding of the conditions under which wind turbine foundations must function in the years to come and document effect of a given change. The vision is that the knowledge gained should be integrated in future designs, and that simple corrosion monitoring should be installed at the time of construction.

1 Introduction

A number of offshore wind turbine designs have now been in operation in the northern part of Europe for 5-10 years. The design life is typically 20-25 years, but in practice, significantly more years of operation can be achieved with proper maintenance and monitoring. Reliable lifetime assessment with the objective of ensuring the safety and integrity of the structures can be obtained by combining on-site inspection with advanced techniques, remote monitoring systems, and thorough analyses of information retrieved.

Different turbine foundation designs exist, but the interest in monopile foundations has been accentuated by the observed setting of the transition piece (TP) in relation to the monopile (MP), causing concern that the structural strength of the construction is at risk, even if crack initiation has not been detected. The possible, changed load pattern might increase the risk of fatigue in specific parts, augmenting the need for inspection and monitoring. The internal sides of the MP and TP are not protected by coating or cathodic protection (CP), as low corrosion rates are expected in a closed compartment. Sea water and oxygen ingress as well as microbial activity in the partially closed compartment may, however, induce localisation of attacks and increased corrosion rates. The presence of corroded inner surfaces should therefore be taken into account when evaluating structural strength and corrosion fatigue risks.

1.1 Monopile design

The general design of a monopile foundation is that a steel pile, the MP, is driven into the sea bed leaving 1-2 m above sea level. The TP is installed on top of and outside the MP with an overlap of typically 6 meters. In this process a number of brackets on the inside of the TP aid adjusting the position of the TP. The gap between the two elements is filled with high strength grout intended to cement the two pipes together.
Inside the foundation typically two platforms are found, a service (lower) platform close to the connection between TP and MP and above this an airtight platform sealing the foundation. In some design the J-tube (curved steel tubular conduit) supporting and guiding the power cable run internally through the airtight platform and down inside the foundations until it goes through a sealed opening in the MP wall. A general sketch is given in figure 1.

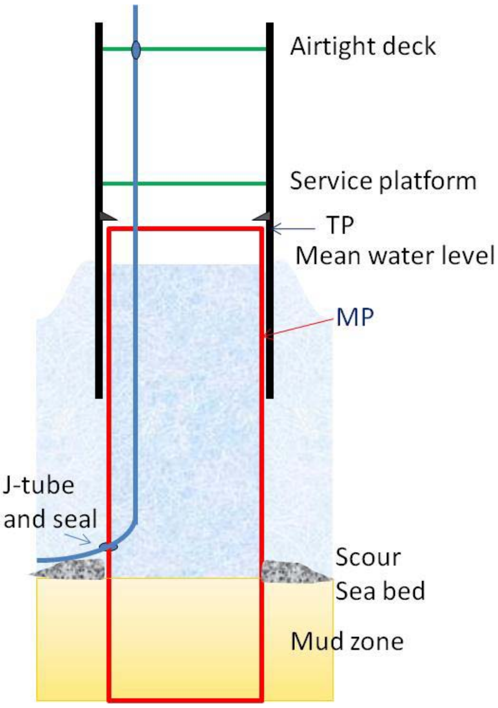

Figure 1. Overview sketch of principle in MP foundation design, here shown for at system with internal J-tube.

In a large number of northern European wind farms setting of the transition piece (TP) in relation to the monopile (MP) has been observed due to grout failure. This causes concern that a changed load pattern might increase the risk of fatigue in specific parts, especially since the TPs now in many cases rest on the adjusting brackets, which was not intended in the design. The inspections related to grout failure have however also revealed that the corrosion conditions are not as expected inside the MP and TP's.

In practice the concept of a fully closed compartment has not been achieved in most foundations. As an example oxygen levels has been measured above water level in 36 foundations of a 5-10 year old windfarm. Only 3 of these foundations (8%) can be characterised as oxygen free and appear fully closed, whereas 25 (70 %) of the foundations can be characterised as aerated with oxygen levels above 15 %. The rest shows intermediate levels. The cause of air access is unclear, but the seals of the airtight platform were intact.

The airtight platform at the top of the foundation is designed to make sure that oxygen ingress occurs only during inspection, but other weak spots in the design may allow continuous oxygen ingress. The cause may be sea water ingress through e.g. leaking seals in connection with the lower exit of the J-tube through the MP wall. The result of this is that tidal variations may occur inside the foundation, the media being either in direct contact with the surrounding sea or as a delayed effect e.g. only at springtide. Ingress of fresh sea water both increases the oxygen content in the media and affects the microbial activity. The tidal variations also increase the risk of localisation of attacks in connection with the tidal zone (figure 2).

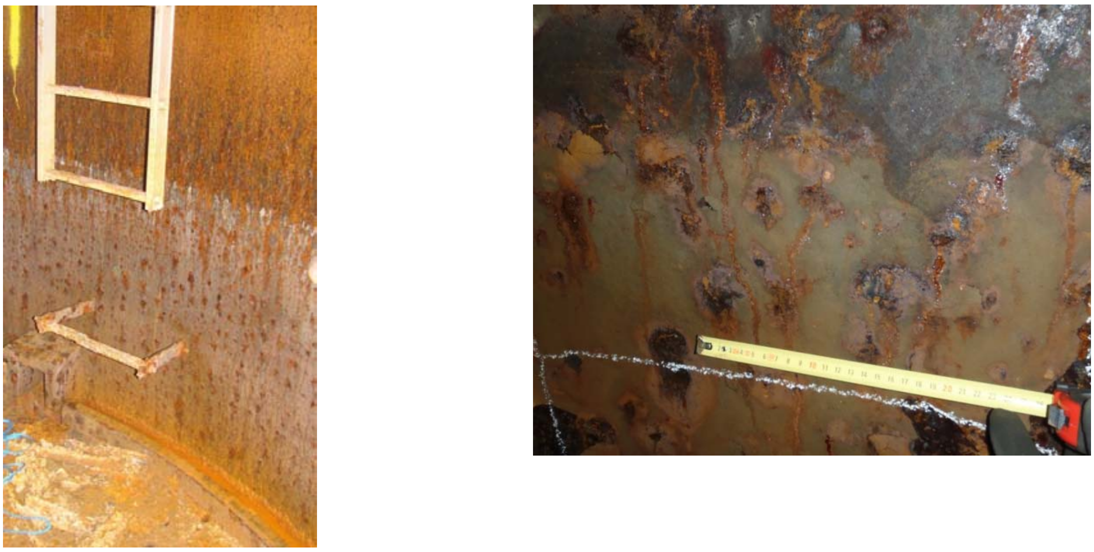

Figure 2.

Left: The lower part of the aluminium ladder above the service platform has corroded away due to the water level increasing above the service platform.

Right: In another foundation areas covered with corrosion tubercles are found.

1.2 Corrosion conditions in sea water

For steel in contact with open sea water, corrosion conditions are typically characterised as atmospheric zone, splash zone, submerged zone and mud zone respectively, where the highest rate is in the splash zone or in the zone just below the water level for more stagnant water. In general, a corrosion rate in the order of 0.1-0.15 mm/y is expected for unprotected steel surfaces fully immersed in sea water. The corrosion attacks will be uniform corrosion with some degree of localisation giving localised corrosion rates of up to 0.4 mm/yr [1]. The rate reduces in time as the surfaces are covered with corrosion products. To keep corrosion rates under control, corrosion protection is required, similar to the systems applied on the outside of the MP and the TP. This includes corrosion protective organic coatings and CP. If CP is to be used in a closed compartment, e.g. inside a foundation, ventilation is required for hydrogen gas.

In a completely airtight structure the dissolved oxygen in seawater is quickly consumed by uniform corrosion of the entire steel surface. As the media turns anaerobic corrosion rates will decrease, however microbial activity in the sediment and in the entrapped sea water may generate H_2S and the sulphur and iron cycle affect corrosion. As renewal of nutrients is difficult, the activity is expected to decrease in time and the corrosion rate likewise. Maximum rates are found just below the water line estimated to 0.1 mm/yr and locally 0.2 mm/yr, whereas the fully immersed surfaces will show much lower rates. In the part of the MP buried in the sediment, the bacterial activity is also expected to decrease, when the majority of nutrients have been consumed, unless nutrient transport can occur via the sediment below. Consequently, critical corrosion is not expected here either. Formation of black corrosion products, presumably a combination of iron sulphides and iron oxy-hydroxides, generally result in a low corrosion rate, if conditions stay continually anaerobic. The effects of hydrogen sulphide or risk of hydrogen induced cracking should furthermore be considered for anaerobic media, especially if CP is applied.

The risk of corrosion fatigue for surfaces with a low degree of corrosion is insignificant. Unprotected steel surfaces in marine environment are, however, known to be susceptible to corrosion fatigue failure. Corrosion affects both the crack initiation life and crack growth period. Surface roughness is increased by corrosion and corrosion pits are geometric discontinuities at the surface, which, depending on the shape and size, may have a notch effect facilitating crack initiation. More important it is that aggressive media affect the crack growth rate, depending of the load frequency and the load wave shape [2]. Corroding steel does not show a fatigue limit in sea water in contrast to steel in air or with CP. This means that crack growth may occur assisted by on-going corrosion at even low stress amplitudes, and that there is no safe limit under which cracks do not grow. Corrosion is a time-dependant process, so the risk is large also for low frequency loads, where corrosion at the crack tip may facilitate crack growth. For off-shore structures the standard procedure is therefore to protect external surfaces by coating and CP, as are the outsides of the TP and MP.

The inside of monopile foundations is in practice neither airtight nor in full contact with open sea water. An inspection should therefore identify how partial oxygenation has affected the corrosion state, whether corroded surfaces with pits as well as continually corroding surfaces are present, and whether critical areas with risk of stress concentration, e.g. at welds, have a specific corrosion morphology.

2 Effects of sea water and oxygen ingress

The direct ingress of air is only possible, if the airtight platform is not properly sealed. In that case the gas phase inside the foundation will affect the atmospheric corrosion rate of the humid top walls of the TP and the platforms above sea level. Corrosion rate may initially be high, but as corrosion products cover the surfaces, the rates will decrease. Below the water-line, corrosion is facilitated by differential aeration between the upper water layer and active steel surfaces below. If the water level is completely stagnant, the corrosion will be much localised. The corrosion element will, however, have limited coverage, so no considerable effect on corrosion at greater depths in the foundation or for the parts buried in sediment is expected.

The range of the galvanic elements depends on the conductivity and diffusivity of the marine sediment and the oxygen gradient. Generally it is expected that corrosion rates for structures in marine sediment are low, approximately 10 times lower than in the submerged zone, thus 0.015 mm/yr, as the oxygen diffusion rate is low and the galvanic elements formed will also have a limited range depending on the conductivity of the mud. In a laboratory test setup of only 0.5 m height is was shown that corrosion rates of uncoupled steel elements decrease with depth from the air/water interface (0.12 mm/yr) down to the water/sediment interface (0.04 mm/yr), and stay constantly low in the sediment [3]. If the elements are coupled the corrosion rate of the upper parts is lowered, whereas the corrosion rate of the elements at the water-sediment interface and in the sediment is slightly increased, and for the worst case, fine sand, the corrosion rate at 20 cm below a simulated sea bed surface is up to 0.12 mm/yr. This is due to the macrogalvanic elements formed between anaerobic and aerobic zones. In another abiotic laboratory test of corrosion in marine sediment very low rates were found for elements only in the anaerobic zone (0.008-0.015 mm/yr), and the rates increased with the oxygen diffusivity [4].

The oxygen content in the foundation can also change due to *slow* sea water ingress e.g. through minor leaks at the J-tube seal, degraded grout connections or small J-tube openings/perforations. In this case sea water with dissolved oxygen enters the system, increasing corrosion over the entire surface. However, in the air-depleted mud-zone there is a larger risk of accelerated corrosion, mainly due to the differential aeration. Moreover the renewal of sea water will affect the microbiological and chemical processes inside the compartment.

If the ingress of sea water is large, e.g. if the J-tube sealed has fully failed, tidal variations may directly occur inside the foundation and water level change daily or at extreme events like spring tide. In this case the inside foundation resembles almost the conditions for a sea port with fairly stagnant water and tidal effects, or a ballast tank, where the access of air is also restricted. In this type of systems accelerated low water corrosion (ALWC) [5] has been found to occur in the alternating aerated and deaerated and alternating wet and dry zone. Microbial involvement in this mechanism has in recent years increasingly been studied [6].

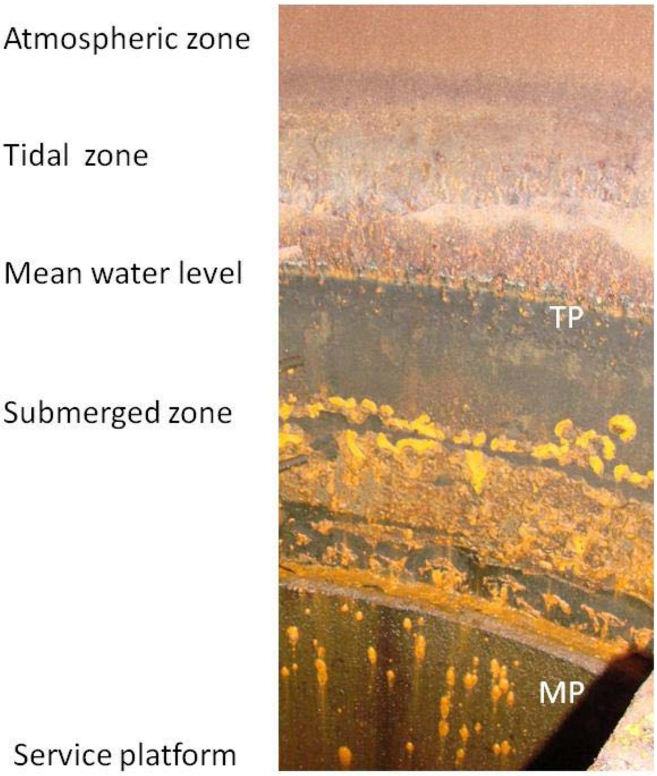

Figure 3. Foundation where water ingress through internal J-tube has increased the mean water

level to approximately 1 m above the service platform and allowed tidal variations. Different corrosion zones are identified within a few meters.

Moreover, growth of various bacteria (sulphate reducing bacteria (SRB), sulphur oxidising Bacteria (SOB), organic acid producing bacteria (APB), iron related bacteria (IRB)) and other microorganisms in biofilm on the MP walls and in the mud zone may contribute to the formation of local aggressive conditions that could promote localised corrosion. This mechanism is also known under the general term, MIC (microbiologically influenced corrosion). Experience from harbour sheet piles, offshore constructions and buried artefacts in the seabed do generally not suggest that MIC is a major problem deep in sediment, but buried pipelines and other off-shore constructions below the seabed typically require protection by cathodic protection and often also coating. Usually MIC is a much worse problem if a periodically aerated zone is formed.

A review paper on corrosion in sea bed sediment [7] summarises a number of suggested mechanisms and also that the understanding of MIC is under development. They refer that MIC may increase expected corrosion rates with a factor of 4-7. Rates of MIC of 0.1 mm/yr (uniform) and 0.7 mm/yr localised are given, and it is stated that oxygen access may promote these rates to even higher values. However, they find that generally differential oxygen concentration is the major accelerating factor for corrosion in marine sediments. An example is described in [8] for specimens in an approximately 3 m thick layer of marine mud covered with 0-1 m water. The steel specimens were not constantly buried, but exposed periodically to wet/aerated conditions. In this case MIC developed resulting in a uniform corrosion rate of 0.08 mm/yr as wide hemispherical pits. After 5 years exposure the maximum pit depth was 0.64 mm.

For a scenario with periodic renewal of sea water and tidal variations inside the partially closed compartment the following conditions could exist:

- Atmospheric corrosion above sea level increases, however scale will slow down rates in time.
- Possibly ALWC for tidal, but fairly stagnant conditions just below the water level (up to 0.5 mm/yr, localised corrosion)
- Increased uniform corrosion on the sea water submerged parts (0.1-0.15 mm/yr, locally 0.2-0.3 mm/yr), generally depending on depth and oxygen access.
- Differential aeration accelerating corrosion on lower parts close to the sea bed and in the upper max 1 m of the of mud zone (0.2 mm/yr)
- MIC as localised corrosion (wide shallow pits forming grooves) expected especially at the upper parts of the mud zone (0.1-0.25 mm/yr) or in areas where shifting degrees of oxygenation change the growth potential
- Uniform corrosion in deeper sediments (0.015 mm/yr), possible local zones of higher rates (0.25 mm/yr)

3 Inspection methodology

The frequency of inspections is generally limited by the high costs related to off-shore work and the variable weather conditions. Furthermore the access and working conditions inside the partially water-filled, confined space are difficult. A major part of the inspection therefore relates to planning the inspection details, risk assessment, as well as practical handling. The surfaces of the lower part of the MP are furthermore poorly accessible and can generally only be inspected by either lowering the water level inside the foundation, by use of divers, or - with some effort - by remotely controlled automated equipment. An inspection is a disturbance of the media and e.g. the consequences of oxygenation of an otherwise anaerobic area should be considered.

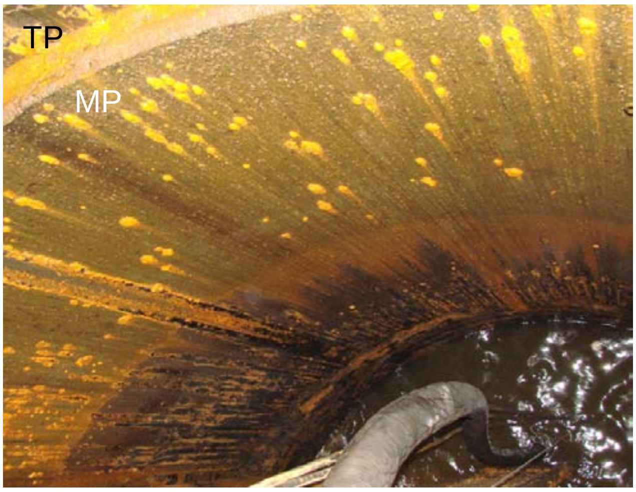

Figure 4. Left: View of MP top below service platform.
Right: The water level is lowered by pumping in order to inspect the area below the service platform.
The surfaces are exposed to oxygen during the inspection.

A corrosion inspection inside a monopile could include:

- Visual inspection and photo documentation – morphology, localisation
- Wall thickness measurements by e.g. ultrasonic testing (UT) either from the outside surface of the TP or from the inside.
- Pit depth after cleaning surfaces
- Scale morphology and sampling for determination of composition, local pH
- Sampling for microbiological analyses of biofilm, scale, and water samples
- Crack examination in areas with predicted risk stress concentration
- J-tube corrosion state
- Water level measurements as well as recording variation
- Oxygen level, concentrations of other gasses (H_2S, CH_4)
- Locating possible ingress of water/air

The corrosion survey should include examinations at various levels characterising the possible different zones of the media, e.g. atmospheric, tidal, submerged, and mud zone, if possible. In order to predict the future corrosion behaviour and suggest mitigation strategies, the last point on the list, locating ingress of water/air is of major importance.

For NDT inspection, various methods can be combined to perform automated or manual wall thickness measurement (e.g. UT) and pit depth estimation and location (UT, visual evaluation and pit wheel gauge).

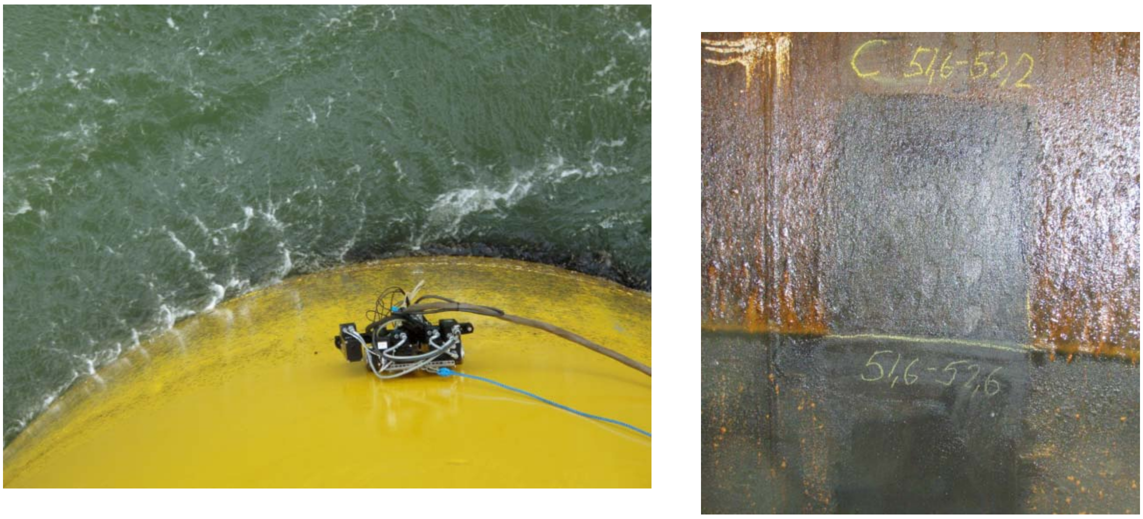

Figure 5.
Left: Thickness measurement by UT on the external side of the TP wall by remotely controlled equipment.
Right: Thickness measurements on inside surfaces cleaned from scale.

Figure 5 shows how external UT by automated equipment can be used for thickness measurement of the TP wall for the section above mean water level. Subsea equipment may also be applied. In figure 5 an example is also given of manual measurements of inside surfaces cleaned off for UT and pit depth examination. In this case uniform corrosion is insignificant and the original wall thickness almost intact. The survey includes thorough photo documentation and sampling of scale samples for off-site analysis. Figure 6 shows an example where localised corrosion attacks of maximum 1-1.3 mm depth are found after cleaning off scale. Crack examination of critical parts may also be conducted on cleaned areas by UT and magnetic particle inspections, MPI.

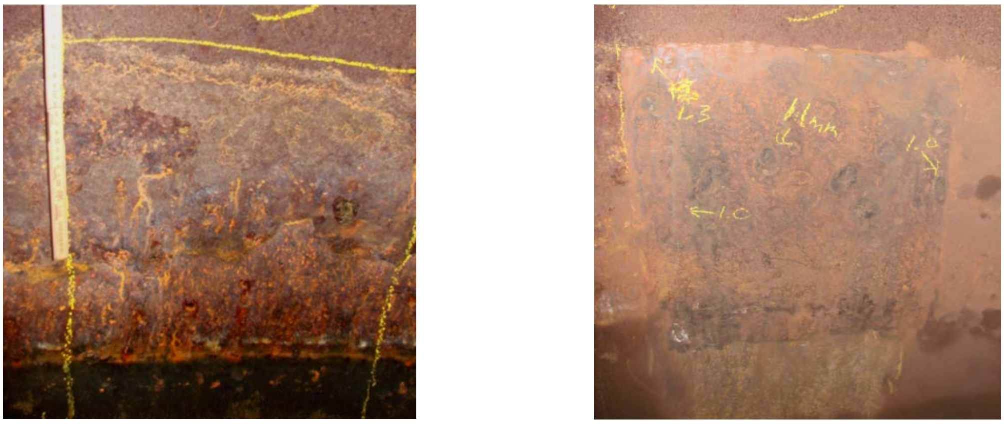

Figure 6. Corroded area (50*50 cm) before and after scale removal and pit depth measurements. Here the maximum pit depth was 1.3 mm.

The off-site work includes chemical and microbiological analyses. Furthermore the scale morphology can be examined by microscopy, especially examining tubercles. Relevant parameters in a water analysis could be pH, conductivity, salts, soluble metals and anions to evaluate whether the media is typical sea water or differs from this. On site the media may also have be characterised by measurement of electrochemical potentials on the TP/MP walls vs. a reference electrode, or redox potential measurements on platinum electrode at different heights.

Examining the composition of the scale can reveal if this is typical for steel in sea water including apart from iron oxyhydroxides, and calcium also high levels of chlorine and sulphur. The latter can indicate presence of ferrous sulphides formed during anaerobic corrosion. More detailed analyses may be of relevance.

Microbiological data may be relevant in order to evaluate the conditions for MIC. The key problem is that presence or activity of specific organisms is not a proof of MIC, but merely an indication of a possible mechanism. Classical techniques like growth media techniques can be used to evaluate the number of culturable cells of marine organisms typically related to corrosion e.g. SRB, APB, IRB etc. To evaluate the potential for forming biofilm, other techniques may be included. Recently molecular microbiological methods are being introduced in different fields, with the very strong benefit that non-culturable organisms can also be identified even from dried scale samples, but whether this will significantly change our understanding of MIC mechanisms is yet to be shown.

4 Monitoring options

As a supplement to inspection, the development in time can be registered by monitoring techniques, increasing the reliability of service life assessment and giving the option of corrective actions, if corrosion rates are unexpectedly high. Reliable monitoring requires that robust methods be chosen and that probes or sensors be placed in correct positions; either critical hot spots or representative areas monitoring the general state. Environmental parameters may also be monitored as an indirect measure, e.g. monitoring the water level variations or oxygen content.

The results obtained from inspections should be included in the planning and choice of technique, e.g. if corrosion attacks have appeared fairly uniform, the use of standard monitoring techniques may readily be introduced, whereas more localised attacks may require other techniques and specific placement of probes.

4.1 Corrosion monitoring

In order for monitoring to be successful, obtained data should be assessed relative to accept criteria set for the system. Therefore knowledge of expected rates, sensitivity of equipment, artefacts and actions, if critical rates are exceeded, should be considered on beforehand.

A number of factors affect the choice of technique and design of probe, e.g.

- Purpose (long term data or early warning capacity)
- Working life time without service
- Detection of the relevant failure type /mechanism
- Installation conditions

- Aqueous or dry media
- Pressure
- Zone – e.g. mounted in several heights
- Data transfer options

Based on experience from inspections both uniform corrosion rates and localised corrosion are relevant, corrosion rates in both wet and dry conditions could be of interest, and some challenges regarding installation and data transfer have to be considered. Monitoring is easier if planned into the original design, whereas mounting coupons and probes after construction can be a somewhat challenging task.

For real time techniques the data acquisition is usually performed by a data logger run by a computer which stores the data on a hard disc. The data can be transmitted to shore either via an internet connection (LAN) or by manually picking up an external data store when convenient. In some cases, where the wind farm is located close to shore, a mobile modem connection can be established. Figure 7 shows installation of cables for a large number of sensors. The cabinet with a complete data acquisition system mounted just above the airtight deck. A special airtight lock is made for penetration of the measuring cables.

Figure 7. Installation of cables and equipment for monitoring of large number of sensors. Cables continue below the platform. The cabinet with a complete data acquisition system mounted just above the airtight deck.

Coupons (weight loss) are the direct technique providing reliable data including the option of examining scale and corrosion attacks. The only drawback is the need for retrieval to obtain data, slow response rate, and that only historical data are obtained, not real time data. Corrosion rates vary in time so, in order to measure the actual corrosion rates and record changes, techniques such as electrical resistance (ER) or electrochemical corrosion rate measurements like linear polarisation resistance (LPR) can be introduced.

If corrosion rates are low, ER and LPR probes will generally have a long functioning time – whereas in the case of high corrosion rates or localised corrosion, the service life of the sensor is shortened. In that case, however, inspections are probably also necessary, and the monitoring has given the intended early warning. Awareness should be given to the fact that sulphide rich media introduce limitations on the applicability of techniques [9]. In order to detect effects of differential aeration as those in the mud zone or tidal zones, designs may be installed including two sensors electrically coupled, but placed in each zone.

A galvanic probe is an indirect measurement very sensitive to oxygen ingress, based on zero resistance amperemetry between a steel probe and a noble copper or brass probe. When installed just below the water level, it will be sensitive to ingress of oxygen from both top and bottom. The recorded output of this probe type is galvanic current which can be transformed to an approximate corrosion rate (mm/y). Rapid changes in the oxygen level will be registered and the design life of this type of probe can be long.

Biofilm monitoring can be obtained by on-line techniques in e.g. cooling systems, but for this application it seems useless, as biofilm formation is inevitable. The relevant issue is to develop a corrosion probe sensitive to MIC, e.g. by placing it in the high risk areas or giving the sensor a geometric susceptibility towards MIC.

Uniform corrosion is easy to monitor and if conditions do not change, predictable design lives can be calculated for a construction. More difficult are time depending changes of mechanism, or localised corrosion attacks appearing in a more stochastically manner. Melchers [10] has tried to model the growth of maximum pit depth in marine media (figure 8) illustrating that this process may go through various phases, where the corrosion pit develops at different pace. The only certain monitoring of localised corrosion available is weight loss and visual inspection by coupons, but efforts to overcome this problem have improved the detection of localised corrosion by both electrochemical techniques (e.g. electrochemical noise, advanced data analysis) and ER (size and shape of sensors, advanced data analysis).

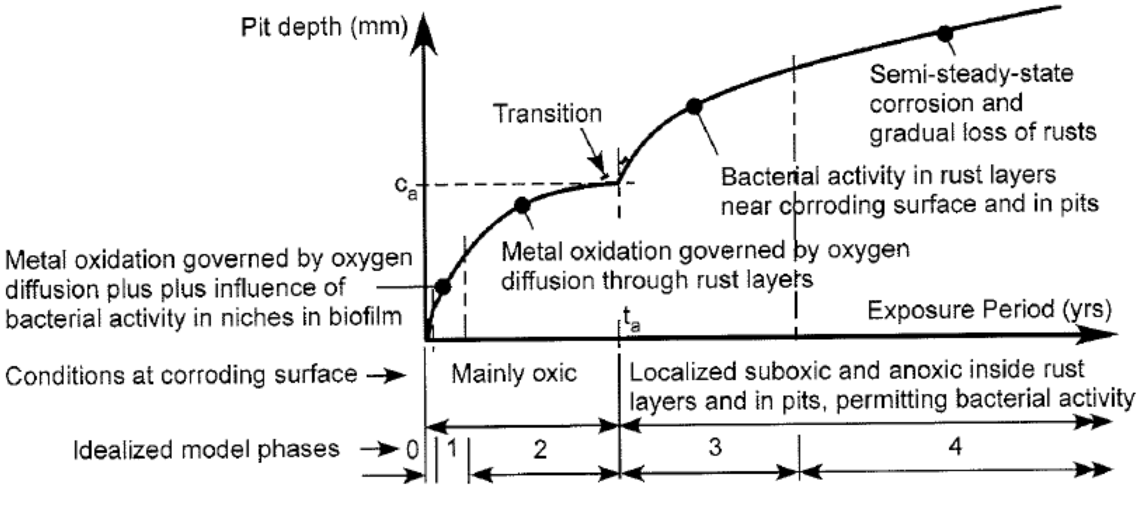

Figure 8. Idealised model for growth in maximum pit depth as a function of exposure period, with brief summaries of rate controlling mechanism for each phase [10]

4.2 Monitoring corrosion fatigue

To our knowledge there is no simple approach to this issue, but an evaluation must be based on predicting crack initiation as well as crack propagation. If corrosion is on-going there is in principle no fatigue limit, and for corroded and pitted surfaces crack initiation may be easier. This condition is often only taken into account by the choice of SN curve, but neither steel in air, freely corroding in sea water, nor CP protected are really adequate models for the partially closed compartment inside of foundations.

To evaluate whether the structural strength is at risk, finite element modelling or fracture mechanics may be applied, but this modelling requires a large number of parameters that may be difficult to estimate, if the conditions have changed due to different loads, corrosion or e.g. grout setting. The general structural strength of e.g. the TP wall may not require measurements for adjustment of the model, but unknown factors such as e.g. the actual friction coefficients between steel and grout and changed loads in critical areas like welds are of relevance for risk assessment. In this relation stress monitoring by strain gauges may be a useful tool to verify the models and the choice of parameters used as input. Figure 9 shows strain gauge sensors mounted at bracket detail.

Figure 9. Strain gauge sensors close to bracket.
MPI has also been conducted to check for cracks at welds.

By comparison with stresses in e.g. the TP wall the stress concentration factor valid for a specific detail can be determined. With sufficient data measured under various wind loads, a credible prediction of future behaviour may be modelled.

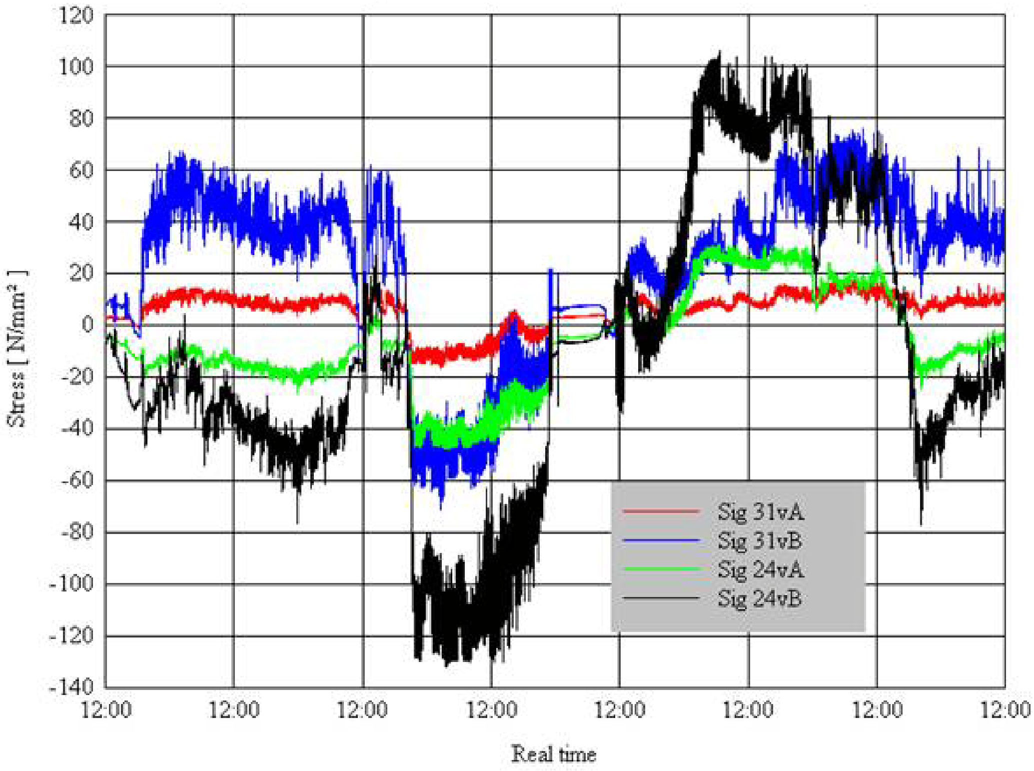

Figure 10. Example of strain gauge measurement close to two individual brackets in the same foundation, monitored one week in October 2010. *A* refers to horizontal sensors (red and green); *B* refers to vertical sensors (blue and black).

Figure 10 shows an example of on-line monitoring of stresses during an October week for two brackets. It appears that the stress variation in the horizontal direction is quite low compared to the variation in the vertical direction. Furthermore both high frequency - low amplitude events as well as low frequency - high amplitude events appear. The latter was concurrent with a change of wind direction. The results can - combined with inspections and records on turbine operation - facilitate the continuous risk evaluation.

An on-going project, CORFAT [11], has focused on applying acoustic emission measurements (AEM) for corrosion fatigue monitoring. In this project the intention is to utilise AEM for both active corrosion and active crack growth monitoring, and the focus is e.g. ballast tanks of ships. This approach could also in future be implemented for turbine foundations.

5 Outlooks

Experience from inspection and monitoring campaigns increases our understanding of the conditions under which wind turbine foundations must function. The vision is that the knowledge gained through the first decade, should be integrated in future designs. For new installations better sealing and J-tube designs are applied and corrosion protective coatings installed also internally. The corrosion conditions in many existing monopile foundations are not according to the original design, but by the help of inspections the consequences can be evaluated and the necessary countermeasures taken. These will have to depend on the condition of the turbine foundation, the prevailing corrosion mechanism, and expected design service life. Furthermore identification of critical risks such as e.g. penetration of J-tube wall or cracks at weld details should be prioritised. In any case a choice must be made, if options are available for repair or if thorough monitoring or frequent inspections can provide the necessary warning capacity.

Today corrosion inspections inside monopile foundations are based on application of well proven NDT methods, but as the requirements for better evaluation increases and new needs appear – e.g. better access to submerged and mud zones - innovation is also necessary in this field. Furthermore we strongly advocate that corrosion monitoring should be installed at the time of construction. It is a minimum effort to install coupons, which can later be retrieved during an inspection and help estimating directly the actual corrosion rates and morphology. Standard on-line techniques like ER or galvanic probes for oxygen warning are used in many other similar systems by remote access. The use of on-line real time monitoring of corrosion rates and intelligent fatigue detection requires a more visionary approach, but it is a question of priority.

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