Postprint of: Orlikowski J., Szociński M., Żakowski K., Igliński P., Domańska K., Darowicki K., Actual field corrosion rate of offshore structures in the Baltic Sea along depth profile from water surface to sea bed, OCEAN ENGINEERING Vol. 265 (2022), 112545, DOI: 10.1016/j.oceaneng.2022.112545

Actual field corrosion rate of offshore structures in the Baltic Sea along depth profile from water surface to sea bed

Juliusz Orlikowski[a)], Michał Szociński[a)*], Krzysztof Żakowski[a)], Piotr Igliński[b)], Kinga Domańska[b)], Kazimierz Darowicki[a)]

[a] Department of Electrochemistry, Corrosion and Materials Engineering, Faculty of Chemistry, Gdańsk University of Technology, G. Narutowicza Str. 11/12, 80-233 Gdańsk, POLAND,

[b] LOTOS Petrobaltic S.A., Stary Dwór Str. 9, 80-758 Gdańsk, POLAND

Abstract

The paper presents the results of field electrochemical investigations on the corrosion rate of carbon steel in seawater of the Baltic Sea at the location of the Baltic Beta production rig. The measurements were conducted throughout the year in seawater at different depths from the sea surface to the sea bed (about 75 m). The results revealed corrosion aggressiveness of the seawater along the entire depth profile. There was no multiple decrease in the corrosion rate of carbon steel at deeper levels (below 15 m), which had been observed in the literature reporting the investigations in the seas and oceans of higher salinity (3.5%) than southern Baltic Sea (about 0.8%). A model for monitoring water physico-chemical parameters along a depth profile showed the presence of a substantial amount of oxygen far below the sea surface, which translated into high corrosion aggressiveness of the Baltic seawater. Throughout the year corrosion rate is higher than 0.8 mm/year at the sea surface and even 0.4 mm/year at the sea bed. Presented results can constitute a guideline for the design of the anticorrosion protection systems for offshore wind farms or oil and gas production platforms in the Baltic Sea region.

*Corresponding author. Phone: +48 58 348-63-96 Fax: +48 58 347-10-92
E-mail: micszoci@pg.edu.pl

Keywords: Baltic Sea; corrosion aggressiveness of water; offshore wind farms; offshore oil production platforms; corrosion depth profile

1. Introduction

The Baltic Sea is a large water reservoir, the chemical composition of which differs significantly from ocean water (Hakanson and Bryhn, 2008). Baltic seawater contains much fewer inorganic salts due to poor water exchange with the North Sea via the narrow Danish straits and due to a substantial inflow of sweet water from the surrounding rivers (Hakanson and Bryhn, 2008). The Baltic Sea is a very convenient localization for wind farms, because of the relatively low depths of the sea allowing building of the farms at distant offshore locations, as well as oil and gas platforms (List of offshore wind farms in the Baltic Sea, 2022). This asset is confirmed by the onset of new energetic investments in the Baltic Sea region. Building of the wind farms and oil production platforms requires suitable anticorrosion protection, especially because of very limited possibilities for future maintenance and repair (submerged zones). Applied anticorrosion protection technology should be effective throughout most of the lifetime of hydrotechnical structures. To achieve this goal, corrosion aggressiveness for the submerged structures must be precisely recognized (Khodabux et al., 2020).

In general, corrosion rate in seawater depends on many factors: water temperature (an increase in temperature is accompanied by higher kinetics of corrosion processes – corrosion rate increases) (Porte, 1967), the content of inorganic salts in water (presence of more corrosive zone depending on salt content) (Heldtberg et al., 2004), oxygen content in water (lower oxygen content enhances diffusion control over corrosion process and corrosion rate decreases) (Porte, 1967; Nevshupa et al., 2018), the erosive impact of water causing a local increase in oxygenation and primarily the removal of the corrosion products which limit the corrosion rate, presence of aerobic and anaerobic bacteria imposing an additional risk of microbiological corrosion (Bale et al., 1997; Barnes et al., 1998; Dick et al., 2013). The influence of solar radiation on the corrosion rate of cathodically protected carbon steel in shallow seawater was investigated by Benedetti and co-workers (Benedetti et al., 2009). The evaluation of the impact of particular water components on the corrosion rate is a very difficult task and there are attempts to employ artificial neural networks to solve that problem (Paul, 2012).

In principle, corrosion risk in seawater is divided into a few zones (American Bureau of Shipping, 2018). The first one is a splash zone, in which the structure experiences periodical contact with seawater. It is the region with the highest corrosion rate due to water erosive impact on formed corrosion products (Refait et al., 2020). The next is a tidal zone where corrosion risk is lower (periodical mechanical water impact on a structure). A permanent immersion zone (water column zone) is characterized by the corrosion rate 5-times lower than the splash zone. The deepest zones include a sea bed zone with a much lower corrosion rate (oxygen deficit) and a marine sediment zone with the lowest corrosion rate (Chen et al., 2020). The corrosion rate of carbon steel was evaluated in detail for the aforementioned zones in the Atlantic Ocean (Yan et al., 2019). Corrosivity of particular zones was also addressed regarding the application of protective coatings (Lopez-Ortega et al., 2019; Det Norske Veritas AS, 2015). The literature provides data on a detailed analysis of corrosion risk along the depth profile of the Atlantic Ocean, including significant depths (Khodabux et al., 2020; Venkatesan et al., 2002; Imbert et al., 1999; Massi et al., 2019). Haynes et al. revealed that in deep regions oxygen content in water was 3 ppm, which suggests that corrosion with oxygen depolarization can still occur at high depths (Haynes, 1967). The investigations were also conducted in deep ocean regions, for instance in the geothermal water release zone (Lavaleye et al., 2014).

The results of investigations on the corrosion rate of steel in seawater of the Baltic Sea are available in the literature. Aromaa and Forsén carried out long-term exposure of the corrosion coupons placed in the vicinity of the sea surface in the Gulf of Finland (Aromaa and Forsen, 2016). Żakowski et al. reported very diversified water aggressiveness near the river mouths due to big changes in salinity (Żakowski et al., 2014). Nevertheless, there is a lack of information on the Baltic seawater corrosion aggressiveness at different depths of immersion of the hydrotechnical structures, on a seasonal basis.

The aim of this paper is the evaluation of the corrosion rate of carbon steel based on electrochemical measurements performed in the seawater at different depths from the sea surface to the sea bed. The results of the investigations will facilitate the proper design of the anticorrosion protection systems for offshore wind farms or oil and gas platforms in the Baltic Sea region.

2. Material and methods

A comparative analysis employed the data from an eco-hydrodynamic numerical model (Ołdakowski et al., 2005; Jędrasik and Kowalewski, 2019). The ProDeMo (Production and Destruction of Organic Matter Model), a 3D coupled hydrodynamic-ecological model, was elaborated and applied to the whole Baltic Sea and the subregion of the Gulf of Gdansk. The model generates numerous data related to the physical, chemical, and biological composition of water from the entire area of the Baltic Sea. More importantly, the model also provides seawater parameters along a depth profile, which is valuable information allowing verification of the results of electrochemical measurements. The model consists of two modules – hydrodynamic M3D_UG and ecosystem ProDeMo ones. It works in a pre-operational mode over the southern Baltic Sea, Gdansk Bay, and Pomeranian Bay. 60-hour forecasts engulf surface currents, temperature, and seawater salinity. Moreover, the prognoses concern biogenic salts, including nitrates, ammonia, phosphates, and silicates, as well as total nitrogen and phosphorus, oxygen concentration in seawater and biomass of phytoplankton. The results of prognoses are archived and they were taken advantage of in this paper. The eco-hydrodynamic model is verified with the data on seawater level, temperature, and salinity, which are received from the measurement stations (the buoys) distributed in various places over the Baltic Sea. The investigations presented in this paper were carried out at the location of one of these measurement-verification stations, which ensures relatively low error in conducted studies. Archive and prognosis data from the model are available at http://model.ocean.univ.gda.pl/php/frame.php?area=Baltyk.

The electrochemical measurements were conducted with an electrochemical workstation Gamry Reference 600. The following tests were carried out:

- Linear Polarization Resistance (LPR) measurements – analysis of the corrosion rate of carbon steel. Potentiodynamic measurement was performed for the following parameters: potential scan rate 0.125 mV/s, polarization range ±20 mV with respect to OCP (open circuit potential),
- Measurement of Tafel curves – analysis of Tafel coefficients regarding changes of the control over corrosion processes depending on oxygen content in water. Potentiodynamic measurement was performed for the following parameters: potential scan rate 1 mV/s, polarization range ±250 mV with respect to OCP,
- Electrochemical Impedance Spectroscopy (EIS) measurements – analysis of the electrolyte resistance changes regarding the variation of water salinity. The measurement frequency range was from 5 Hz to 0.01 Hz and the amplitude of ac perturbation signal was 10 mV.

The measurements were conducted using a dedicated three-electrode sensor (the working, reference and auxiliary electrode, each of them made of S235JR steel, the surface area of each electrode was 0.5 cm^2) submerged on a long cable from a deck of the Baltic Beta platform. The sensor was gradually dropped towards the sea bed (75 m) with periodical stops for the execution of the measurements at precisely determined depths. The production rig was located 60 km offshore at the Baltic Sea with the following geographical coordinates (55 28.82'N; 18 10.77'E). On this production rig, the modernized cathodic protection system has been in continuous operation since 2009 (Żakowski et al., 2020).

Fig. 1 illustrates the measurement location and position. The selection of the measurement cable ensured the limitation of its resistance (cross-section 2.5 mm^2) and minimization of interferences (shielded insulation).

a) b)

c)

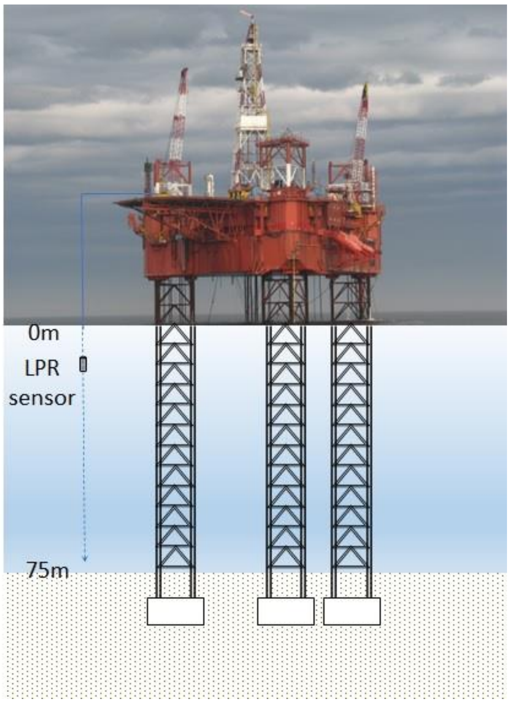


Fig. 1. The measurement location (a), position (b), and scheme of sensor orientation with respect to the Baltic Beta production rig.

The field measurements were preceded by a series of laboratory measurements in seawater aimed at evaluating the influence of the long cable (100 m) on the measurement error. They revealed no significant measurement error in the case of the LPR and Tafel curves techniques (less than 2%). For EIS, the error higher than 10% was identified in the frequency range above 10 kHz. That is why it was decided to execute the impedance measurements between 10 kHz and 0.01 Hz.

The field measurements were conducted on three dates throughout the year to evaluate the corrosion rate of carbon steel along a depth profile depending on water temperature and its seasonal chemical composition. The measurement dates were as follows:

- 22.11.2020 – autumn and spring conditions,
- 19.04.2021 – winter conditions,
- 3.07.2021 – summer conditions.

These measurement dates do not fully correspond to the calendar seasons of the year, which results from a delayed reaction of seawater temperature to seasonal changes in air temperature. The selection of the measurement dates was based on data from the eco-hydrodynamic model (Ołdakowski et al., 2005; Jędrasik and Kowalewski, 2019).

The measurements were carried out at depth intervals of 10-15 m starting from the sea surface down to the sea bed at 75 m.

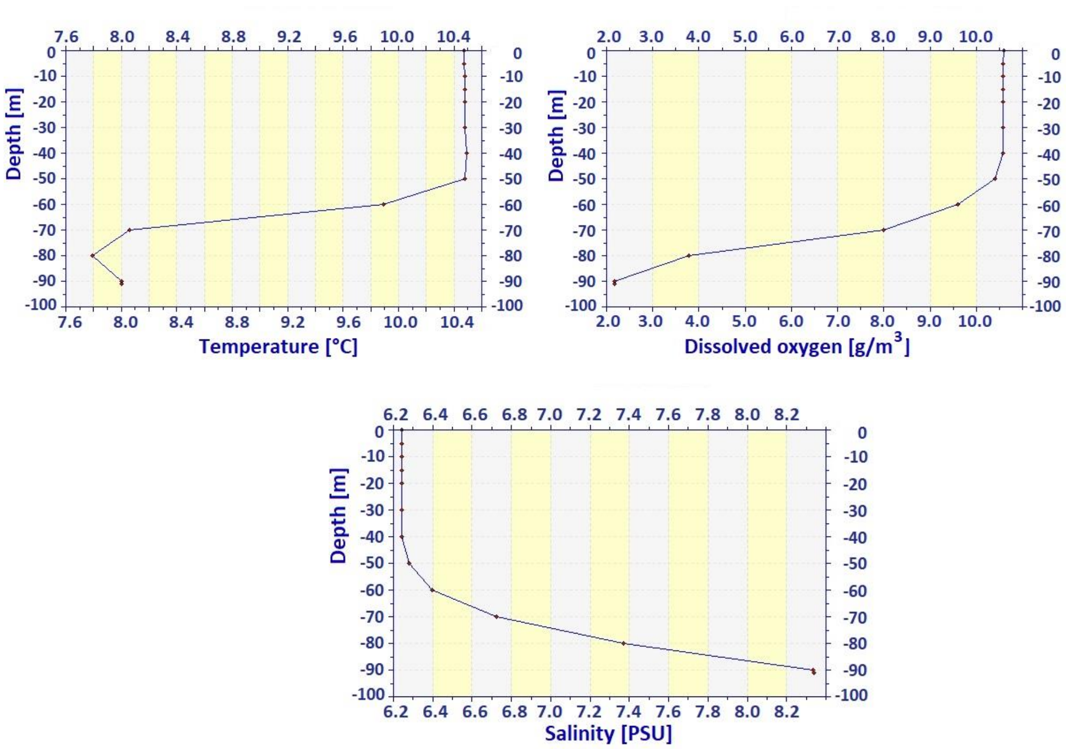
The investigation also involved corrosion rate measurement with a gravimetric method employing corrosion coupons. 3 coupons were mounted to the steel structure of the production rig at the depth of 0.5 m below the sea surface. The coupons were made of S235JR steel, which is the construction material of the Baltic Beta production rig. They were in the form of plates having the following dimensions: 35 cm x 10 cm x 0.2 cm (thickness). Before exposure, the coupons were ground with abrasive paper of 120 gradation and degreased with acetone.

3. Results and discussion

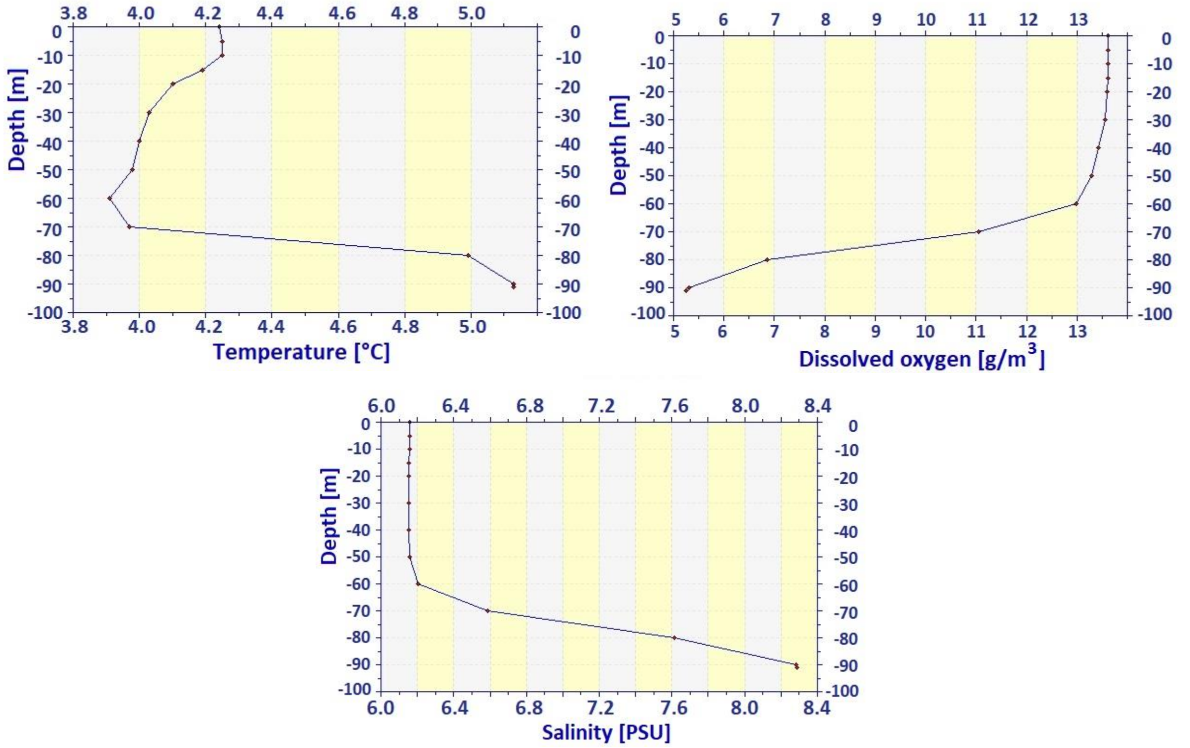
3.1 Physical properties of the Baltic seawater

Fig. 2 presents basic data on the physical properties of the seawater based on the data from the eco-hydrodynamic model.

a)

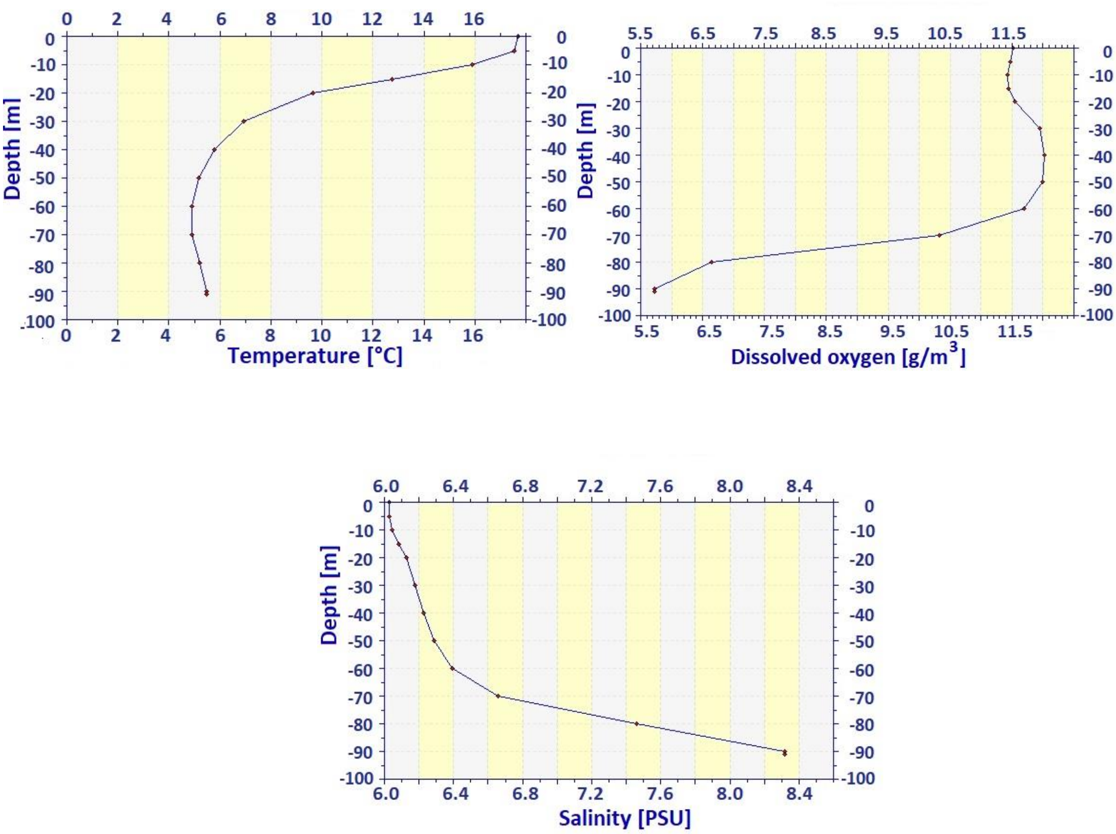


b)



Depth [m]
Temperature [°C]
Depth [m]
Dissolved oxygen [g/m^3]
Depth [m]
Salinity [PSU]

c)



Depth [m]
Temperature [°C]
Depth [m]
Dissolved oxygen [g/m^3]
Depth [m]
Salinity [PSU]

Fig. 2. Data on temperature, salinity, and oxygen content in water based on the eco-hydrodynamic model: (a) 22.11.2020, (b) 19.04.2021, (c) 03.07.2021.

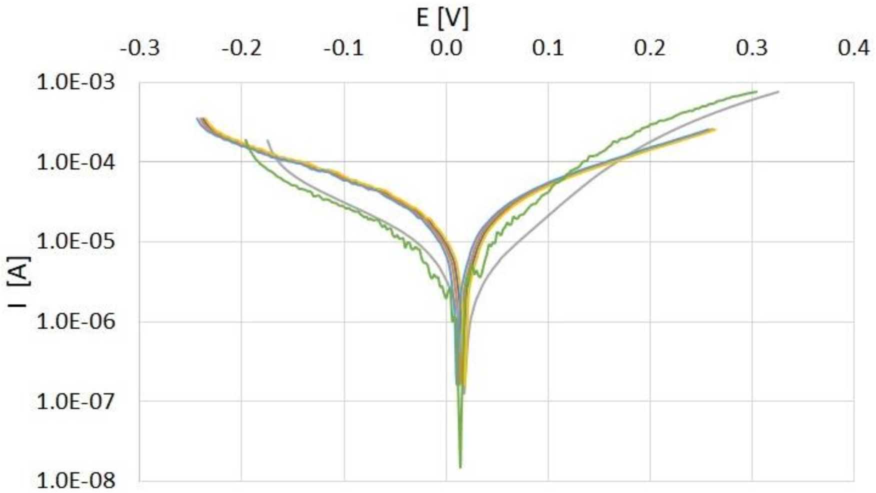
Presented data from the model engulf temperature, salinity, and oxygen content in water along a depth profile from the sea surface to the sea bed. It must be emphasized that the model data do not necessarily overlap with the actual data, nevertheless, they can be the basis for evaluation of corrosion aggressiveness of water. The data show that seawater in the Baltic Sea is characterized by relatively high oxygen content along a wide range of the depth profile, which indicates no significant diffusion limitations of the corrosion rate due to oxygen deficit. Results of the measurements reveal that oxygen deficit can occur only in autumn. This phenomenon is connected with hypoxia, which is a seasonal oxygen deficit near the sea bed of the Baltic Sea that has practically occurred since prehistoric times (Conley et al., 2009; Zillen et al., 2008). The main factors responsible for this effect are the meteorological conditions connected with wind direction and speed, which pushes oxygenated and more saline water from the North Sea towards the Baltic Sea. This water of higher specific gravity migrates to the regions close to the sea bed (higher salinity visible in Fig. 2). Initially it contains a significant amount of oxygen, however, during the periods of poor or no water exchange between the North Sea and the Baltic Sea there is oxygen depletion due to the biological processes. Horizontal exchange with sweet water is limited as a halocline occurs. Due to this barrier, there is the seasonal formation of a low-oxygen water layer in the vicinity of the sea bed, especially in deeper regions of the Baltic Sea (Conley et al., 2002).

An increase in salinity near the sea bed is not high, which suggests that it may not have a substantial impact on oxygen content and the corrosion rate of carbon steel. The investigations show a high water temperature gradient during the summertime, which can influence changes in corrosion rate along the depth profile.

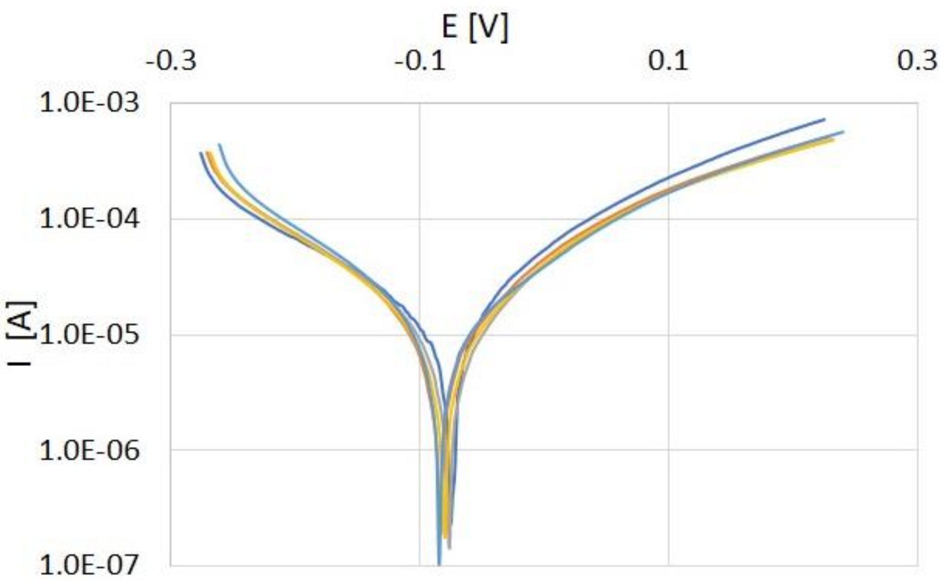
3.2 Results of electrochemical investigations

Fig. 3 presents the Tafel curves obtained during the electrochemical measurements conducted in the Baltic Sea at the platform location.

a)



b)



c)

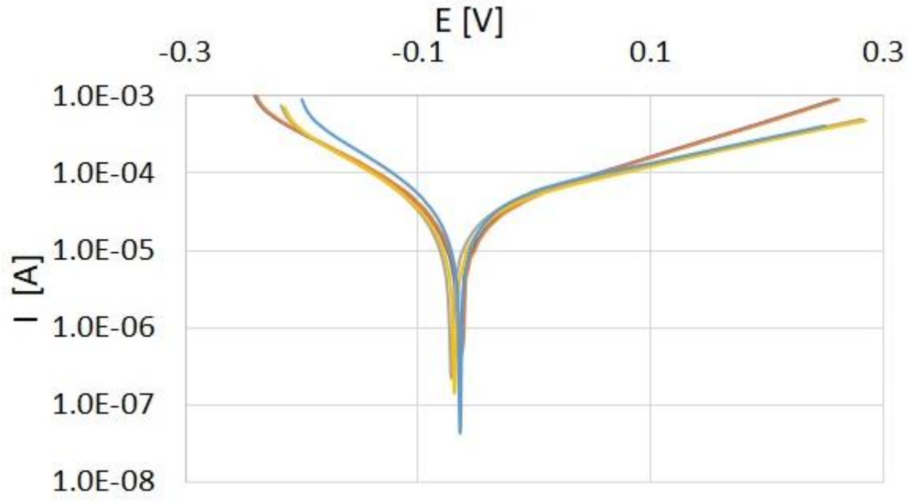


Fig. 3. Results of Tafel curves measurement along a depth profile: a) 22.11.2020, b) 19.04.2021, c) 3.07.2021. Depths: light blue – 0 m, dark blue – 15 m, orange – 30 m, yellow – 50 m, grey – 60 m, green – 75 m.

There is a high similarity in the courses of the potentiodynamic plots, indicating a similar corrosion rate of carbon steel along the entire depth profile. Significant differences occur only in the case of the measurements at 60 and 75 m, conducted in autumn. The results of a more detailed analysis of the Tafel curves are gathered in Tab. 1.

Tab. 1. Values of Tafel coefficients and corrosion rate calculated based on potentiodynamic measurements.

	22.11.2020			19.04.2021			03.07.2021		
Depth [m]	b_a [V]	b_k [V]	Vcorr [mm/y]	b_a [V]	b_k [V]	Vcorr [mm/y]	b_a [V]	b_k [V]	Vcorr [mm/y]
0	0.286	0.316	0.753	0.216	0.334	0.732	0.221	0.134	0.950
15	0.283	0.286	0.630	0.229	0.251	0.702	0.283	0.13	0.832
30	0.208	0.255	0.603	0.227	0.221	0.651	0.308	0.132	0.878
50	0.156	0.336	0.605	0.228	0.237	0.634	0.310	0.134	0.786
60	0.131	0.239	0.421	0.195	0.193	0.571	0.315	0.120	0.750
75	0.118	0.142	0.241	0.187	0.165	0.532	0.317	0.117	0.701

The Tafel coefficients exhibit high coherence for particular depth profiles, which means that the corrosion mechanism is similar in each case. One can notice differences in the measurements near the sea bed, especially on 22.11.2020, where a decrease in the Tafel coefficients is recorded, which can be evidence of a decreased level of oxygen in the water. Tab. 2 presents the values of electrolyte resistance determined based on EIS measurements (Narożny et al., 2017). This parameter provides information related to the content of various salts in water. The lower the electrolyte resistance, the higher concentration of salts in water. This dependence also holds for water resistivity changes upon different salt content. Thus, these two parameters are correlated as far as seawater salinity investigation is concerned.

Tab. 2. Electrolyte resistance along a depth profile determined via EIS measurements.

	22.11.2020	19.04.2021	03.07.2021
Depth [m]	Electrolyte resistance [Ω]		
0	75	94	70
15	105	109	94
30	104	109	103
50	78	109	109
60	75	109	109
75	69	77	77

The magnitude of electrolyte resistance can be associated with water salinity level and the presence of other factors contributing to an increase in water conductivity. The investigations (Tab. 2) revealed a decrease in electrolyte resistance near the sea surface and sea bed. The decrease in resistance in the vicinity of the sea bed is in accordance with the results from the eco-hydrodynamic model, which predicts an increase in seawater salinity. The reasons for low electrolyte resistance in the surface zone remain unknown.

Fig. 4 depicts the corrosion rate of carbon steel obtained using the LPR method.

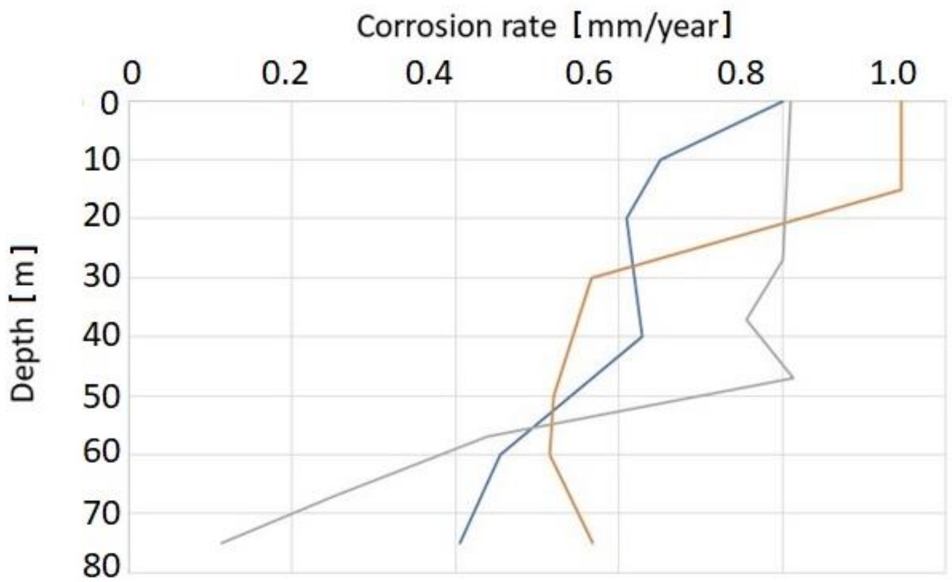


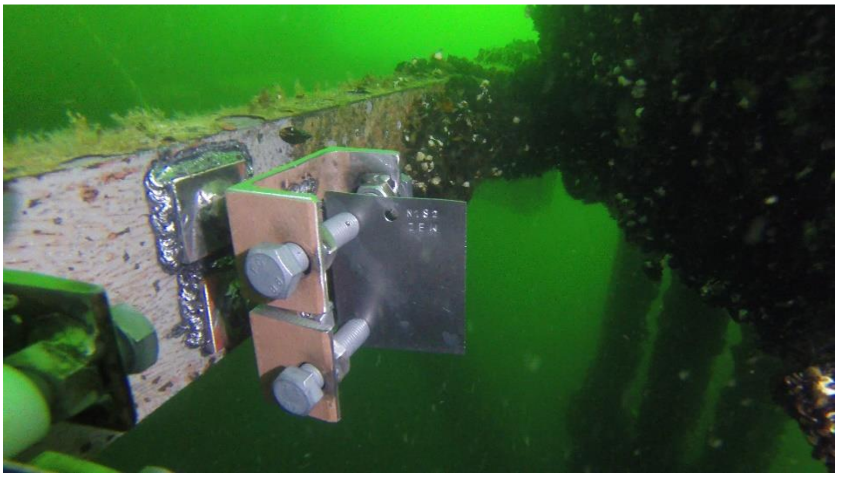
Fig. 4. Corrosion rate of carbon steel along a depth profile determined via LPR measurements: grey – 22.11.2020, blue 19.04.2021, orange – 19.07.2021.

The results show that the corrosion rate of carbon steel in the Baltic Sea is high and generally consistent with the data from the eco-hydrodynamic model. The highest corrosion rate (which is in accordance with the literature data) occurs at the sea surface and is equal to about 0.8-0.9 mm/year and then decreases to only 30% of the surface value in the tidal zone, which is a different result as compared to corrosion rate measurements in the other water reservoirs (Yan et al., 2019). As suggested in scientific literature, the corrosion rate values for carbon steel in a permanent immersion zone amount to 0.20-0.35 mm/year (Yan et al., 2019). A significant decrease in corrosion rate near the sea bed was identified only in autumn. The values of corrosion rate acquired via the LPR method are in high agreement with the ones determined based on the Tafel curves.

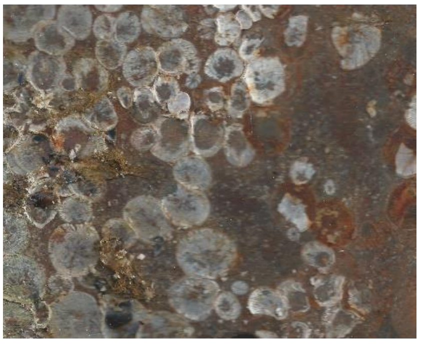
3.3 Results of corrosion rate investigations with coupon method

Presented results were verified with the gravimetric method employing corrosion coupons and non-destructive ultrasonic wall thickness measurements. Fig. 5a presents an underwater coupon exposure system, which was mounted to the steel structure of the production rig at the depth of 0.5 m below the sea surface. The condition of an exemplary corrosion coupon after 6-month exposure is depicted in Fig. 5b and Fig. 5c.

a)



b)



c)

Fig. 5. Underwater coupon exposure system mounted to production rig (a), condition of exemplary corrosion coupon after 6-month exposure: before cleaning (b) and after removal of corrosion products and biological deposits (c).

The exposure involved 3 corrosion coupons located directly below sea level, in the immersion zone. After retrieving, an inspection of the coupons revealed the presence of biological deposits (diatoms) and corrosion products on their surface (Fig. 5). In order to determine the corrosion rate, the coupons were cleaned and their mass was measured. Tab. 3 shows the corrosion rate of the coupons exposed in the immersion zone of the production rig.

Tab. 3. Corrosion rate of coupons exposed in immersion zone of the Baltic Beta production rig.

Coupon no.	Corrosion rate [mm/year]
1	0.376
2	0.335
3	0.356

The corrosion rate determined using the gravimetric measurements is lower than the one obtained with the LPR investigations. The reason is the inhibitive action of the organic deposits and corrosion products.

3.4 Results of non-destructive tests

Additionally, non-destructive ultrasonic wall thickness measurements were carried out on the submerged structure of the production rig. An exemplary report from such tests is presented in Tab. 4.

Tab. 4. Exemplary report from ultrasonic wall thickness measurements performed in immersion zone on the steel structure of the Baltic Beta production rig.

Ship's name: BALTIC BETA	Class Identity No. 680112		Report No. 38/16	
Structural member: CHORD No. 1 – BRACINGS CONNECTION				
Location of structure: LEG No. 1; BAY 15				
Description	Org. Thx. [mm]	Gauged [mm]	Diminution	
			[mm]	[%]
Vert. diagonal bracing VD1 plating:				
section D (casting) – read. 1	19.0	16.4	2.6	13.7
section D (casting) – read. 2	19.0	16.5	2.5	13.2
section D (casting) – read. 3	19.0	17.5	1.5	7.9
section D (casting) – read. 4	19.0	17.4	1.6	8.4
section E – read. 1	19.05	15.0	4.1	21.3
section E – read. 2	19.05	15.3	3.8	19.7
section E – read. 3	19.05	16.4	2.7	13.9
section E – read. 4	19.05	16.7	2.4	12.3
section F – read. 1	19.05	14.6	4.5	23.4
section F – read. 2	19.05	16.9	2.2	11.3
section F – read. 3	19.05	17.5	1.6	8.1
section F – read. 4	19.05	18.5	0.6	2.9
section G – read. 1	19.05	15.9	3.2	16.5
section G – read. 2	19.05	17.1	2.0	10.2
section G – read. 3	19.05	18.0	1.1	5.5
section G – read. 4	19.05	17.9	1.2	6.0

The investigations revealed the maximum corrosion loss of ca. 4.5 mm during 20 years of exposure. The corrosion rate was equal to 0.225 mm/year. During the initial exposure period, the corrosion rate was impeded by the presence of organic protective coatings applied on the legs of the production rig.

The novelty of the work, with respect to other data and papers available, is different from the expected corrosion risk of hydrotechnical structures. In most cases, the corrosion rate is believed to decrease significantly below the splash zone due to lower oxygen content in water. Moreover, oxygen is believed to be practically absent in water in deep regions. These observations are the basis for the design of anticorrosion protection for hydrotechnical structures. For instance, no organic coatings and significantly simplified cathodic protection systems are accepted in Baltic seawater at depths exceeding 15 m. The results of conducted studies indicate that the limitation of the anticorrosion protection measures in deep regions may be an incorrect approach in this case. Implementation of experience and experimental results acquired from other oceans and seas (with completely different chemical compositions) is not entirely correct. The uniqueness and novelty of performed investigations are also connected with the fact that the measurements were carried out on a real hydrotechnical structure, which is located at high depths of the Baltic Sea. Most of the literature data available so far originate from the measurement stations at the seashore. The presented findings can be key data for the design of anticorrosion protection of offshore wind farms, which soon are going to be built in the Baltic Sea.

The investigations have been conducted at one location in the Baltic Sea. Despite the evident correlation between corrosion rate and physico-chemical properties of seawater, one cannot exclude local deviations from the obtained results, especially during stormy weather.

4. Conclusions

The performed field investigations involved electrochemical, gravimetric, and non-destructive measurements to determine the corrosion rate of carbon steel in seawater of the Baltic Sea at the location of the Baltic Beta production rig. The obtained data were discussed with respect to the physico-chemical parameters of the Baltic seawater collected within the frame of the eco-hydrodynamic model. Accordingly, the following conclusions can be drawn:

– The investigations revealed that the corrosion rate of carbon steel in the Baltic seawater along the depth profile differed significantly from the corrosion rate in the water reservoirs of higher salinity and located in other climatic zones. Contrary to them, in the Baltic Sea, no multiple decrease in the corrosion rate of carbon steel was noticed along the water column due to high oxygen content, confirmed by the data from the eco-hydrodynamic model. For most time throughout the year, the corrosion rate is higher than 0.8 mm/year at the sea surface and 0.4 mm/year at the Baltic Sea bed.

- Analysis of the Tafel coefficients indicates no distinct changes in the corrosion mechanism at each depth. At every investigated level the corrosion process occurs with oxygen depolarization as a cathodic reaction.
- Differences in water salinity at various depths of the Baltic Sea are not big, which does not translate into a significant reduction in the corrosion rate in the sea bed zone.
- It was found that oxygen content decreases near the sea bed only in a seasonal way, which limits the corrosion rate at the sea bed from about 0.4 mm/year to 0.2 mm/year.
- From the obtained results it follows that in the future design of the hydrotechnical structures intended for submersion in the Baltic Sea, the anticorrosion protection technology (cathodic protection, protective coatings) should be selected in the way, which takes substantial corrosion risk along the entire depth profile into account.

In general, future work will focus on the analysis of the corrosion rate acquired from the coupon investigations, which are currently being conducted along the entire depth profile. Moreover, the emphasis will be put on changes in the corrosion rate in the vicinity of a sea bed due to significant fluctuations of oxygen content in water. Accordingly, the investigations will be carried out at higher depths as well as below the sea bed.

References

American Bureau of Shipping, 2018. ABS – 306: Guidance Notes On Cathodic Protection Of Offshore Structures, Spring, Texas.

Aromaa, J., Forsen, O., 2016. Factors affecting corrosion in Gulf of Finland brackish water. Int. J. Electrochem. Sci. article ID 3720280. http://dx.doi.org/10.1155/2016/3720280.

Bale, S.J., Goodman, K., Rochelle, P.A., Marchesi, J.R., Fry, J.C., Weightman, A.J., Parkes, R.J., 1997. *Desulfovibrio profundus* sp. nov., a novel barophilic sulfate-reducing bacterium from deep sediment layers in the Japan Sea. Int. J. Syst. Evol. Microbiol. 47, 515–521. https://doi.org/10.1099/00207713-47-2-515.

Barnes, S.P., Bradbrook, S.D., Cragg, B.A., Marchesi, J.R., Weightman, A.J, Fry, J.C., Parkes, R.J., 1998. Isolation of sulfate-reducing bacteria from deep sediment layers of the pacific ocean. Geomicrobiol. J. 15, 67-83. https://doi.org/10.1080/01490459809378066.

Benedetti, A., Magagnin, L., Passaretti, F., Chelossi, E., Faimali, M., Montesperelli, G., 2009. Cathodic protection of carbon steel in natural seawater: effect of sunlight radiation. Electrochim. Acta. 54, 6472–6478. doi:10.1016/j.electacta.2009.06.022.

Chen, Z., Xia, W., Yao, C., Lin, Z., Zhang, W., Li, W., 2020. Research on the metal corrosion process in the sea mud/seawater/atmosphere interface zone. Coatings. 10, 1219. doi:10.3390/coatings10121219.

Conley, D.J., Humborg, C., Rahm, L., Savchuk, O.P., Wulff, F., 2002. Hypoxia in the Baltic Sea and basin-scale changes in phosphorus biogeochemistry. Environ. Sci. Technol. 36, 5315-5320. https://doi.org/10.1021/es025763w.

Conley, D.J., Bjorck, S., Bonsdorff, E., Carstensen, J., Destouni, G., Gustafsson, B.G., Hietanen, S., Kortekaas, M., Kousa, H., Markus Meier, H.E., Muller-Karulis, B., Nordberg, K., Norkko, A., Nurnberg, G., Pitkanen, H., Rabalais, N.N., Rosenberg, R., Savchuk, O.P., Slomp, C.P., Voss, M., Wulff, F., Zillen, L., 2009. Hypoxia-related processes in the Baltic Sea. Environ. Sci. Technol. 43, 3412-3420. https://doi.org/10.1021/es802762a.

Det Norske Veritas AS, 2015. Recommended Practice DNVGL-RP-C302 Risk Based Corrosion Management.

Dick, G.J., Anantharaman, K., Baker, B.J., Li, M., Reed, D.C., Sheik, C.S., 2013. The microbiology of deep-sea hydrothermal vent plumes: ecological and biogeographic linkages to seafloor and water column habitats. Front. Microbiol. 4, article 124. https://doi.org/10.3389/fmicb.2013.00124.

Hakanson, L., Bryhn, A.C., 2008. Eutrophication in the Baltic Sea, Springer, Berlin, Heidelberg.

Haynes, W.S., Outline of an approach to a long range research, development and evaluation program on prevention of deterioration of materials of construction, as an appendix in Porte, H.A., 1967. The Effect of Environment on the Corrosion of Metals in Sea Water – A Literature Survey, U.S. Naval Civil Engineering Laboratory, Port Hueneme, California.

Heldtberg, M., MacLeod, I.D., Richards, V.L., 2004. Corrosion and cathodic protection of iron in seawater: a case study of the James Matthews (1841). Proceedings of Metal 2004. National Museum of Australia Canberra ACT. 75-87.

Imbert, C.A.C., Ragoonath, D., Lewis, W.G., 1999. Corrosion of offshore platforms off the south-east coast of Trinidad. WIJE. 21, 1-8.

Jędrasik, J., Kowalewski, M., 2019. Mean annual and seasonal circulation patterns and long-term variability of currents in the Baltic Sea. J. Mar. Syst. 193, 1-26. https://doi.org/10.1016/j.jmarsys.2018.12.011.

Khodabux, W., Causon, P., Brennan, F., 2020. Profiling corrosion rates for offshore wind turbines with depth in the North Sea. Energies. 13, 2518. doi:10.3390/en13102518.

Lavaleye, M., Morales, F.L., Duineveld, G., Verichev, S., de Jong, A., Boomsma, W., Smit, M., 2014. Study of deep sea corrosion near hydrothermal vents. Deployment of 5 x 37 construction materials for in-situ long-term exposure. Report from MIIP Project: Deep Corr On Site, Nederland Maritiem Land.

List of offshore wind farms in the Baltic Sea. https://en.wikipedia.org/wiki/List_of_offshore_wind_farms_in_the_Baltic_Sea (accessed 26 April 2022).

Lopez-Ortega, A., Bayon, R., Arana, J.L., 2019. Evaluation of protective coatings for high-corrosivity category atmospheres in offshore applications. Materials. 12, 1325. doi:10.3390/ma12081325.

Masi, G., Matteucci, F., Tacq, J., Balbo, A., 2019. State of the Art Study on Materials and Solutions against Corrosion in Offshore Structures, NeSSIE - North Sea Solutions for Innovation in Corrosion for Energy.

Narożny, M., Żakowski, K., Darowicki, K., 2017. Time evolution of electrochemical impedance spectra of cathodically protected steel in artificial seawater. Constr. Build. Mater. 154, 88–94. doi: 10.1016/j.conbuildmat.2017.07.191.

Nevshupa, R., Martinez, I., Ramos, S., Arredondo, A., 2018. The effect of environmental variables on early corrosion of high–strength low–alloy mooring steel immersed in seawater. Mar. Struct. 60, 226-240. https://doi.org/10.1016/j.marstruc.2018.04.003.

Ołdakowski, B., Kowalewski, M., Jedrasik, J., Szymelfenig, M., 2005. Ecohydrodynamic model of the Baltic Sea. Part 1. Description of the ProDeMo model. Oceanologia. 47, 477-516.

Paul, S., 2012. Modeling to study the effect of environmental parameters on corrosion of mild steel in seawater using neural network. Int. Sch. Res. Notices. article ID 487351. https://doi.org/10.5402/2012/487351.

Porte, H.A., 1967. The Effect of Environment on the Corrosion of Metals in Sea Water – A Literature Survey, U.S. Naval Civil Engineering Laboratory, Port Hueneme, California.

Refait, P., Grolleau, A-M., Jeannin, M. , Remazeilles, C., Sabot, R., 2020. Corrosion of carbon steel in marine environments: role of the corrosion product layer. Corros. Mater. Degrad. 1, 198–218. doi:10.3390/cmd1010010.

Venkatesan, R., Venkataswamy, M.A., Bhaskaran, T.A., Dwarakadasa, E.S., Ravindran, M., 2002. Corrosion of ferrous alloys in deep sea environments. Br. Corros. J. 37, 257-266. doi:10.1179/000705902225006633.

Yan, X., Wang, Y., Du, Q., Jiang, W., Shang, F., Li, R., 2019. Research progress on factors affecting oxygen corrosion and countermeasures in oilfield development. E3S Web Conf. 131, 01031. https://doi.org/10.1051/e3sconf/201913101031.

Żakowski, K., Narożny, M., Szociński, M., Darowicki, K., 2014. Influence of water salinity on corrosion risk - the case of the southern Baltic Sea coast. Environ. Monit. Assess. 186, 4871-4879. https://doi.org/10.1007/s10661-014-3744-3.

Żakowski, K., Iglinski, P., Orlikowski, J., Darowicki, K., Domanska, K., 2020. Modernized cathodic protection system for legs of the production rig – Evaluation during ten years of service. Ocean Eng. 218, 108074. https://doi.org/10.1016/j.oceaneng.2020.108074.

Zillen, L., Conley, D.J., Andren, T., Andren, E., Bjorck, S., 2008. Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change and human impact. Earth Sci. Rev. 91, 77-92. https://doi:10.1016/j.earscirev.2008.10.001.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Figure captions

Fig. 1. The measurement location (a), position (b), and scheme of sensor orientation with respect to the Baltic Beta production rig.

Fig. 2. Data on temperature, salinity, and oxygen content in water based on the eco-hydrodynamic model: (a) 22.11.2020, (b) 19.04.2021, (c) 03.07.2021.

Fig. 3. Results of Tafel curves measurement along a depth profile: a) 22.11.2020, b) 19.04.2021, c) 3.07.2021. Depths: light blue – 0 m, dark blue – 15 m, orange – 30 m, yellow – 50 m, grey – 60 m, green – 75 m.

Fig. 4. Corrosion rate of carbon steel along a depth profile determined via LPR measurements: grey – 22.11.2020, blue 19.04.2021, orange – 19.07.2021.

Fig. 5. Underwater coupon exposure system mounted to production rig (a), condition of exemplary corrosion coupon after 6-month exposure: before cleaning (b) and after removal of corrosion products and biological deposits (c).

Table captions

Tab. 1. Values of Tafel coefficients and corrosion rate calculated based on potentiodynamic measurements.

Tab. 2. Electrolyte resistance along a depth profile determined via EIS measurements.

Tab. 3. Corrosion rate of coupons exposed in immersion zone of the Baltic Beta production rig.

Tab. 4. Exemplary report from ultrasonic wall thickness measurements performed in immersion zone on the steel structure of the Baltic Beta production rig.