

Corrosion Data from Offshore Wind Turbines - A Case Study

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ABSTRACT

This paper presents the results of a case study regarding corrosion data from 14 No. internal wind turbine structures within the flooded sections. The study analyzed 342 No. test coupons used to determine the corrosion rates within different locations within the monopiles under the air tight deck over a period of several years and timescales. Coupons were inserted below the air tight deck (also referred to the gas tight floor) at various elevations from top in the atmospheric region to the seabed. The coupons were carefully removed and treated to avoid further corrosion occurring, cleaned and weighed. Corrosion rates were established from this and further analysis of pitting rates were carried out. The results were compared to published literature and standards.

Keywords: Marine, corrosion rates, corrosion coupons, wind-turbine, internal, flooded, pitting rates

INTRODUCTION

In the UK a huge effort was made in the mid to late 2000's to minimize carbon emissions and the country had seen a rapid increase in wind-turbine generators being installed onshore and increasingly in offshore waters, nearly 2000 were operating in September 2018 and many more are expected in the coming decades.¹ One operator took the challenge to install a number of wind-turbines in the southern sector of the North Sea, just off the coast of south east England. These wind-turbines are constructed using the monopile foundation type principle.

Whereas great strides have been made by the corrosion industry to coat the upper sections internally and externally, one area often overlooked is the "sealed" compartment under the air tight hatch floor between the transition piece (TP) and monopile foundation, where a monopile structure is left flooded

with seawater, as shown in figure 1. The corrosion industry has reported on misgivings in this section of the monopile and much discussion was reported in the early 2010's.^{2,3}

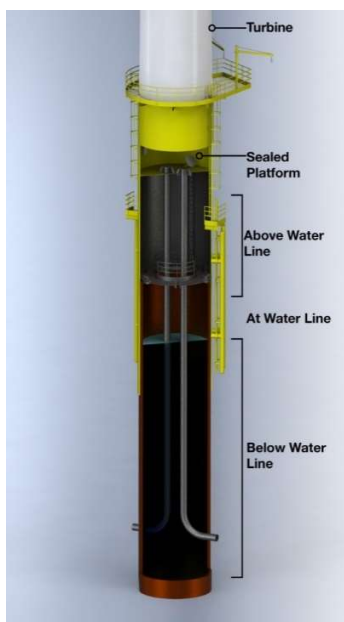


Figure 1: Typical Monopile structure Cut-through

The owner/ operator of the wind-turbine field, which is the subject of this paper, carried out an initial assessment on two structures below the sealed platform or airtight deck around the same era other operators were finding unexpected conditions in this zone. On seeing the conditions, the operator wanted a further understanding of how concerned they should be on the corrosion risk and whether any remedial works were necessary. It should be noted at this point that published mechanical fatigue curves at the time, relied on one of two curves in seawater, corroding and non-corroding (i.e. in the case of submerged conditions this would be for example with or without cathodic protection). Having established the internal monopile was corroding, with no cathodic protection, the owner wanted a better understanding of the extent of corrosion that was occurring. Subsequent to this study, further improvements to the design standards have been implemented with lessons learned based on this and other studies carried out by a number of windfarm owner/ operators.^{4,5,6}

The windfarm was installed in approximately 30 m of seawater. At the time of the initial assessment, the windfarm was completed having being 4 years in construction and the study to assess the conditions inside the monopile was performed over 2 years.

Corrosion coupons were primary used to determine the rates of corrosion below the gas tight floor in the atmospheric zone, in the submerged section and on the installation/ inspection deck below the gas tight floor.

Historical Data

Whereas general corrosion rates are important, pitting corrosion rates are particularly important in a marine environment as they can have an impact on the structure fatigue life. As part of the work scope a literature review was undertaken. It was clear the effect of pitting has not necessarily been a concern of submerged structures given that offshore engineered steel structures are normally coated and/ or receive levels of cathodic protection (CP). The other aspect to consider with pitting of carbon steels is that the mechanism is not necessarily as pronounced or directed as would be considered for those metals that generally suffer from extreme pitting, for example stainless steels, as a result of a local breakdown of the protective layer generally formed by the passivation film build-up on the metallic surface. Carbon steel

doesn't have this protective film and measuring pitting on carbon steel becomes more of an art than science.

There is a considerable amount of historical information on the pitting of mild steel but there are not many recent papers or publications on the subject.

Pitting corrosion rates are subject to considerable degree of variation with a mean maximum pit depth corrosion rate ranging between 0.23 to 0.47 mm per year where the mean corrosion rate maybe only 0.10 to 0.12 mm per year i.e. 2 to 4 times as much.

BS⁽¹⁾ 6349 Part 1 had been a useful standard for corrosion rates but has been replaced with BS 6349-1-4:2013, whilst EN⁽²⁾ 12500 which referred to atmospheric conditions, has been replaced by EN ISO⁽³⁾ 9223, EN ISO 9224, EN ISO 9225 and EN ISO 9226. ^{7,8,9,10,11,12,13}

The guidance given in DNV⁽⁴⁾-OS-J101 would be applicable to offshore windfarms the guidance given in EN 1993-5 and EN ISO 9223, whilst applicable to marine structures is not strictly applicable to offshore windfarms particularly the internal surfaces due to the slightly different environmental exposure conditions. DNV-OS-J101 that was used a guide for the wind industry, also has been replaced with DNVGL-RP-0416. ^{14,15}

It should be noted that the corrosion rates given in the various standards are typical general marine corrosion rates and do not reflect the corrosion rates that may be experienced on offshore windfarms particularly the internal surfaces due to the slightly different environmental exposure conditions. These also include accelerated corrosion conditions e.g. galvanic corrosion at steel in water to steel in concrete interfaces, relatively high humidity levels, locations where microbial induced corrosion (MIC) may occur and there is a risk of accelerated low water corrosion (ALWC) or where there is a risk of preferential weld corrosion (PWC).

In such situations accelerated corrosion rates in the region of 1 to 2 mm per year would not be untypical.

The corrosion rates given in the various standards for different zones are summarized on Table 1.

Table 1
Typical Published Corrosion Rates of Mild Steel Based Upon Current Standards

Standard	DNVGL-RP-0416	DNV-OS-J101	BS 6349 Part 1 (pre 2013)	BS 6349 Part 1 (pre 2013)	EN 1993-5	EN ISO 9223	EN 12500
Area	Corrosion Rate mm/ y	Corrosion Rate mm/ y	Mean Corrosion Rate mm/ y	Pitting Corrosion Rate mm/ y	Mean Corrosion Rate mm/ y	Mean Corrosion Rate mm/yr	Not Given
Atmospheric Zone	0.10	0.10	0.04	0.10	Not Given	0.08 to 0.20	0.050 to 0.080
Splash Zone External	(temperate) 0.30	0.30	0.08	0.17	0.076 - 0.11	Not Given	NA
Splash Zone Internal	(temperate) 0.10	0.15	Not Given	Not Given	Not Given	Not Given	NA

⁽¹⁾ British Standard (BS), 389 Chiswick High Road, London, W4 4AL, UK

⁽²⁾ European Standard (Euro Norm) (EU), Central Secretariat: rue de Stassart, 36 B-1050 Brussels, Belgium

⁽³⁾ International Standard (ISO), Case postale 56, CH-1211, Geneva 20, Switzerland

⁽⁴⁾ Det Norske Veritas (DNV). now known as DNV GL, Veritasveien 11363 Høvik, Norway

Standard	DNVGL-RP-0416	DNV-OS-J101	BS 6349 Part 1 (pre 2013)	BS 6349 Part 1 (pre 2013)	EN 1993-5	EN ISO 9223	EN 12500
Area	Corrosion Rate mm/ y	Corrosion Rate mm/ y	Mean Corrosion Rate mm/ y	Pitting Corrosion Rate mm/ y	Mean Corrosion Rate mm/ y	Mean Corrosion Rate mm/yr	Not Given
Tidal Zone External	Not Given	0.30	0.04	0.10	0.035 – 0.05	Not Given	NA
Tidal Zone Internal	Not Given	0.15	Not Given	Not Given	Not Given	Not Given	NA
Inter Tidal Low Water Zone External	Not Given	0.30	0.08	0.17	0.035 – 0.05	Not Given	NA
Inter Tidal Low Water Zone Internal	Not Given	0.15	Not Given	Not Given	Not Given	Not Given	NA
Continuous Seawater Immersion zone	0.10	0.10	0.04	0.13	0.035 – 0.05	Not Given	NA
Below seabed level in contact with soil	0.10 Only 1-2 m depth	0.10	0.015	0.015	0.035 – 0.05	Not Given	NA
Inside Flooded brace members	0.10	-	-	-	-	--	-

Pitting

Melchers has published papers on measurements of pit depths on mild steel in marine environments. Melchers quotes information from a study carried out by Blekkenhorst et al, where tests had been carried out on a number of different steel grades in a marine environment to determine the variation in maximum pit depth with time. Blekkenhorst et al used a number of novel steel grades and typical commercially available steel grades. The data on 13 commercially available steel grades of maximum pit depth (MPD) over a 2.6, 4.2 and 7 year period is summarised on Table 2. The mean maximum pit depth after 2.6 years was 0.59 mm, after 4 years it was 1.86 mm and after 7 years 2.64 mm. In terms of corrosion rate of the maximum pit depth the mean corrosion rate after 2.6 years was 0.23 mm per year, after 4.2 years it was 0.47 mm per year and after 7 years it was 0.37 mm per year. ^{16,17,18}

Blekkenhorst et al in their studies for unalloyed alloy mild steels recorded a mean corrosion rate over a 4 year period of 0.11 to 0.12 mm per year. The corrosion rate of the steels varied with alloying content and a maximum corrosion rate of 0.16 mm per year was recorded over a 7 year period with a minimum corrosion rate of 0.06 mm per year.

Pit depths up to 8 times the depth of the general corrosion rate have been reported for mild steel in a marine environment by Melchers. ¹⁶ Melchers provides a detailed review of the pitting process and differentiates between micro pits which grow rapidly and then cease growing after reaching depths of 0.1 to 0.2mm and macro pits which are slightly broader pits.

Table 2
Maximum pit depth (MPD) predicted for area of 1m² after various exposure times: for conventional steels Extracted from a Paper by Blekkenhorst ¹⁸

Commercially Available Steel Designation	Maximum Pit Depth 2.6 Years mm	Maximum Pit Depth 4.0 Years mm	Maximum Pit Depth 7.2 Years mm
I1	0.75	2.52	2.85
I2	0.73	1.49	1.89
I3	0.55	2.24	4.18
I4	0.39	1.51	2.68
I5	-		
I6	-		
I7	0.48	0.72	1.27
I8	0.47	2.08	1.76
I9	0.59	1.93	3.33
I10	0.53	2.17	5.92
I11	0.48	1.57	1.63
I12	0.48	2.38	2.18
I13	0.83	1.88	1.99
I14	0.75	1.82	2.85
I15	1.14	1.87	1.81
Mean Max Pit Depth (mm)	0.59	1.86	2.64
Standard Deviation Max Pit Depth (mm)	+/- 0.04	+/-0.19	+/-1.49
Mean Max Pit Depth Corrosion Rate (mm per y)	0.23	0.47	0.37

EXPERIMENTAL PROCEDURE

- Corrosion coupons were placed and subsequently replaced in the submerged zone of the monopiles at varying depths, namely Elevation Levels (EL), EL -1.5m, EL -13m and EL -27m. All levels are with respect to chart datum. The positions were marked from the access ladder as the reference point in either the 6 o'clock or 12 o'clock position. (Generally the 6 o'clock position).
- A further six coupons were placed in the atmospheric (in air) zone of the confined space. One coupon was placed at the very top of the confined space EL +9m, one coupon half way down the confined airspace EL +7m, two at the walkway EL +5m and two below the walkway at EL +3.5m all with respect to chart datum.
- Having removed the coupons these were photographed in-situ, dried, and packaged in inhibited plastic bags and transported onshore