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Effects of Simulation Length and Flexible Foundation on Long-Term Response Extrapolation of a Bottom-Fixed Offshore Wind Turbine

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ABSTRACT

This paper deals with statistical and modeling uncertainty on the estimation of long-term extrapolated extreme responses in a monopile offshore wind turbine. The statistical uncertainty is addressed by studying the effect of simulation length. Modeling uncertainty is explored by evaluating the effects of considering a rigid and flexible foundation. The soil’s flexibility is taking into account by considering the improved apparent fixity method. To identify the most relevant environmental conditions, the modified environmental contour method is used.

The analysis focuses on the fore-aft shear force (FASF) and the fore-aft bending moment (FABM) at the mudline. The results show that using a simulation length of 10-min, does not provide sufficient

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accuracy. It was found that for the FASF, simulation lengths of at least 30-min are required to achieve an accuracy of about +/-5%. For the FABM, it was found that both the extrapolations made with 20-min and 30-min simulations achieved similar levels of accuracy of about 20%. Meanwhile, the results obtained from 10-min simulations reached deviations of about 40%.

Finally, from the comparison made between a rigid and flexible foundation, it was found that the extrapolated responses exhibit maximum deviations up to around 5% and 10% for the FASF and the FABM, respectively. Also, for the FABM, it was observed that the consideration of a flexible foundation causes the critical wind speed to shift from 16.5 m/s (rigid) to 18 m/s (flexible).

INTRODUCTION

Offshore wind energy has been growing in importance over the last few years. Although there are many advantages associated with adopting the use of offshore wind energy, one of the most important is undoubtedly associated with its great potential for reducing environmental emissions, which will be essential to curbing global warming.

There is particular interest in the development of offshore wind farms, as higher capacity factors can be achieved. This is because the resource is stronger and more stable in marine environments. However, the main problem that persists in the industry is the Levelized Cost of Energy (LCOE), which in some cases is still high compared to other conventional technologies [1].

In an offshore wind energy project, there are a variety of factors that will affect the LCOE [2], however, the individual capacity of the turbine draws special attention. Manufacturers are continually pushing established power capacities to new levels [3] as larger turbines provide increased capacity per foundation. Similarly, a major component in the investment cost is the foundation which can represent up to 25% of the total project investment cost [4].

Considering these two points, it is expected that a significant reduction in the LCOE can be achieved by using very large turbines with the most economical foundation available that fully satisfies the reliability requirements of the project. For offshore, fixed foundations have been preferred by most of the projects installed in the world, especially the monopile as it has the lowest relative cost [5]. Given the popularity of this type of foundation, there is still interest in optimizing it to reduce costs without sacrificing reliability.

This cost reduction can be achieved through a more detailed understanding of the key uncertainties present in the initial phase of the project that may lead to changes in the current design processes. These key uncertainties are associated with direct impacts on turbine loads (i.e. extreme events, aero-hydro-servo-elastic response, soil-structure interaction, and load extrapolation) [6]. Controlling the level of uncertainty in the probabilistic models is expected to produce good and robust predictions of the extrapolated loads/responses associated with target return periods [7], and thus obtain an optimized product with reduced LCOE.

The present research addresses the statistical and modeling uncertainty. For the first type of uncertainty, the study is centered on exploring the errors incurred when length simulations shorter than one hour are used for the 50-yr long-term response extrapolation. Simulation lengths of 10, 20, and 30 minutes are evaluated and compared against the 1-hr and 50-yr extreme values. Thus, it is intended to cover certain aspects not taken into account in the current state of the art and provide relevant conclusions to guide future efforts in this area, in which there is still no consensus.

The second type of uncertainty is assessed by taking into account the flexibility of the foundation to evaluate its influence on the long-term responses of a bottom-fixed offshore wind turbine (OWT). The improved apparent fixity model is considered and the results from 1-hr coupled simulations are compared against the results obtained with a fully rigid foundation model. This is done to identify the divergences generated in the extreme long-term responses, particularly concerning the identification of the critical environmental condition. This is a very important aspect that has not received sufficient attention in the current literature.

This document is structured as follows. First, a brief description of the uncertainty related to wind energy is presented. Then, the theory behind the environmental contour method is introduced, covering the traditional (ECM) as well as the modified (MECM) version. Later, the statistical extrapolation procedure based on the Global Maxima Method is presented. In the following section, the details of the numerical model are explained. Then, the results obtained are presented and discussed. In the last section, the conclusions and suggested aspects for future research are summarized.

UNCERTAINTY IN WIND ENERGY

Uncertainties are present in any natural random process. It is difficult to make appropriate decisions without considering them in the design process. Many parameters for structural design are rarely known with great confidence and, they should be taken as random variables when considering a stochastic approach. In general, at least three types of uncertainty can be recognized in structural reliability theory [8]:

- *Physical uncertainty*, related to physical quantities and measurements such as loads and material properties.
- *Statistical uncertainty*, related to deviations arising from the estimation of parameters of probability distributions caused by insufficient sample size or insufficient observations.
- *Model uncertainty*, related to simplifications, assumptions, other effects (e.g. non-linearities), and interactions with other variables not initially considered in the physical or mathematical models.

A comprehensive understanding of the nature of uncertainties and how to quantify them is crucial to optimize the design phase of offshore wind structures. This aspect has been highlighted in the conclusions of the literature review performed by Jiang et al. [9]. The ultimate goal is to estimate loads as accurately as possible with appropriate levels of reliability but minimizing computational effort. The following two subsections will explore how two specific types of uncertainty arise in the offshore wind industry. The first one, related to the simulation length, and the second one, associated with the foundation flexibility.

a) STATISTICAL UNCERTAINTY

The offshore wind energy industry can be considered to be still at an early stage of development. For this reason, real data is not often available, or at least not in the required volume. As a consequence, it is necessary to rely on computational models that accurately represent real-world physical phenomena. Similarly, since extreme events have a very small probability of occurrence, it is necessary to perform several stochastic realizations to reach an acceptable level of accuracy on the statistical parameters. This involves time-consuming activities and the use of very large computational resources, which can make this a prohibitive process.

To alleviate this problem, it is often necessary to perform shorter simulations that can be later extrapolated and, thus, obtain answers about long-term processes. However, this consideration will introduce statistical uncertainty into the results. Therefore, the simulation length needed to achieve an acceptable accuracy of an extrapolated load is a crucial aspect. Choosing a very short time may greatly decrease the computational effort, but will cause the results to have a significant error level in the statistical estimates. Conversely, longer simulations may require more calculation time, but the result will be closer to the true values of the stochastic process parameters.

In the wind industry, a simulation length of ten minutes has been considered enough to ensure statistical independence and stationarity [7], and it is currently the standard applied in the industry [10]–[13] for OWTs. However, this assumption is already being considered conservative for the offshore environment [10]. Similarly, it is common practice in the offshore industry to consider simulation lengths between 3 to 6 hours for floating structures [14]. However, if the combined wind and wave loading is considered, the assumption of stochastic independence for periods longer than one hour cannot be considered entirely true, especially for the wind spectrum. This discrepancy has been highlighted by Kvittem et al. [15]. Then, it is expected that simulations of more than ten minutes will be required to reduce the uncertainty in the extrapolation of dynamic responses of OWTs. Although there is research focused on obtaining clear conclusions on this subject, unfortunately, there is still no clear consensus.

The first effort found in the literature addressing the simulation length problem was made by Haid et al. [16]. They analyzed simulation lengths between ten minutes to six hours on an OWT supported by a spar-type structure (OC3 Hywind). This study assessed ultimate loads but only in the short term, without applying any type of extrapolation. No technique was applied to obtain some kind of statistical distribution of the extreme values, instead, maximum single values extracted from time series were averaged and then compared. The main conclusion of the study was that a simulation length longer than ten minutes makes little difference to the ultimate loads.

Following the line of the previous study, Zwick et al. [17] also focused on the simulation length problem, but this time applied to a bottom-fixed OWT (OC4 Jacket). In this work, the extrapolation of loads to 50 years is considered, and the peak-over-threshold method adjusted to an exponential function is used. The paper concludes that using different simulation lengths has an appreciable impact on ultimate loads.

More recently, Hübler et al. [18] focused their efforts on studying the effects of simulation length on a monopile and a jacket OWT. The analysis was centered on short-term loads, so no extrapolation technique was applied. Furthermore, they did not use any method to statistically characterize the distribution of the extreme values, so the results were based on singular maximum values extracted from simulations. The conclusions of this work indicate that the simulation length is not relevant.

Finally, Pillai et al. [19] studied the impact of simulation length on a semi-submersible OWT. In this work, no joint distribution of environmental parameters was considered, and only a limited number of wind speeds were evaluated. The results were based on a comparison of the maximum values of the time series, so no characterization of the statistical distribution of the extreme values was made, nor any extrapolation technique was applied. The authors concluded that simulations longer than ten minutes are required to correctly capture the behavior of the system, in contrast to the results found by Haid et al. [16].

Two things can be concluded from the previous paragraphs: there are discrepancies among the conclusions of the studies and, there are aspects that have not been taken into account in the current state of the art. The studies have been mainly focused on extreme short-term loads, and only one of them has considered the extrapolation of long-term loads. Also, the analyses have not contemplated fitting the extreme values to a statistical distribution (e.g. Gumbel), this is because in some cases, few stochastic realizations have been considered for the environmental conditions analyzed, and in other cases, the averaging technique have been preferred by the authors. Later, it will be seen that in this work it has been possible to cover these pending aspects thanks to the use of the MECM, which has allowed focusing the computational effort on a specific set of environmental conditions.

b) MODELING UNCERTAINTY

This uncertainty is related to the soil-structure interaction. For bottom-fixed OWTs, this aspect is particularly relevant as there are large and direct connections between the substructure and the seabed. The work required to avoid this type of uncertainty is not easy. It is necessary to use more complete models that replicate the physical phenomena with sufficient precision. Particularly, in this paper, we are interested in the long-term extreme responses. Surprisingly, within the literature it is rare to find studies that address the effect of the soil on extreme dynamic responses, being the effects of the foundation model on the fatigue loads or the prediction of the natural frequencies of the system the most addressed topics.

An early work that addressed the issue of extreme responses was performed by Bush et al.[20]. In that research, a comparison of a rigid foundation versus a flexible foundation based on the apparent fixity (AF) method was performed in a monopile OWT. In this case, only one wind speed was analyzed and only the fore-aft bending moment at the mudline was considered. Subsequently, this research was extended [21] to include the coupled springs (CS) and the distributed springs (DS) foundation models. Again, only the fore-aft bending moment at the mudline was analyzed for two wind speeds. They concluded that the rigid model underestimates the extreme responses. However, it is important to note that this study was quite limited, and although 150 stochastic realizations were performed for each wind speed, the results were mainly based on statistical measures calculated from the samples. They did not fit an extreme value probability distribution to the data obtained from the simulations to find the most probable extreme response.

Considering the four foundation models mentioned in the previous paragraph i.e. fully rigid, AF, CS, and DS; the last two are the most complex, but they are expected to replicate the soil flexibility more accurately. However, using very complex models can increase the computational effort required to complete the simulations. Thus, the same problem that was observed with statistical uncertainty arises again. Therefore, it is necessary to use a model that allows finding a trade-off between computational cost and accuracy to reflect the soil-structure interaction. In this way, the most influential aspects can be identified to delimit the domain of the different environmental variables, which will deserve to be analyzed using more complex models at a later stage.

The simplest model to take into account the soil-structure interaction is the AF model. Unfortunately, there are some problems with this method, since it is common that only the diagonal terms of the stiffness matrix of the fictive beam are matched, and the cross-coupling stiffness between the horizontal and rotational degree of freedoms are neglected. Løken et al. [12] managed to solve this problem by considering a second fictitious beam with different properties. This method is known as the Improved Apparent Fixity (IAF) Method. The advantage of this model is that it is still simple as AF, and can be properly implemented SubDyn module of FAST. The IAF provides a better replication of the foundation conditions than a rigid model, but at the same time does not increase the computational complexity dramatically. This is the model employed in the present study.

ENVIRONMENTAL CONTOUR METHOD: TRADITIONAL AND MODIFIED

Haver et al. [22] proposed the ECM as a practical approach for estimating long-term extreme responses by using short-term analysis. In general terms, the method can be summarized in Eq. 1. In this expression, it is assumed that the short-term period is one hour. **F** is the cumulative distribution function of the extreme value (**ξ**) of the analyzed response X. Hereafter, **U_W** represents the mean wind speed at the hub height, while **u, h,** and **t** represent the mean wind speed measured at 10 m above the still water level, the wave height, and the wave peak period, respectively. The set {u_N, h_N, t_N} represents the most relevant environmental condition for a given return period **N**.

$$F_{X_{1\,\mathrm{hr},N\,\mathrm{yr}}}(\xi) \approx F^{ST}_{X_{1\mathrm{hr}\,|\,U_W,H_S,T_P}}(\xi|u_N,h_N,t_N) \tag{1}$$

To apply the traditional ECM, it is needed to define the reliability index β_S, Eq. 2. Here, **Φ** represents the standard normal cumulative probability function, and **md** is the expected number of d-hour sea states per year. The environmental conditions associated with a specific return period can be found by using the Rosenblatt transformation [23].

$$\beta_s = \Phi^{-1}\left(1 - \frac{1}{N * md}\right) \tag{2}$$

Once the environmental conditions to be evaluated have been identified, the corresponding dynamic responses are determined. For a given environmental condition, short-term extreme values of the response are used to fit an empirical probability distribution to find the most probable extreme value. The combination which gives the maximum extreme response, among all the sets, is known as the “design point” and, the response value for this condition is considered the long-term extreme response (N-yr response). However, since the ECM omits the response variability at the beginning, it is necessary to correct the calculated extreme value. This correction is made by applying an empirical fractile level higher than 50%. Values between 70% and 90% are usual for practical applications [24].

Although the traditional ECM is a widely used method in the offshore industry, it does not give accurate responses for systems that have survival mechanisms based on an active control system. This aspect causes the ECM to underestimate the long-term extreme responses, which are mainly influenced by environmental conditions within the operational range and with a higher probability of occurrence.

To bypass that problem, Li et al. [25] proposed the MECM. It is based on the widely accepted assumption that the long-term probability distribution of a response can be extrapolated from the short-term distribution as short-term extreme values are considered statistically independent in a short-term period e. g. one hour. Then, the 50-yr 1-hr extreme cumulative distribution function (CDF) can be written as Eq. 3. This equation implies that the 50-yr extreme response can be found by estimating an extreme response with a lower return period N_0. This procedure helps to bypass the non-linearity on the limits of the operational range of the wind turbine. Since the return period (N_0) will be lower than 50 years, it is necessary to apply an extrapolation to the probability distribution between brackets to estimate the corresponding value of the response at 50 years. This extrapolation is achieved by applying the exponent $50/N_0$. The expression between brackets can be found by applying the traditional ECM, Eq. 1, then it becomes Eq. 4 but, considering the return period N_0. In this case, the extreme response is calculated using one-hour short-term extreme distribution.

$$F_{X_{1\,hr,50\,yr}}(\xi) = \left[F_{X_{1\,hr,N_0\,yr}}\right]^{50/N_0} \tag{3}$$

$$F_{X_{1\,hr,50\,yr}}(\xi) = \left[F^{ST}_{X_{1\,hr|U_W,H_S,T_P}}\left(\xi|u_{N_0}, h_{N_0}, t_{N_0}\right)\right]^{50/N_0} \tag{4}$$

Consequently, the MECM focuses on finding the return period N_0 in which the maximum long-term extreme response is achieved. To reach this goal, many inner environmental contours corresponding to wind speeds within the operational range of the turbine need to be tested. The condition that provides the greatest response among all the conditions tested will be the most important environmental condition or, it can be also referred as the **critical environmental condition**. The return period that corresponds to this important condition will be the return period required, N_0. A specific procedure to apply the MECM to bottom-fixed OWTs under the combined action of wind and wave can be found in [25].

LOAD EXTRAPOLATION

In this research, the Global Maxima Method is used to obtain a short-term probability distribution. The extreme values obtained from coupled simulations are fitted to a Gumbel distribution, Eq. 5. In this expression, X is the analyzed response, β_G is the shape parameter, and μ_G is the location parameter and, at the same time, the most probable value of the probability distribution (Mo_X), also known as the mode.

$$F(X) = \exp\left(-\exp\left(-\frac{(X-\mu_G)}{\beta_G}\right)\right) \tag{5}$$

As previously stated, it is necessary to have the 1-hr extreme probability distribution for the extrapolation of 50-yr extreme responses using the MECM. This can be achieved by running one-hour simulations or by using shorter simulations and then applying an extrapolation to arrive at a one-hour level. For this purpose, extreme values extracted from 10-min, 20-min, 30-min, and one-hour simulations are used to compare the deviations in the most probable values of the fitted Gumbel distributions. After extrapolation, the most probable value of the Gumbel distribution is given by Eq. 6. In this equation, N_0 is the return period of the environmental condition (EC) tested. The parameter **r** will depend on the simulation length from which we have extracted the extremes for fitting purposes. The value of r is 1, 2, 3, or 6 if the extremes for the Gumbel fitting come from 1-hr, 30-min, 20-min or 10-min simulations, respectively.

$$\mathrm{Mo_X} = \mu_G + \beta_G \cdot \ln(r \cdot 50/N_0) \tag{6}$$

In the original paper where the MECM was developed [25], as well as in further research [10], the simple linear regression approach is used to obtain the coefficients of the empirical distribution. This approach is based on the least-squares method; however, some limitations have been identified when it is used for extreme value fitting [26]. For this reason, the maximum likelihood method is employed in this work.

Considering that 2 dynamic responses, 12 environmental conditions, 2 different foundation models, and 4 simulation lengths were analyzed, a total of 120 parameter estimates were made. The goodness of fit is determined by the p-value obtained after performing a hypothesis test based on Moran's statistic, which is implemented in WAFO [27]. The criterion for accepting the parameter fit is that the calculated p-value is greater than 0.05 (significance level). The higher the p-value, the better the goodness of fit. Table 1 presents the number of parameter estimation cases grouped by the range of the p-value obtained. It is observed that in 102 cases, out of a total of 120, the p-values are higher than 0.10.

NUMERICAL MODEL

For the development of this research, the NREL 5 MW wind turbine model [28] supported on a monopile foundation is considered. This wind turbine is a variable speed and collective pitch wind turbine with rated, cut-in, and cut-out wind speeds of 11.4, 3, and 25 m/s, respectively. The hub is 90 m above the mean sea level and, it has a rotor and hub diameter of 126 m and 3 m, respectively.

The offshore reference site used in this study is the one labeled as “Site 15” presented by Li et al. [29], which is located in the North Sea center. The joint probability distribution considers three environmental parameters. The coefficients of the statistical distributions can be found in the referred work [29]. Under the MECM procedure, different environmental conditions are obtained; these conditions are listed in Table 2.

In the first part of the work, it is necessary to generate the inflow wind profiles for each wind speed to be evaluated, and considering several random seeds, this is done with the help of TurbSim [30]. The Kaimal turbulence spectral model is used, with a characteristic and turbulence type of “B” and “NTM”, respectively. The wind power-law is used to extrapolate wind speeds along the tower and rotor height. For the generation of the stochastic wind field, it is considered the coherence model given by IEC 61400-1 (3rd ed.) [31] and, a time step of 0.05 s.

For each wind speed, there will be an associated sea state and then, it is necessary to set the values for the wave height (Hs), peak spectral period (Tp), and the cut-off frequencies of the wave spectrum in the input files of FAST [32]. Wave profiles are generated internally with HydroDyn [33] and using the JONSWAP spectrum with a peak-shape parameter of 3.3. The heading wave direction is set to 0° and the water depth is 20 m. The analysis time considered for incident wave calculations is 3630 s. Additionally, one hundred simulations have been performed with different random seeds for each environmental condition tested.

The monopile that supports the turbine has a diameter of 6 m and a thickness of 0.06 m, and it is considered fully constrained at the seabed for the first part of this work. An important part of achieving accurate dynamic responses when considering wave loading is to properly set the Morison coefficients for drag (C_D), added mass (C_A), and pressure (C_P). The usual ranges for these values are: $1.5 \leq C_P + C_A \leq 2$ and, $0.6 \leq C_D \leq 1.2$, according to [34]. For this work, the coefficients have been taken as $C_D=0.9$, $C_A=0.75$, $C_P=1$, for a detailed explanation about the selection of these values the reader is referred to [35] which is also supported by [36]. Other input parameters have been left as they were defined in the NREL 5MW baseline. For the part of the analysis regarding the inclusion of the soil flexibility, the IAF method has been taken into account, more details of this model can be found in [12]. A scheme of these two fictitious beams with three nodes can be seen in Fig. 1. Here, the lowest node (N_1) has a fully rigid condition. A summary of their main properties is summarized in Table 3. Finally, all these models and, workflows are implemented in a Python script to generate the output files from FAST. The post-processing for Gumbel fitting is made with WAFO [27].

RESULTS

The results of the analysis for the fore-aft shear force (FASF) and fore-aft bending moment (FABM) at the mudline are presented below. First, the effect of the simulation length on the extrapolation will be analyzed, both for the extrapolated loads at a level of 1-hr and 50-yr. In the case of 1-hr extrapolation, there is no effect of the return period of each wind speed, factor $50/N_0$, in the extrapolated load, Eq. 6. But, for the 50-yr extrapolation, this factor does have an influence. A rigid soil model is considered in all cases.

In a later section, the results obtained from the comparison between the responses using the rigid soil model and the IAF soil model are discussed. In this case, 1-hr simulations are used. In each case, both the trends of the values and the relative errors are shown. In both sections of the results, the relative error is plotted. For the case of simulation length analysis, the relative error is calculated according to Eq. 7, and for the case of the study of the effect of soil flexibility, the relative error is given by Eq. 8.

$$\mathrm{R.E.} = \left(\frac{\mathrm{X_{i-min}} - \mathrm{X_{1\,hr}}}{\mathrm{X_{1\,hr}}}\right) \times 100\% \; ; \; \mathrm{i} = \{10, 20, 30\} \tag{7}$$

$$\mathrm{R.E.} = \left(\frac{\mathrm{X_{IAF}} - \mathrm{X_{Rigid}}}{\mathrm{X_{Rigid}}}\right) \times 100\% \tag{8}$$

a) Effects of simulation length

First, the trend of the most probable values extrapolated from extreme values obtained from 10-min, 20-min, and 30-min simulations will be analyzed. All these values have been extrapolated to the level of 1-hr. The trend for the FASF is shown in Fig. 2; it can be also observed the most probable value obtained from one-hour simulations fitting. As can be seen, the difference between the extrapolated most probable values is small in comparison to the trend obtained with the one-hour simulations (black line with diamonds). In the case of the FABM, Fig. 3, a slightly greater variation is observed. In this case, the extrapolation obtained from 30-min simulations is the one that best agrees with the one-hour simulations trend.

Figures 4 and 5 show the relative errors obtained for the FASF and FASBM respectively. In these figures, the most probable values of the extremes obtained from 10-min, 20-min, and 30-min simulations extrapolated to a 1-hr level are compared to the most probable value obtained from 1-hr simulations. In the case of the FASF, the relative error varies between -2% and 6% whereas this variation ranges from -6% to +6% for the FABM depending on the wind speed considered. In both cases, it is observed that the 30-min simulation offers lower levels of relative error.

From Figs. 2-5, it can be seen that when extreme values characteristics obtained with shorter simulations are extrapolated to the one-hour level, there is no large difference with simulations that have been run for one full hour. Now it will be explored what happens when the extrapolation is done at a level of 50 years. In this case, the factor $50/N_0$ will influence the most probable extrapolated value of the extreme response since it is different for each wind value. As it can be noticed in Fig. 6, the divergence for FASF becomes greater; being the extrapolation obtained from the 30 minutes simulations the one that comes closest to the value obtained from 1-hr simulations. In the case of the FABM, Fig. 7, all extrapolations show a significant deviation from the 1-hr case, but the extrapolation obtained from 10-min has the largest difference. It can also be seen that both the 20-min and 30-min extrapolations perform almost the same. Also, it is observed that the critical environmental condition for 10 minutes simulations moves from 16.5 m/s to 17 m/s for the case of 20-min and 30-min simulations.

These differences are better understood when the relative errors are plotted. In the case of the FASF, Fig. 8, the relative error is higher for the 10-min and 20-min cases, and the error for the extrapolation obtained from the 30-min varies in the range of +-5%. In the case of the FABM (Fig. 9), it is observed that both 20-min and 30-min perform similarly, but using 10-min gives the highest relative error. In the 20-min and 30-min cases, the error varies between +20% (for critical wind speed) and -10% (for higher speeds and near the cut-out wind speed).

b) Effects of flexible soil

In this section, the effects of considering the soil flexibility through the IAF soil model on load extrapolation will be explored. For this analysis, 1-hr simulations are used and extrapolation is applied to reach 50-yr levels. In Figs. 10 and 11, the trend of the most probable values of the extreme responses in 1-hr can be observed for FASF and FSBM, respectively. As it can be noticed, the difference between both curves is small. Similarly, in Fig. 12 the relative errors for the FASF and the FABM are observed. In this case, the comparisons are made between the response obtained considering the IAF and the response obtained with the rigid foundation. So, an increase of up to about 3% for the FASF and about 2% for the FABM is observed when considering soil flexibility.

In Fig. 13, it can be seen that there is no great variation in the values of FASF when the extrapolation to a 50-yr level is applied. In contrast, the FABM experiences some variations, Fig.14. The critical environmental condition moves slightly from the 16.5 m/s speed to 18 m/s. Also, the most likely value after extrapolation increases. This behavior can be seen more clearly in Fig. 15. The FASF has maximum deviations close to 4%, and the FABM reaches up to 10% for 18 m/s where the critical mean wind speed is found.

CONCLUSIONS

One of the main concerns for the development of offshore wind energy is the reduction of the LCOE. It has been identified that one of the ways to achieve this is to control the level of uncertainty present in the initial phase of the projects that could lead to changes in the current design processes and thus help to avoid over-conservative designs with excessive material. This would produce good and robust predictions of the short- and long-term dynamic responses associated with specific return periods. However, this is not an easy task, especially when dealing with extreme responses, as it involves the simulation of several stochastic realizations for each environmental condition. This implies the use of large computational resources, which are not often accessible. So a mandatory step in this line of research is to find a trade-off between the accuracy of the results and minimizing the computational cost.

The present work has focused on the understanding of uncertainties in a monopile OWT and, it has addressed the study of two issues of particular importance: the simulation length (statistical uncertainty) and the foundation flexibility (model uncertainty). In the initial part of this research, attention was focused on analyzing the influence of the simulation length on the long-term extrapolation process of two types of dynamic responses. From the review of previous research, it was seen that there is no consensus on the minimum time to be considered in the simulations. Also, it was found that in most of the papers, certain aspects had not been taken into account and that could have influenced their conclusions. Among these aspects, which have been covered in the present study, we can mention that:

- Most authors limited their analysis to short-term extreme values extracted from the time series (except [17]). In those cases, it was concluded that the simulation length did not have much influence on the final results. However, in the present work, it was found that simulation length has a more pronounced effect in the long term.
- In the only study in which an extrapolation process was applied, the Peak Over Threshold (POT) method was used. Although this method is preferable for characterizing dynamic responses when a large number of time series is not available, this was not our case. For this reason, it was preferred to use the GMM based on one hundred stochastic realizations that guarantee the stability of the statistical parameters. The goodness of

fit of the method was assessed through a hypothesis test, which gave good results.

- In the papers where only short-term maximum responses were considered, the authors chose to compare singular values of the different stochastic realizations or to average them, rather than characterize them by statistical fitting. In contrast, in the work developed in this paper, the extreme values were fitted to a statistical extreme value distribution (Gumbel), which allowed determining the most probable extreme loads to be used as a more advanced and accurate comparison metric.
- It was observed that joint probability distributions of the environmental variables were considered only in some studies. This could have led to analyzing environmental conditions that did not correspond to a target return period. In the present investigation, the joint probability distribution of a specific site has been taken into account and, this is a mandatory requirement to use the MECM and apply the 50-year extrapolation.

Although there were certain gaps in the previous investigations, this is completely reasonable, since covering all these aspects to perform an analysis and characterization of extreme response involves an important computational effort. In this work, it has been possible to consider all these missing aspects because the MECM made it possible to significantly reduce the number of environmental conditions to be evaluated.

The main finding of the initial part of this work has been to determine quantitatively that the simulation length of 10-min is not sufficient to achieve low levels of uncertainty in the long-term extrapolation (50 years), as is widely believed. In the short term, this aspect does not have much influence (one hour). It was also observed that good results are obtained with at least 30-min of simulation for the FASF. For FABM, there is a significant deviation for a duration of 10-min, which is reduced when considering 20 or 30-min, although the level of deviation is still appreciable.

In the final part of this work, the effects of a flexible foundation on two dynamic responses have been evaluated. The behavior of these responses has been addressed in the short and long term. The IAF foundation model was used to account for this flexibility. This approach solves the shortcomings of the traditional AF model and, at the same time, offers a good trade-off between enhanced reproduction of soil conditions and the computational effort required to run several stochastic simulations.

In previous research on this topic, it was found that some aspects had not been taken into account in the analysis. These gaps were addressed in the present research as follows:

- For the present study, attention was focused on two dynamic responses of particular relevance for monopile design, the FASF, and the FABM. In previous literature, only the FABM was analyzed.
- The extreme value analysis was done based on one-hour simulations, since shorter simulations produce significant deviations when applying

extrapolation, especially for FABM. In previous research, 10-minute simulations were used.

- In the analysis developed, extreme values were adjusted to a probability function to obtain the most probable extreme value in the short term. This function was used to obtain long-term values by extrapolation, which revealed the influence of the foundation flexibility in the location of the critical wind speed. In contrast to earlier work, where the technique of averaging singular maximum short-term values was used.
- In this work, a wide range of wind speeds within the operational range of the wind turbine has been evaluated. This allowed determining the trends of extreme responses, as well as points where there is a change in the critical wind speed when considering a rigid and flexible foundation. In a previous analysis, only two wind speeds had been evaluated, an insufficient number to capture these inflection points.

The main finding of this research is that the inclusion of a flexible foundation in the model leads to a shift of the critical wind speed, as well as an increase in the value of the extrapolated response for the FABM. This wind speed is very important since it allows restricting the short-term conditions to be considered when more accurate techniques are required to find the value of the long-term extreme response, e.g. the simplified long-term analysis (SLTA). An additional finding is that FASF and FABM are found to be weakly sensitive to the inclusion of foundation flexibility in the short term, and the FASF is also almost insensitive in the long term.

The results obtained in the present research are intended to serve as a basis for orienting efforts related to structural optimization, establishing guiding parameters on which aspects are crucial and which are irrelevant for the control of uncertainty propagation in reliability-based designs. In that sense, it contributes to the main objective of reducing the LCOE of offshore wind energy.

Future research should consider the effects of uncertainties related to wind turbulence level and turbulence models. In addition, the inclusion of higher-order wave kinematics and advanced wave load models should be evaluated since their influence is greater in cases of shallow water. Also, the effect of phenomena such as ringing and springing should be considered, as they can influence the value of extreme response values. Finally, future research should address the effect of uncertainties on the behavior of larger turbines.

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Figure Captions List

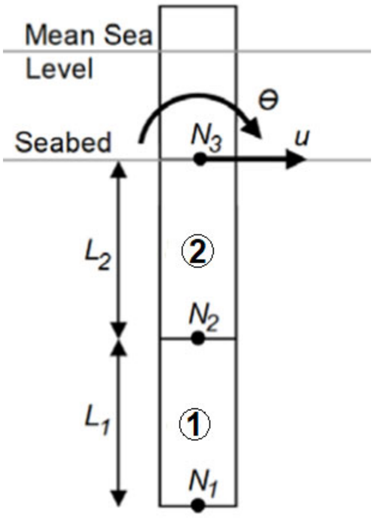
Fig. 1	Diagram of the fictitious beams considered in the IAF method, adapted from [12].
Fig. 2	Most probable value from 10-min (red circles), 20-min (blue squares), 30-min (green triangles) simulations extrapolated to a 1-hr level, and most probable value from 1-hr (black diamonds) simulations versus mean wind speed for FASF.
Fig. 3	Most probable value from 10-min (red circles), 20-min (blue squares), 30-min (green triangles) simulations extrapolated to a 1-hr level, and most probable value from 1-hr (black diamonds) simulations versus mean wind speed for FABM.
Fig. 4	Relative errors of the most probable values extrapolated to a 1-hr level with respect to most probable values from 1-hr simulations for the FASF.
Fig. 5	Relative errors of the most probable values extrapolated to a 1-hr level with respect to most probable values from 1-hr simulations for the FABM.
Fig. 6	Most probable value from 10-min (red circles), 20-min (blue squares), 30-min (green triangles), and 1-hr (black diamonds) extrapolated to a 50-yr level from simulations versus mean wind speed for FASF.
Fig. 7	Most probable value from 10-min (red circles), 20-min (blue squares), 30-min (green triangles), and 1-hr (black diamonds) extrapolated to a 50-yr

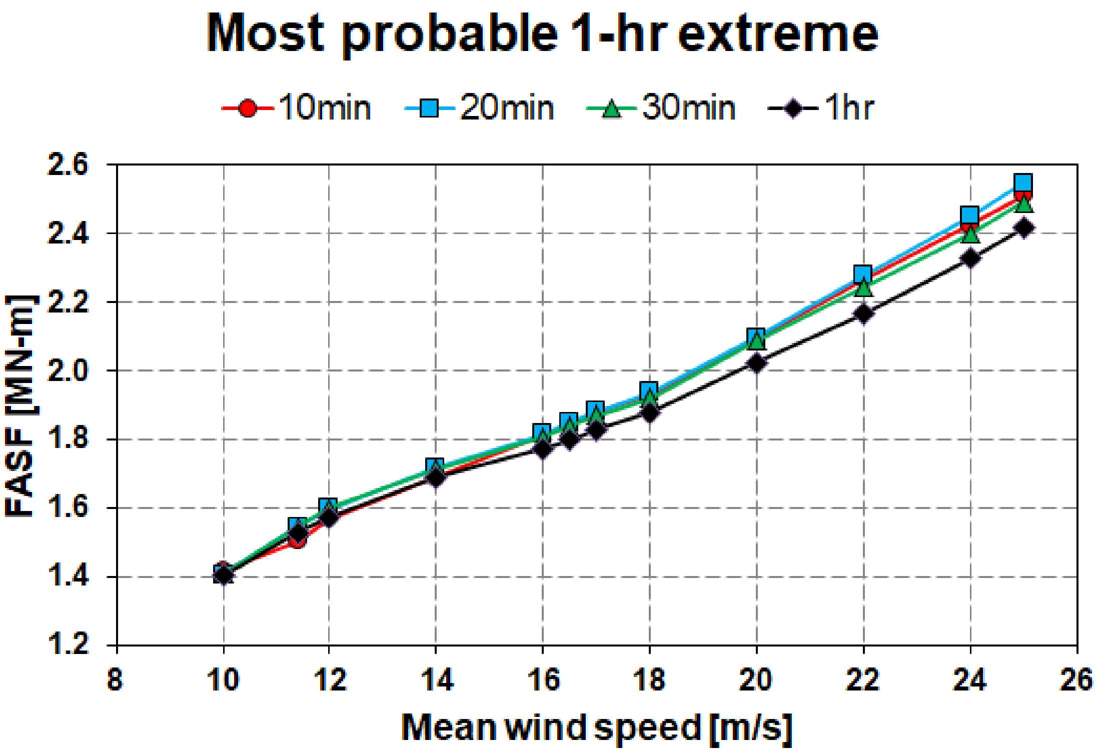
	level from simulations versus mean wind speed for FABM.
Fig. 8	Relative errors of the most probable values extrapolated to 50-yr level with respect to most probable values extrapolated from 1-hr simulations for the FASF.
Fig. 9	Relative errors of the most probable values extrapolated to 50-yr level with respect to most probable values extrapolated from 1-hr simulations for the FABM.
Fig. 10	Most probable value of extreme response for FASF from 1-hr simulations considering rigid foundation (red circles) and IAF foundation (black diamonds) versus mean wind speed.
Fig. 11	Most probable value of extreme response for FABM from 1-hr simulations considering rigid foundation (red circles) and IAF foundation (black diamonds) versus mean wind speed.
Fig. 12	Relative error of 1-hr extreme response for FASF (Red) and FABM (black) when a flexible soil model is considered.
Fig. 13	Most probable value of extreme response for FASF extrapolated to 50-yr level considering rigid foundation (red circles) and IAF foundation (black diamonds) versus mean wind speed.
Fig. 14	Most probable value of extreme response for FABM extrapolated to 50-yr level considering rigid foundation (red circles) and IAF foundation (black diamonds) versus mean wind speed.

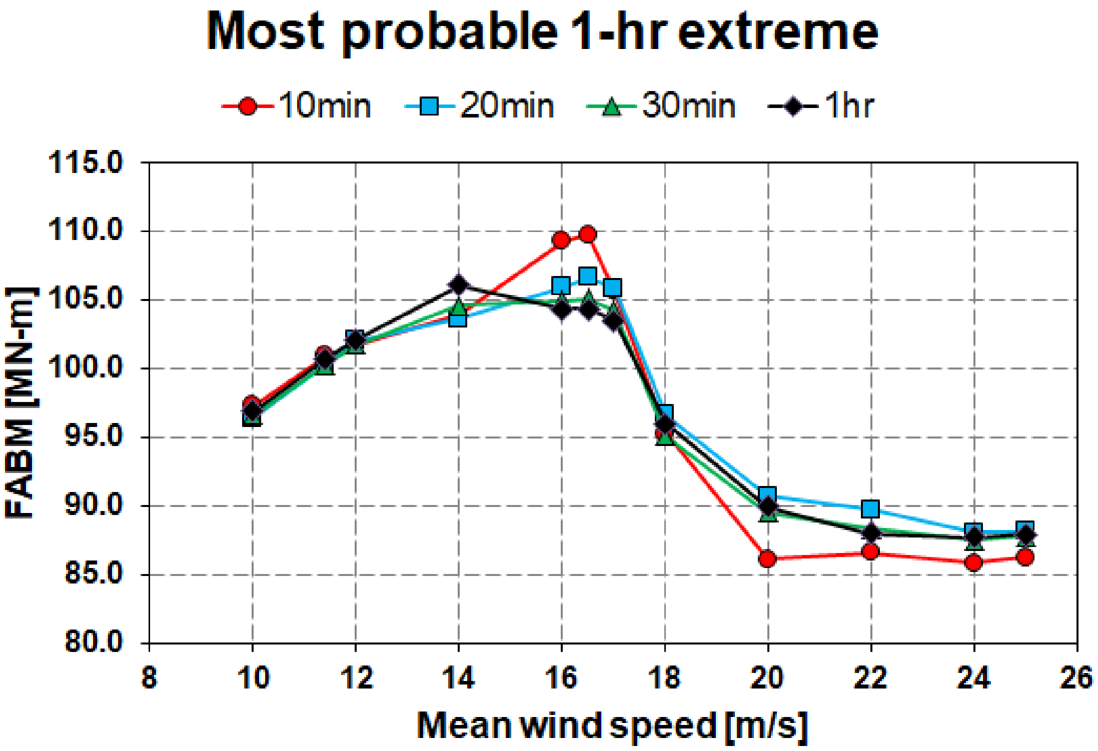
Fig. 15 Relative error of extreme response extrapolated to 50-yr level for FASF (Red) and FABM (black) when a flexible soil model is considered.

Table Caption List

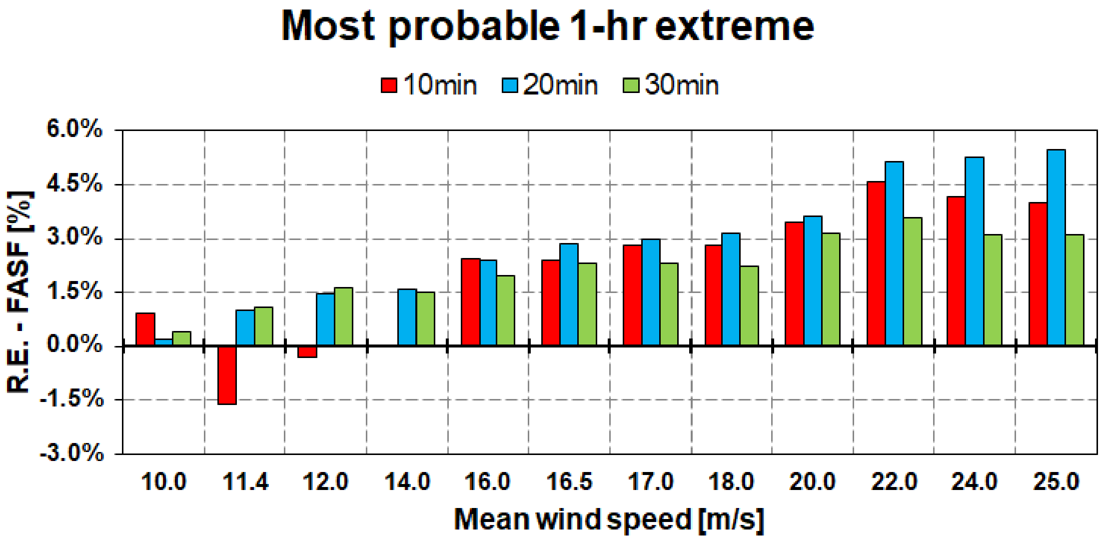
Table 1	Number of cases of Gumbel parameter estimation grouped by the range of p-values.
Table 2	Environmental conditions considered for the calculation of extreme responses, including 50-yr environmental conditions at “Site 15” [29].
Table 3	Properties of the two fictitious beams employed in the IAF model [12].


Mean Sea Level
Seabed
θ
u
N_3
L_2
②
N_2
L_1
①
N_1


Most probable 1-hr extreme
10min
20min
30min
1hr
FASF [MN-m]
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]


Most probable 1-hr extreme
10min
20min
30min
1hr
FABM [MN-m]
115.0
110.0
105.0
100.0
95.0
90.0
85.0
80.0
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

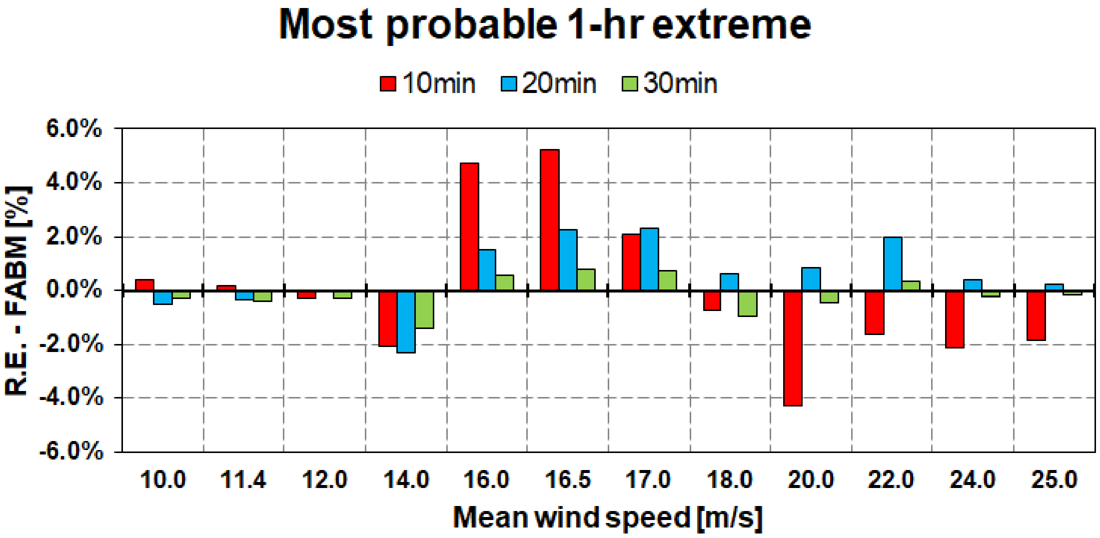
690


Most probable 1-hr extreme
10min
20min
30min
R.E. - FASF [%]
6.0%
4.5%
3.0%
1.5%
0.0%
-1.5%
-3.0%
10.0
11.4
12.0
14.0
16.0
16.5
17.0
18.0
20.0
22.0
24.0
25.0
Mean wind speed [m/s]

691

692

693



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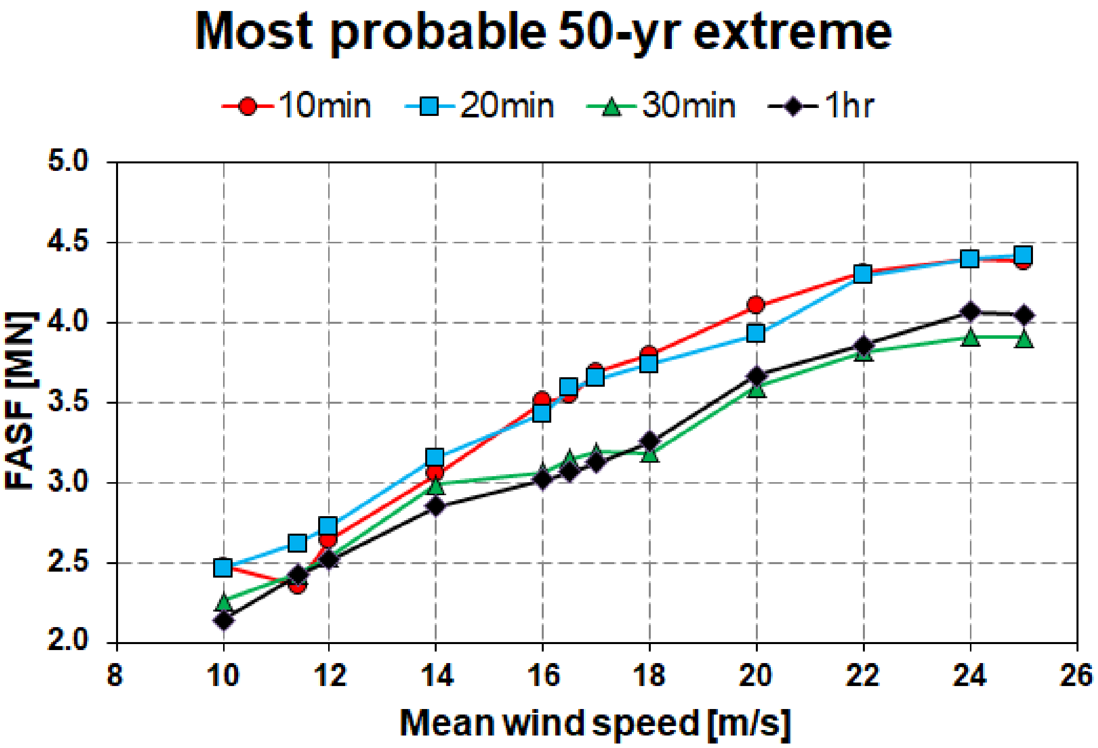
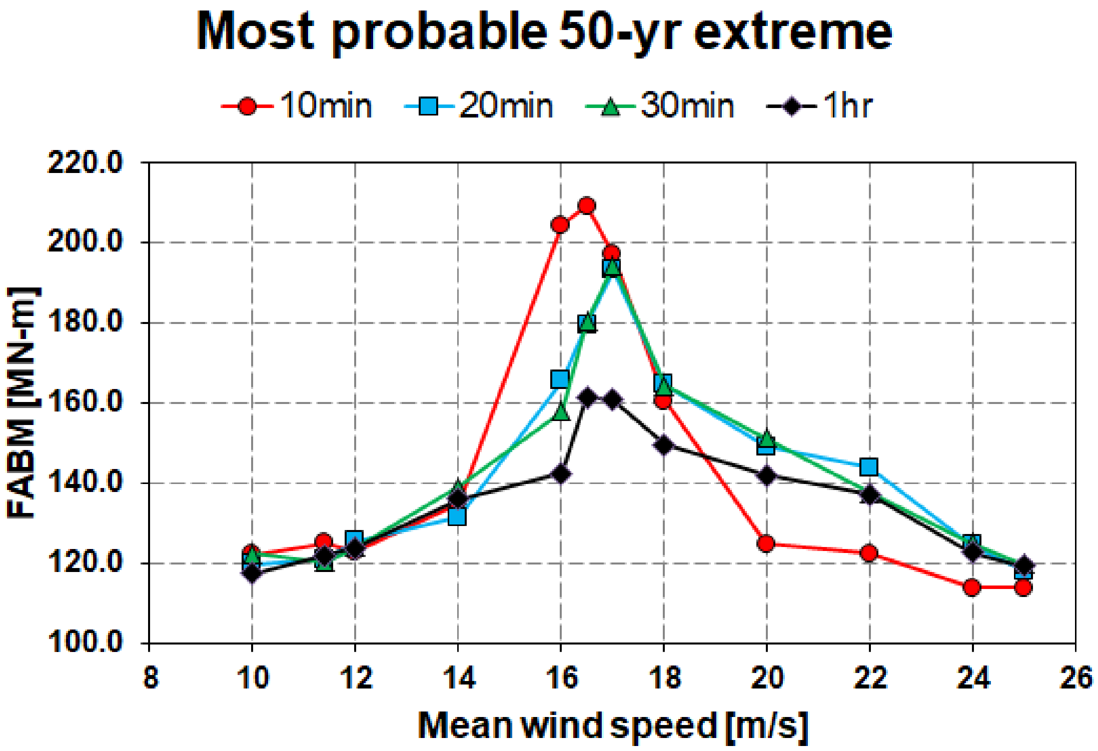
695
696

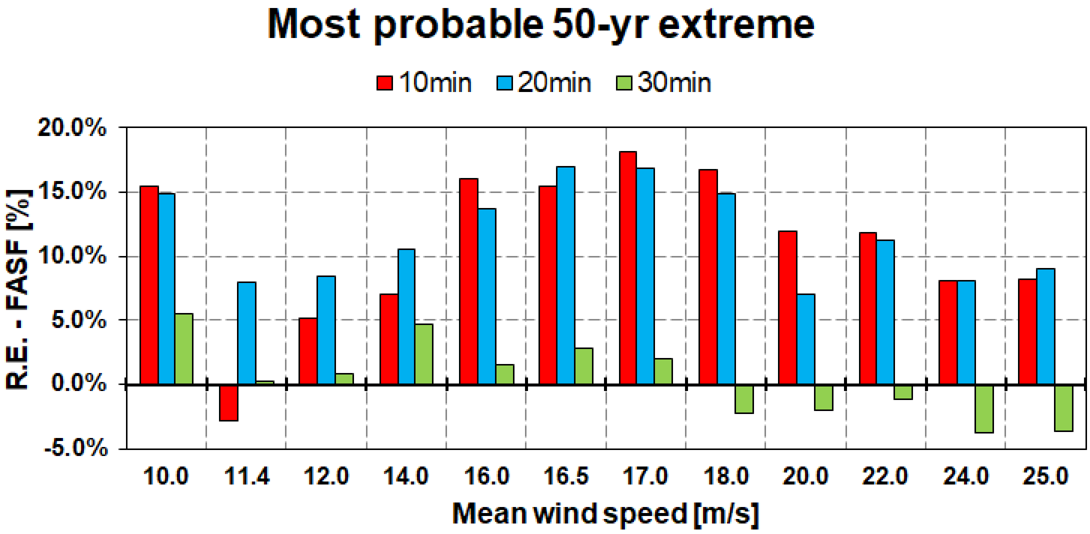

Most probable 50-yr extreme
10min
20min
30min
1hr
FASF [MN]
5.0
4.5
4.0
3.5
3.0
2.5
2.0
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

700


Most probable 50-yr extreme
10min
20min
30min
1hr
FABM [MN-m]
220.0
200.0
180.0
160.0
140.0
120.0
100.0
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

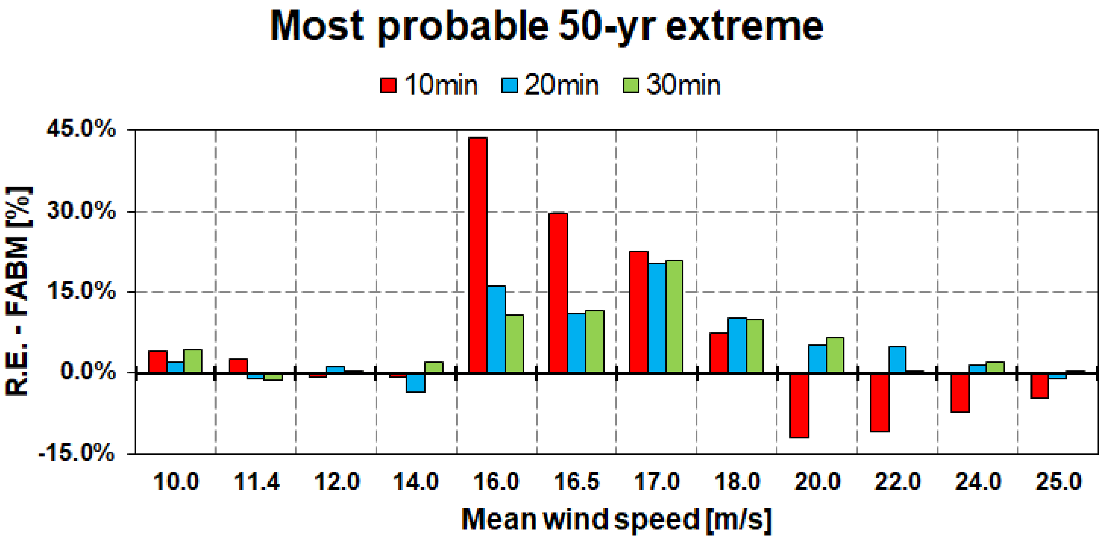
701
702

703


Most probable 50-yr extreme
10min
20min
30min
R.E. - FASF [%]
20.0%
15.0%
10.0%
5.0%
0.0%
-5.0%
10.0
11.4
12.0
14.0
16.0
16.5
17.0
18.0
20.0
22.0
24.0
25.0
Mean wind speed [m/s]

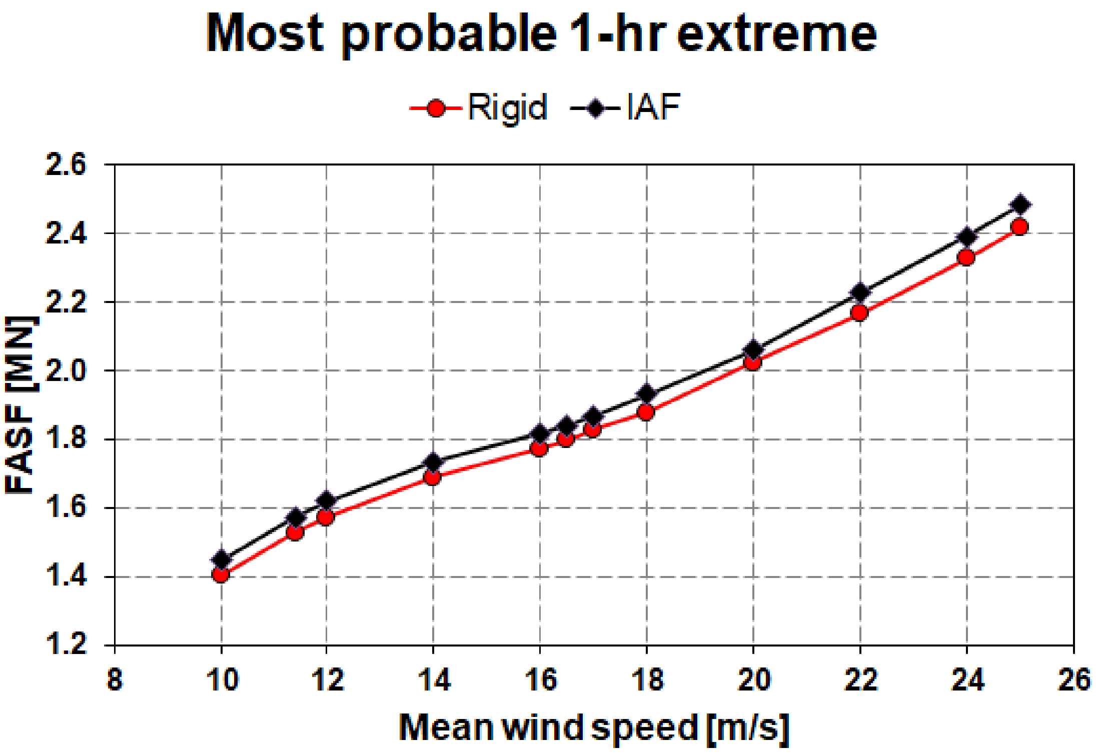
704
705

706


Most probable 50-yr extreme
10min
20min
30min
R.E. - FABM [%]
45.0%
30.0%
15.0%
0.0%
-15.0%
10.0
11.4
12.0
14.0
16.0
16.5
17.0
18.0
20.0
22.0
24.0
25.0
Mean wind speed [m/s]

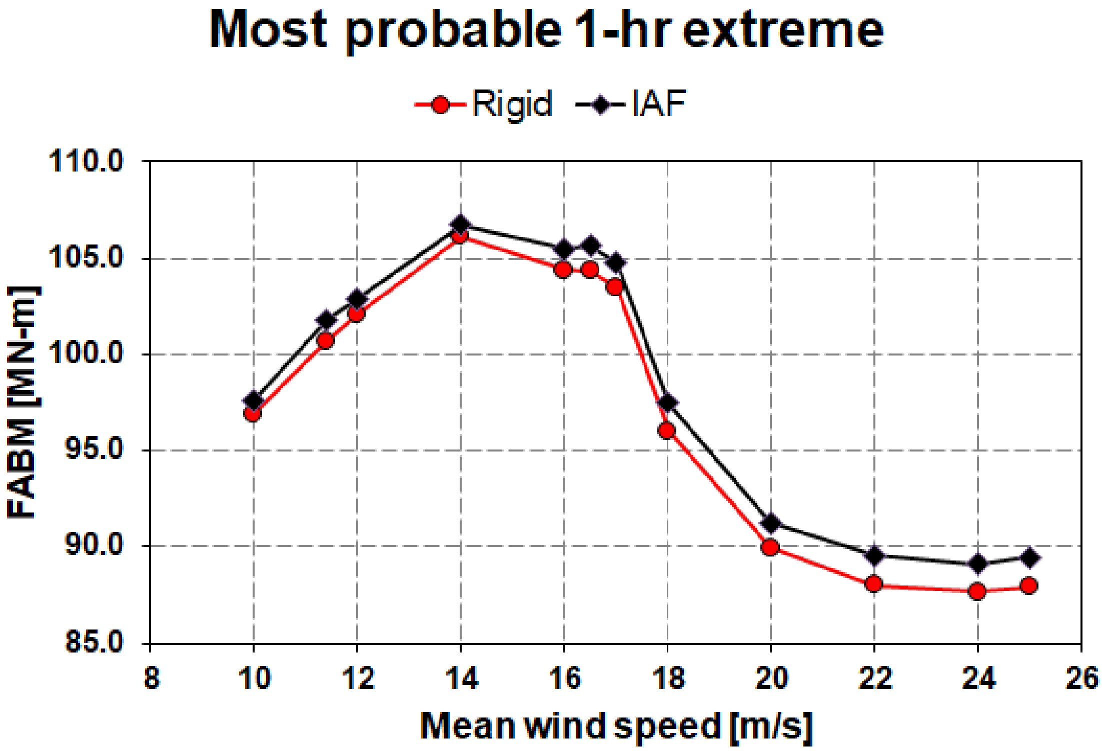
707
708

709

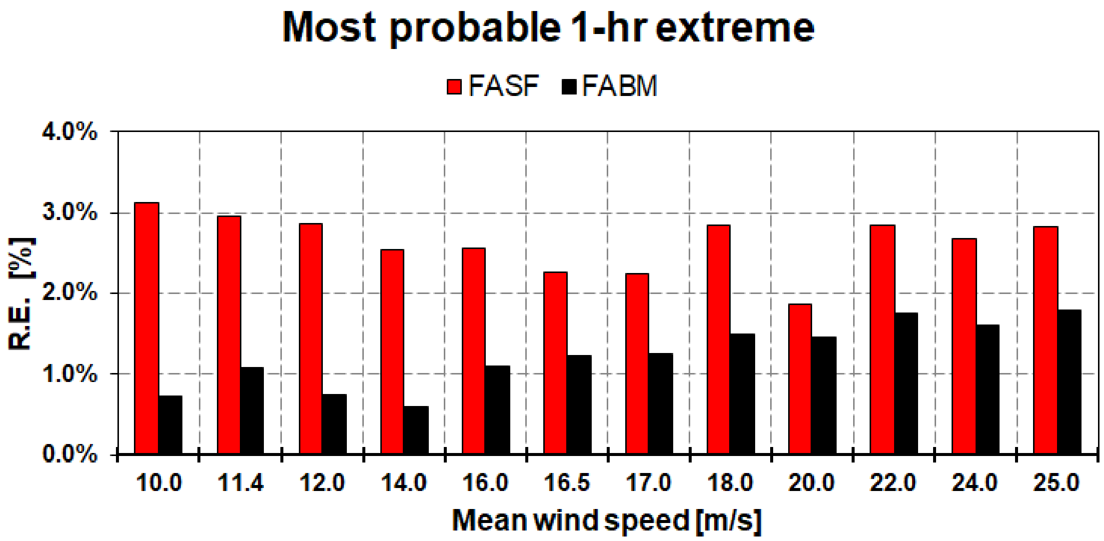

Most probable 1-hr extreme
Rigid
IAF
FASF [MN]
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

710
711

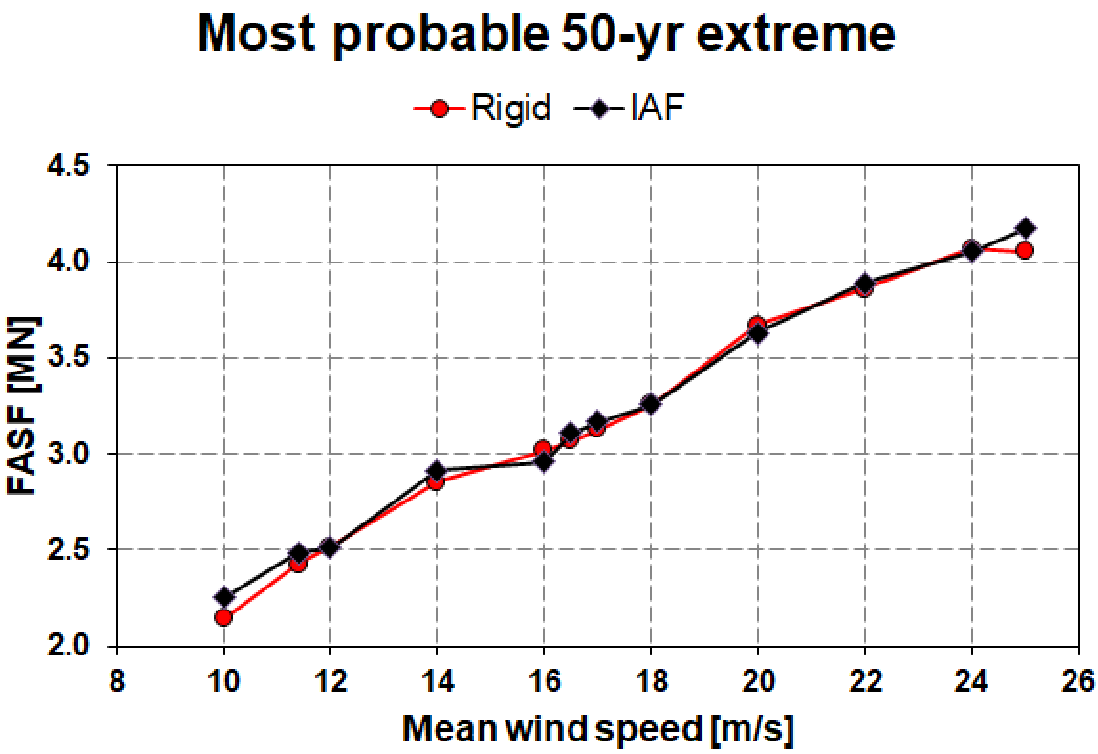
712


Most probable 1-hr extreme
Rigid
IAF
FABM [MN-m]
110.0
105.0
100.0
95.0
90.0
85.0
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

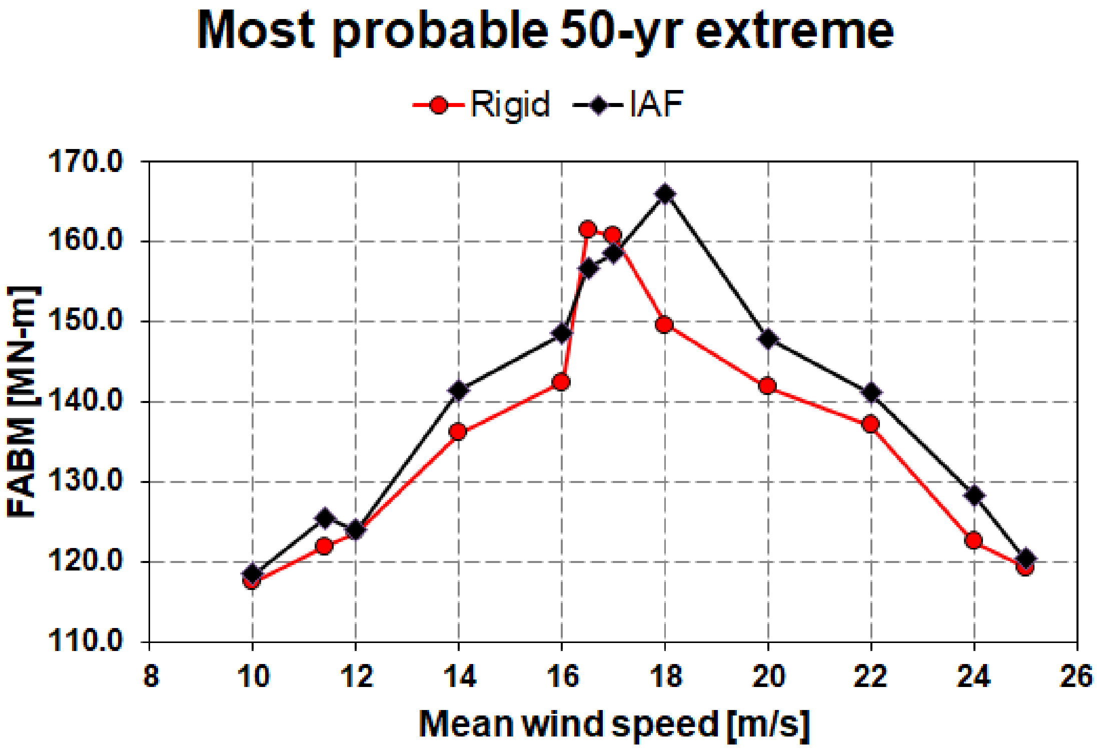
713
714


Most probable 1-hr extreme
🟥 FASF
■ FABM
R.E. [%]
4.0%
3.0%
2.0%
1.0%
0.0%
10.0
11.4
12.0
14.0
16.0
16.5
17.0
18.0
20.0
22.0
24.0
25.0
Mean wind speed [m/s]

718


Most probable 50-yr extreme
Rigid
IAF
FASF [MN]
4.5
4.0
3.5
3.0
2.5
2.0
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

719
720


Most probable 50-yr extreme
Rigid
IAF
FABM [MN-m]
170.0
160.0
150.0
140.0
130.0
120.0
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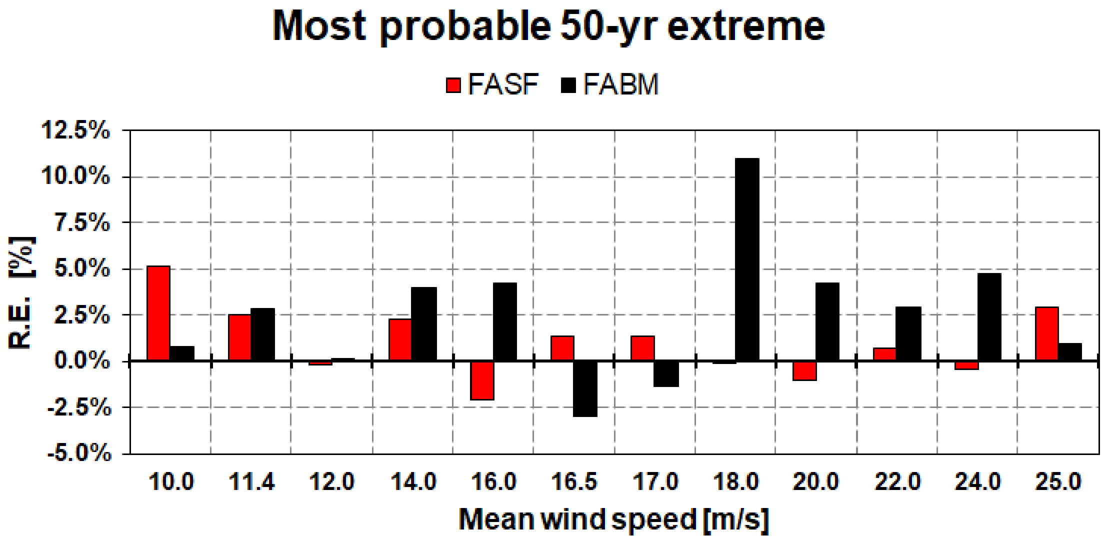
8
10
12
14
16
18
20
22
24
26
Mean wind speed [m/s]

724



725
726
727

Range of p-value	**Quantity of cases**
0.05 - 0.10	18
0.10 - 0.60	68
0.60 - 0.99	34

Environmental Condition	**U_W [m/s]**	**H_S [m]**	**T_P [s]**
1	10.00	1.564	6.969
2	11.40	1.801	6.996
3	12.00	1.908	7.016
4	14.00	2.280	7.112
5	16.00	2.678	7.247
6	16.50	2.781	7.287
7	17.00	2.886	7.328
8	18.00	3.100	7.415
9	20.00	3.545	7.610
10	22.00	4.011	7.828
11	24.00	4.497	8.067
12	25.00	4.748	8.194

50yr conditions for site 15:

U_W=27.20 m/s @10m H_S=8.66 m T_P=6.93 s

Beam	L [m]	D [m]	Thickness [m]	I [m^4]	E [N/m^2]
1	19.88	6.00	0.06	5.089	1.743×10^{12}
2	5.00	6.00	0.06	5.089	1.388×10^{11}