Probabilistic Assessment and Comparison of Scour Protections at Horns Rev 3 and Egmond aan Zee Offshore Wind Farms

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ABSTRACT: *Offshore wind foundations have seen a remarkable growth in over the last three decades. Up to date, this growth has been mainly registered in North Sea locations, where water depths do not exceed 30 m and monopile diameters typically range between 4 to 9 m. In these cases, scour phenomena can be a main reason for structural instability and fatigue induced damage, thus there is often a need to apply scour protection. Given the complexity and uncertainties of scour phenomena, the design of scour protection is mostly based on semi-empirical formulations. These often result in conservative design, which in turn leads to excessive costs when installing offshore wind foundations. To account for the uncertainty in scour protection design and to assess the reliability of existing solutions, recent developments have been made regarding the application of probabilistic based analysis, which aim to either quantify the protection's reliability or to derive the median stone size associated to a target value for the probability of failure. However, there are few to almost no case studies reported in the literature concerning the reliability analysis of scour protection for offshore wind monopiles. Hence there is a need to extend this probabilistic analysis to a broad range of locations, to further improve their application for both design and median stone size optimization purposes. This research provides a study on the probabilities of failure at Horns Rev 3 and Egmond aan Zee offshore wind farms. The results show that the values of the probability of failure of a scour protection for the same design criterion can vary significantly depending on the site-specific conditions. Variations can be of two orders of magnitude, from 10^{-4} to 10^{-6}. Still, the probabilistic assessment is able to provide indications on the potential optimization of the median stone size. Based on the comparison between both locations, this study also provides guidelines for future applications to other locations.*

KEYWORDS: Offshore wind, scour, scour protection, probability of failure, reliability.

SITE LOCATION: **Geo-Database**

INTRODUCTION

Offshore wind energy is a vital contribution to promote a viable transition from fossil fuels to a renewable, clean, and more sustainable energy mix. With an estimated technical potential of about 192 800TWh/yr, offshore wind energy has the capacity to meet the current primary energy consumption, which is estimated to be circa 162 500 TWh/yr (Taveira-Pinto et al., 2020). Floating offshore foundations still strive to reach the same level of commercial implementation as bottom-fixed ones, of which monopiles are the most common type of foundation used. Monopiles correspond to about 81.2% of the foundations installed in European offshore wind projects to date (Wind Europe, 2021).

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In offshore wind foundations, the costs may represent about 35% of the total cost of the project (Esteban et al., 2019a). Of this percentage, a portion is related to the need of applying scour protection measures—which, even if representing a small part of the 35%, can be in the order of a million euros. Therefore, the optimization of scour protections and accurate estimations of their reliability are important contributions to improve the overall competitiveness of offshore wind energy, namely when it comes to reducing the Levelized Cost of Energy (Fazeres-Ferradosa et al., 2019).

Most scour protection applied at offshore wind monopiles are comprised rock material and consist of a filter layer covered by an armor layer, i.e., the so-called rip-rap protection. The design of rip-rap scour protection is typically made by means of semi-empirical approaches that can be further validated through physical modelling tests. In terms of the armor layer definition, the most common way to design a scour protection is to derive the median stone size (D_{50}) and associated weight that ensures a stable material under wave- and current-induced bed-shear stresses, which tend to be amplified by the foundation's presence and its interaction with the flow. To have a statically stable protection, one typically applies a stone size that has a critical shear-stress that is larger than the maximum shear stress expected at the location. For several years, the common procedure to design a static scour protection was to follow Soulsby's method (Soulsby, 1997). Alternatively, one can opt for a design where a controlled movement of the stones in the armor layer is allowed, as long as no excessive exposure of the filter layer occurs, e.g., as in De Vos et al.(2012), i.e., dynamic scour protections.

Since scour protection design has a semi-empirical nature, and, to a certain extent, uncertainty related to scour phenomena and due to the lack of long-term data from field protections, it is often difficult to have an accurate perception of the protection's reliability over their design life. Additionally, for the sake of safety, design choices commonly lead to overdesigned protection, which may increase the foundation costs.

In order to estimate the protection's reliability and to assess the optimization potential of the armor layer material in rip-rap protections, Fazeres-Ferradosa et al. (2018a) presented a probabilistic methodology that enables one to derive the probability of failure of an existing scour protection or to obtain the value of D_{50} for a target probability of failure (considered by the designer as the acceptable one). This methodology was developed for both static and dynamic scour protections using the case study of the Horns Rev 3 offshore wind farm. The results of such research indicated that for the same level of safety, a static scour protection could be optimized to have a dynamically stable armor layer, resulting in a reduction of the median stone size roughly from 0.54 m to 0.26 m. Additionally, Fazeres-Ferradosa et al. concluded that between these two values, a range of D_{50} could be used and still yield low probabilities of failures (in the order of 10^{-4}).

Despite the usefulness and promising results of this probabilistic methodology for the Horns Rev 3 case, a key shortcoming is that it is still lacking the application to other offshore wind farms. Hence, the subsequent research and conclusions derived from e.g., Fazeres-Ferradosa et al. (2018c, 2019) still require validation for a broad range of offshore wind farms. Extending this methodology to other cases would enable a deeper discussion on what is the expected order of magnitude of the probabilities of failure for rip-rap scour protections, and also a better understanding of which probability of failure could be considered as acceptable for design purposes.

With the aim of filling in this knowledge gap, the present work extends the probabilistic assessment of Fazeres-Ferradosa et al. (2018a) to the case study of the Egmond aan Zee offshore wind farm, and compares it with the available results for Horns Rev 3. Additionally, given the lack of guidelines and standards to perform the probabilistic assessment and design of scour protections, this work provides recommendations for future case studies.

CASE STUDIES

Horns Rev 3 Offshore Wind Farm

Horns Rev 3 is located in the Danish sector of the North Sea (Figure 1, on the left), and is roughly between 20 - 30 km north-west of Blåvands Huk and 45 - 60 km from Esbjerg. This location is characterized by shallow water depths ranging from 10 - 20 m, and the local seabed is mostly comprised of non-cohesive sands. This offshore wind farm comprises 49 wind turbines with scour-protected monopile foundations. Full details on this case study and associated references are described in Fazeres-Ferradosa et al. (2018a). The hindcast metocean data used for this case study corresponds to the coordinates latitude of 55.725°N and longitude of 7.750°E and includes a time-series of significant wave heights (H_s) and peak periods (T_p) with 90 553 pairs, with an hourly resolution for the period of 01-01-2003 to 01-05-2013. For the present case study, a water depth of 18 m was assumed as in Fazeres-Ferradosa et al. (2018a).

Egmond aan Zee Offshore Wind Farm

Egmond aan Zee is located 10 - 18 km off the Dutch North Sea Coast and comprises 36 wind turbines with scour protected monopile foundations (Figure 1, on the right). The selected hindcast data corresponds to the coordinates latitude of 52.606°N and longitude of 4.419°E. The hindcast data for this case study was obtained from CMEMS hindcast data and has a temporal resolution of 3 hours. The available time-series covered the period between 01-01-1980 to 31-08-2021, which resulted in 117120 pairs of significant height and joint peak periods. The water depth was assumed as 20 m and the remaining details for this case study are provided in Figueiredo et al. (2022).

Figure 1. Location of the Egmond aan Zee (on the left) and Horns Rev 3 (on the right) offshore wind farms.

METHODS

Statistical Models for Wave Data

In order to estimate the probabilities of failure of each scour protection, the wave data requires the fitting of one or more statistical models. These enable the assessment of the joint metocean conditions at the offshore wind farms' locations, which in turn provide the combined significant wave height and peak periods that serve as inputs to calculate the probability of failure. In the present case, a Conditional Modelling Approach as recommended in DNV-RP-C205 and DNV-CN30.6 was implemented.

As discussed in Vanem et al. (2019), these recommended models may not always lead to the most accurate fitting to the local data, namely, in shallow water locations highly influenced by the local bathymetry. In this case, the shallow water effects have different impacts on each location's modelling, since between both locations such effects are non-linear. Nevertheless, the same model is used for both locations since the analysis of the water depth influence is outside the scope of the present work. Future studies on these locations and a proper modelling of the shallow water effects on the simulations of the wave's characteristics could lead to more accurate results of the probabilities of failure; e.g., a potential solution would be the use of the model developed in Vanem and Fazeres (2022).

The conditional modelling approach provides the joint distribution of the two variables and is estimated by assuming that the marginal distribution of the significant wave height is a 3-parameter Weibull distribution, and the marginal distribution of the peak period is a lognormal distribution with location and scale parameters conditioned on the value of the significant wave height (Bitner-Gregersen, 2015).

Figure 2 shows the conditional model applied to both Horns Rev 3 (red-left) and Egmond aan Zee (green-right). Horns Rev 3 data modelling is also provided in detail in Fazeres-Ferradosa et al. (2018a). It is seen that the models generally tend to fit the available time-series reasonably well.

The procedures applied to treat the data for time-dependency and seasonal variability are the same as the ones detailed in Fazeres-Ferradosa et al. (2018b), and lead to simulated pairs of H_s and T_p that correspond to maximum weekly values. As mentioned, the conditional model provides the joint H_s and T_p pairs used to estimate the damage number in the following sections. Here the water depth has been modelled as a Gaussian distribution (see Fazeres-Ferradosa et al., 2018), and the generated wave heights are limited by a ratio of wave height to the water depth of 0.6. This is made to comply with the wave breaking limits, as suggested in Fazeres-Ferradosa et al. (2019).

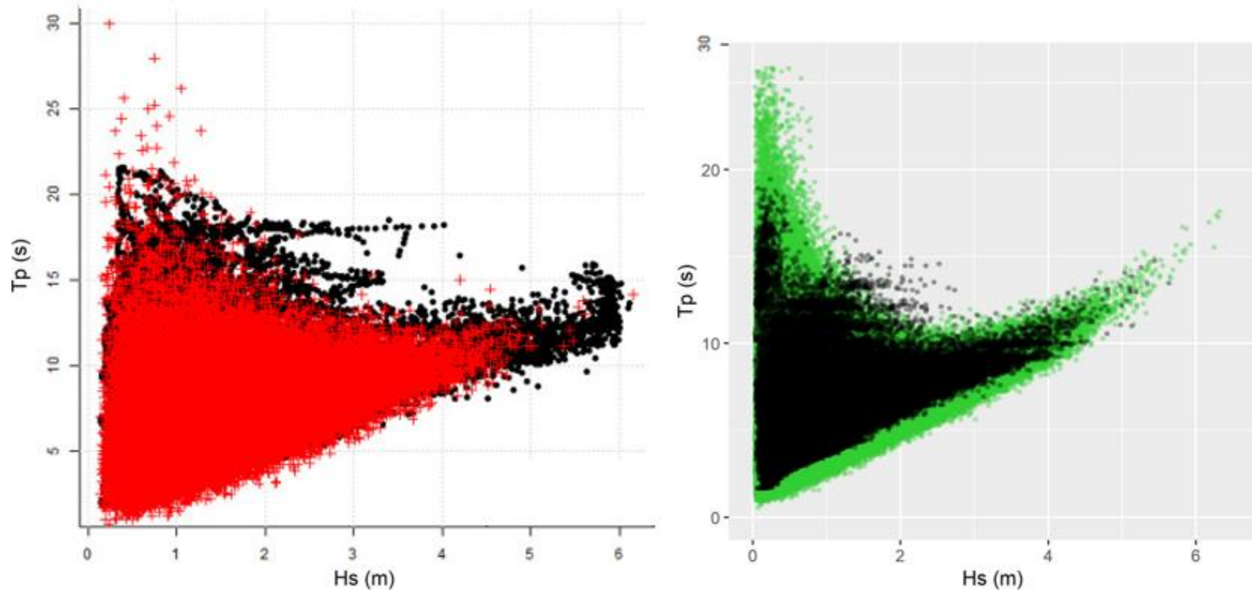

Figure 2. Conditional Model applied to Horns Rev 3 (left, in red) and Egmond aan Zee (right, in green) hindcast data. Samples of 50,000 Hs and Tp pairs are plotted as an example.

Both locations tend to show maximum significant wave heights in the order of 6 m and maximum peak periods above 20 s. Some overprediction of peak periods seems to occur, around 25 - 30 s. However, these are associated with small values of significant wave height and thus do not tend to cause failure of the scour protection applied in both cases. Therefore, their impact on the probability of failure is also expected to be rather small. Once again, these prediction "artifacts" can, to some extent, be avoided with more accurate models, such as the aforementioned Vanem and Fazeres-Ferradosa (2022).

Definition of Failure in Monopile Scour Protections

As described in De Vos et al. (2012), dynamic scour protections are feasible for monopile foundations if the damage number does not exceed the value of 1, which was observed through the physical modelling campaign that it is associated with an area of filter exposure in the order of $4(D_{n50})^2$. A discussion of this value and its relationship with the scour protection thickness has been discussed in Fazeres-Ferradosa et al. (2018c). As an example, $S_{3D}=1$ means that a scour depth $1 \times D_{n50}$ has occurred over a horizontal area of 2 by 2 stones with a size of D_{n50} each; i.e., an area of $4(D_{n50})^2$ is showing the removal of one layer of armoring stones. Thicker armor layers may withstand larger damage numbers; however, for the sake of comparison, in this case the unitary value is assumed for both offshore wind farms.

Considering a dynamic stability design criterion, the armor stones are allowed to move to some extent. This approach contrasts with static scour protection in which the armor layer stones are not allowed to move for a given design condition. As a result, its application generally leads to reduced stone sizes (Fazeres-Ferradosa et al., 2018a). The approach proposed by De Vos et al. (2012) is adopted and the predicted damage number (S_{3D}) is given by:

$$S_{3D} = N_w{}^{b_0} \times \left(a_0 \frac{U_m{}^3 T_{m-1,0}{}^2}{\sqrt{gd}(s-1)^{3/2} D_{n50}{}^2} + a_1 \left(a_2 + a_3 \frac{\left(\frac{U_c}{w_s}\right)^2 (|U_c| + a_4 U_m)^2 \sqrt{d}}{g D_{n50}{}^{3/2}} \right) \right) \quad (1)$$

where N_w is the number of waves in a reference storm, d is the water depth (m), U_c is the depth-averaged current velocity (m/s), U_m is the bottom orbital velocity (m/s), s is the relative density of the stones, and w_s is the rock settling velocity (m/s) based on the median stone size. D_{n50} is the nominal median stone diameter (m), equal to $0.84D_{50}$. The parameters b_0, a_0, a_2, and a_3 are equal to 0.243, 0.00076, −0.022, and 0.0079, respectively. The parameter a_1 takes the value of 0 for $U_c/\sqrt{gD_{n50}} < 0.92$ and waves following current, and 1 for $U_c/\sqrt{gD_{n50}} \geq 0.92$ or waves opposing current; a_4 is equal to 1 for waves following current, and Ur/6.4 for wave opposing current, where Ur is the Ursell number.

In this study, a number of waves N_w of 3,000 is considered, while the values of d and Uc for the case study of Egmond aan Zee location are provided in Esteban et al. (2019b) and used, respectively 20 m and 0.6 m/s. The bottom orbital velocity is computed according to Wiberg and Sherwood (2008). For Horns Rev 3, the reference values can be seen in Fazeres-Ferradosa et al. (2018a). In this case, one has a depth-averaged current velocity of 0.4 m/s and a water depth of 18 m. The rock density was assumed as 2,650 kg/m^3 for Horns Rev 3 (as in Fazeres-Ferradosa et al., 2018a) and 2,800 kg/m^3 for Egmond aan Zee (as in Esteban et al., 2019). These values are summarized in Table 1, as follows:

Table 1. Description (ISSMGE International Journal of Geoengineering Case Histories).

Reference conditions	Egmond aan Zee	Horns Rev 3
Source	Esteban et al. (2019)	Fazeres-Ferradosa et al. (2018a)
N_w (waves)	3,000	3,000
U_c (m/s)	0.6	0.4
Water depth (m)	20	18
$\rho_{arrmour}$ (kg/m^3)	2,800	2,600

Probability of Failure in Dynamic Scour Protections

The detailed framework for probabilistic assessment is provided in Fazeres-Ferradosa et al. (2018a). In summary, the present method consists of Monte-Carlo based simulations, which are carried out to simulate pairs of H_s and T_p, that are used to simulate the protection's response in terms of S_{3D}. In the present case, the number of simulations was defined based on DNV's recommendations (DNV, 1992), which recommends a minimum number of samples equal to $100/AP_f$, where AP_f is the annual probability of failure.

DNV (1992) indicates acceptable annual probabilities of failure of marine structures depending on their class of failure, which considers the possibility for timely warning of failure and the consequences of failure in terms of loss of life. However, as noted by Fazeres-Ferradosa et al. (2018a), guidelines on the acceptable values of probability of failure are not available in the specific case of scour protection for offshore wind structures. Nonetheless, given that risk to life upon failure can be considered small for unmanned offshore wind foundations, values of AP_f between 10^{-3} and 10^{-4} could be considered a reasonable assumption, at least for the sake of comparison of the locations herein studied. This leads to an interval of a minimum number of simulations that stays between 100,000 and 1,000,000.

Fazeres-Ferradosa et al. (2018a and 2019) conducted two studies for Horns Rev 3, where the probability of failure for dynamic scour protections was shown to be reasonably stable after 200,000 simulations, with the study performing up to 1,000,000 simulations of H_s and T_p. It is important to note that in the present work, the simulated values correspond to a space of all possible occurrences of H_s and T_p at each location based on the available data sets. The number of simulated pairs does not entirely relate to a specific return period (T_r) used in the actual design of these scour protections. Despite the fact that one may calculate the correspondent pair associated to T_r=50 years by fitting a joint cumulative distribution function to the simulated values, the interest of this paper is to compare both case studies, and such comparison has been done for the same number of simulated values.

In the present case, since the original data available for Horns Rev 3 had an hourly resolution and the data available for Egmond aan Zee had a 3-hours resolution, it is not simple to directly obtain the annual probability of failure. The influence of the temporal resolution in the probabilities of failures and their annual values was not analyzed in the present study and remains a source of uncertainty that requires further study. However, as mentioned before, in both cases the maximum of each pair corresponded to maximum weekly values of H_s and T_p. This resulted in probabilities of failure calculated for a minimum set of 1,000,000 pairs treated for time and seasonal dependence for both offshore wind farms. Also, the length of data available for both locations had an influence in the results; since simulating 1,000,000 pairs of H_s and T_p with 10 years (Horns Rev 3) or 41 years (Egmond aan Zee), the probabilities of failure obtained with less data have a larger uncertainty than the ones calculated with long data series.

For each case study, and with a reference value of a median stone diameter D_{50}, the probability of failure can then be estimated as (e.g., Puertos del Estado, 2002):

$$P_f = 1 - \exp\left(-\frac{\#(S_{3D} \geq 1)}{N_r}\right) \tag{2}$$

for the case of the simulations based on the original data. The annual probability of failure is given by:

$$AP_f = 1 - \exp\left(-\frac{\#(S_{3D} \geq 1)}{N_y}\right) \tag{3}$$

for the case of the simulations based on the pre-processed data. The $\#(S_{3D} \geq 1)$ expresses the number of cases where the scour protection is considered to fail, N_r is the total number of simulations, and N_y is the number of simulated years. In the present study, for the sake of comparison, only the values concerning Equation 3 are presented.

RESULTS AND DISCUSSION

Despite the uncertainty that arises from the application of different hindcast models, including different temporal and spatial resolution (which is addressed in Figueiredo et al., 2022), the main goal was to compare two different offshore wind farms in terms of their probabilities of failure. The intention was to understand if P_f stays within the same order of magnitude, or if its variability is significant from case study to case study. Figure 3 provides the probabilities of failure for both locations.

It is possible to see, for the same D_{50}, that between both case studies the probability of failure may vary considerably. For example, in the case of D_{50}=0.30 m, P_f varies up to two orders of magnitude, i.e., from 2.95×10^{-4} for Horns Rev 3 to 4.8×10^{-6} in the Egmond aan Zee offshore wind farm. In the latter case, median stone sizes above 0.38 m indicated a virtually null probability of failure, hence these have not been represented in the green curve.

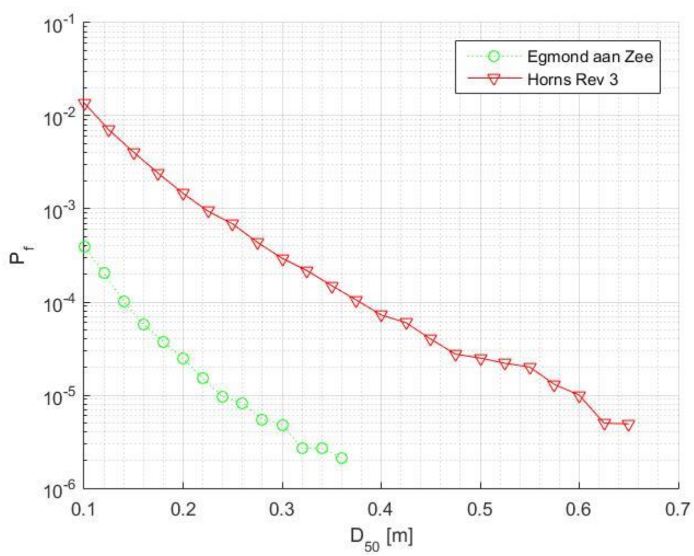

Figure 3. Comparison of the probabilities of failure for both locations, considering a dynamic stability criterion.

According to Fazeres-Ferradosa et al. (2018a) and Esteban et al. (2019b), the scour protection at both locations were designed following a static design criterion (no movement of the stones was allowed). Such design corresponded to $D_{50HornsRev3}$=0.35

m and $D_{50EgmondaanZee}$=0.4 m. The differences in design D_{50} may not only arise from the hydrodynamic and other local conditions, but also from different return periods assumed for the local currents, typically combined with 50 years for wave heights and periods. No information was found by the authors on the actual design return periods being used in both cases. Nevertheless, results show that there is a probability for a filter layer exposure, which is in the order of 10^{-4} for Horns Rev 3. In the case of Egmond aan Zee, the likelihood of failure is virtually non-existent. The practical implication of this is that the probability of generalized failure of the scour protection is rather low, given the fact that the probability of failure for dynamic stability status is also small (e.g., around 10^{-4} or less). Therefore, even if movement occurs at the armor layer, meaning that the static stability is not ensured, the probability of reaching an exposure of the filter layer above $4(D_{n50})^2$ remains small.

Results indicate that Egmond aan Zee could in fact support a considerable reduction of its D_{50}, for example down to 0.24 m. Note that for D_{50}=0.24 m, the probability of failure remains in the order of 10^{-6}, which is a rather small value when compared to the other cases reported in the literature, e.g., Fazeres-Ferradosa et al. (2018a or 2019). In the case of Horns Rev 3, the D_{50} could also, to a certain extent, be optimized depending on what the designer considers an acceptable value for the probability of failure. For example, one could consider reducing the D_{50} down to 0.30 m.

Concerning the acceptable probability of failure, a thorough discussion is made in Fazeres-Ferradosa et al. (2018a, 2019) stating that P_f in the order of 10^{-4} could be considered as a reference value for probabilistic design and reliability assessment purposes. Despite the fact that this is a matter that requires further investigation applied to a broader range of case studies, the results show that Egmond aan Zee has even lower values of the probability of failure than the ones reported in the previous studies. The field studies of Raaijamakers et al. (2008, 2010) and Peterson (2014), reported scour occurrence in some of the offshore monopile foundations up to 2,500 days after the foundations' installation. However, the maximum scour depth of about $0.6D_p$ was caused by edge scour phenomena, which then led to a decrease in the protection's extent. The formulation developed for dynamic stability by De Vos et al. (2012) does not account for such a failure mode. Hence, there is no direct relationship with the failure analysis hereby provided and values reported from field campaigns.

The fact that the median stone size at Egmond aan Zee could be reduced based on the results from Figure 2, relative to the erosion of the armor layer, could contribute to a decrease in the reported edge scour severity, since smaller armor stone sizes can be related to smaller changes in the seabed roughness. Additionally, the reduction of the median stone size might lead to the reduction of the protection's thickness, which also may contribute to reduce edge scour. To the authors' knowledge, no field surveys have been reported for the scour protections at the Horns Rev 3 offshore wind farm.

The results obtained in the present case study show that the probabilities of failure of a scour protection in monopile foundations depend considerably on the site-specific conditions for each offshore windfarm. This is evident due to the large differences noted between both locations studied herein. Nevertheless, the probabilistic assessment enables one to understand the margin for further D_{50} optimizations (reductions) without having unacceptable impacts on the protection's reliability.

CONCLUSIONS

The present study extended the reliability analysis developed in Fazeres-Ferradosa et al. (2018a) to the Egmond aan Zee offshore windfarm and provided a first comparison with the previously reported case concerning the Horns Rev 3 location. The key goal of this research was to understand if the probabilities of failure of a scour protection can register considerable variations from case study to case study.

For the failure mode concerning erosion of the armor layer, it was analytically proven that the probability of failure of scour protections can vary considerably from case to case. In this case, a comparison between Horns Rev 3 and Egmond aan Zee showed that the probability of failure may vary by up to two orders of magnitude for the same D_{50}, meaning that such measure of the protection's reliability can be very site-specific.

Regardless of these differences and considering the median stone sizes applied in both locations, it was shown that the probability of failure had reasonably low values, e.g., in the order of 10^{-4} or below. Both cases consist of scour protection that was designed to be statically stable. Therefore, the analysis performed under the dynamic stability criterion indicated that the scour protection could eventually be optimized to use smaller median stone sizes.

The results showed that further research is required: specifically, by extending this analysis to other case studies, in order to improve current knowledge on the failure mechanisms, likelihood, and reliability of scour protection applied to offshore wind monopile foundations. The present study has several limitations that arise from a broad range of uncertainties and shortcomings associated with the methodologies presented in this paper. These are discussed and analyzed in the literature, e.g., Fazeres-Ferradosa et al. (2018a and 20119). Furthermore, the present paper addresses the failure mode related to the erosion of the armor layer, although other failure modes in the armor, filter, or outer edges of the protection may occur. Future developments are required to properly estimate the reliability of these protections under multiple failure mechanisms. The following recommendations can be provided for future design operations based or partially supported on a probabilistic assessment:

- Probabilistic assessment and design of scour protection can lead to probabilities of failure and associated D_{50} values that vary significantly from one case to another. Thus, it is crucial to avoid generalizations of suitable values of P_f between windfarms at different locations.

- The literature has very few reported cases of probabilistic analyses of scour protection and no general guidelines are available for all cases. Nevertheless, P_f<10^{-4} seems to be a reasonable reference value for this type of rip-rap structure.

- If a dynamic design is to be performed, it is recommended that the P_f vs D_{50} curve is plotted to understand how the reduction to a smaller D_{50} impacts the probability of failure of the scour protection.

- If possible, as performed in Fazeres-Ferradosa et al. (2018a), the P_f vs D_{50} curve should be plotted for both the static and dynamic design criteria, e.g., based on Soulsby (1997) or De Vos et al. (2012).

- Given the large variances in P_f, it is advisable to perform sensitivity analyses, as the ones presented in Fazeres-Ferradosa et al. (2018a or 2019) for a better perception of the protection's reliability behavior.

The probabilistic analysis of scour protection requires further development and application to other case studies, and this remains a key step. However, it is recommended, as a preliminary approach, to check for potential reductions of D_{50} starting from the statically stable value to a dynamically stable one. Such reductions or optimizations should always be validated by means of physical modelling tests as a standard procedure.

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