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

1	David Barreto ¹
2	Facultad de Ingeniería Mecánica, Universidad Nacional de Ingeniería
3	Av. Túpac Amaru 210, Rímac 15333, Lima, Perú
4	<u>dbarretol@uni.pe</u>
5	
6	Madjid Karimirad
7	School of Nature and Built Environment, Queen's University Belfast
8	David Keir Building, Stranmillis Road, Belfast, BT9 5AG, Northern Ireland, United
9	Kingdom
10	<u>madjid.karimirad@qub.ac.uk</u>
11	ASME Membership 102188414
12	
13	Arturo Ortega
14	Universidad Autónoma del Perú
15	Panamericana Sur Km 16.3, Manzana 'A', Lote 06, Villa El Salvador, Lima, Perú
16	aortegam@autonoma.edu.pe
17	
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19	ABSTRACT
20	
21	This paper deals with statistical and modeling uncertainty on the estimation of long-term
22	extrapolated extreme responses in a monopile offshore wind turbine. The statistical uncertainty is
23	addressed by studying the effect of simulation length. Modeling uncertainty is explored by evaluating the
24	effects of considering a rigid and flexible foundation. The soil's flexibility is taking into account by
25	considering the improved apparent fixity method. To identify the most relevant environmental conditions,
26	the modified environmental contour method is used.
27	The analysis focuses on the fore-aft shear force (FASF) and the fore-aft bending moment (FABM)
28	at the mudline. The results show that using a simulation length of 10-min, does not provide sufficient

¹ Corresponding author.

29 accuracy. It was found that for the FASF, simulation lengths of at least 30-min are required to achieve an 30 accuracy of about +/-5%. For the FABM, it was found that both the extrapolations made with 20-min and 31 30-min simulations achieved similar levels of accuracy of about 20%. Meanwhile, the results obtained from 32 10-min simulations reached deviations of about 40%. 33 Finally, from the comparison made between a rigid and flexible foundation, it was found that the 34 extrapolated responses exhibit maximum deviations up to around 5% and 10% for the FASF and the FABM, 35 respectively. Also, for the FABM, it was observed that the consideration of a flexible foundation causes the 36 critical wind speed to shift from 16.5 m/s (rigid) to 18 m/s (flexible).

37

38 INTRODUCTION

39

40 Offshore wind energy has been growing in importance over the last few years. 41 Although there are many advantages associated with adopting the use of offshore wind 42 energy, one of the most important is undoubtedly associated with its great potential for 43 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 totalproject investment cost [4].

55 Considering these two points, it is expected that a significant reduction in the 56 LCOE can be achieved by using very large turbines with the most economical foundation 57 available that fully satisfies the reliability requirements of the project. For offshore, fixed 58 foundations have been preferred by most of the projects installed in the world, 59 especially the monopile as it has the lowest relative cost [5]. Given the popularity of this 50 type of foundation, there is still interest in optimizing it to reduce costs without 51 sacrificing reliability.

62 This cost reduction can be achieved through a more detailed understanding of 63 the key uncertainties present in the initial phase of the project that may lead to changes 64 in the current design processes. These key uncertainties are associated with direct 65 impacts on turbine loads (i.e. extreme events, aero-hydro-servo-elastic response, soil-66 structure interaction, and load extrapolation) [6]. Controlling the level of uncertainty in 67 the probabilistic models is expected to produce good and robust predictions of the 68 extrapolated loads/responses associated with target return periods [7], and thus obtain 69 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

75 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.

77 The second type of uncertainty is assessed by taking into account the flexibility 78 of the foundation to evaluate its influence on the long-term responses of a bottom-fixed 79 offshore wind turbine (OWT). The improved apparent fixity model is considered and the 80 results from 1-hr coupled simulations are compared against the results obtained with a 81 fully rigid foundation model. This is done to identify the divergences generated in the 82 extreme long-term responses, particularly concerning the identification of the critical 83 environmental condition. This is a very important aspect that has not received sufficient 84 attention in the current literature.

85 This document is structured as follows. First, a brief description of the uncertainty related to wind energy is presented. Then, the theory behind the 86 87 environmental contour method is introduced, covering the traditional (ECM) as well as 88 the modified (MECM) version. Later, the statistical extrapolation procedure based on 89 the Global Maxima Method is presented. In the following section, the details of the 90 numerical model are explained. Then, the results obtained are presented and discussed. 91 In the last section, the conclusions and suggested aspects for future research are 92 summarized.

- 93
- 94

UNCERTAINTY IN WIND ENERGY

95

96 Uncertainties are present in any natural random process. It is difficult to make
 97 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.

109 A comprehensive understanding of the nature of uncertainties and how to 110 quantify them is crucial to optimize the design phase of offshore wind structures. This 111 aspect has been highlighted in the conclusions of the literature review performed by 112 Jiang et al. [9]. The ultimate goal is to estimate loads as accurately as possible with 113 appropriate levels of reliability but minimizing computational effort. The following two 114 subsections will explore how two specific types of uncertainty arise in the offshore wind 115 industry. The first one, related to the simulation length, and the second one, associated 116 with the foundation flexibility.

- 117 a) STATISTICAL UNCERTAINTY
- 118

119 The offshore wind energy industry can be considered to be still at an early stage 120 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.

127 To alleviate this problem, it is often necessary to perform shorter simulations 128 that can be later extrapolated and, thus, obtain answers about long-term processes. 129 However, this consideration will introduce statistical uncertainty into the results. 130 Therefore, the simulation length needed to achieve an acceptable accuracy of an 131 extrapolated load is a crucial aspect. Choosing a very short time may greatly decrease 132 the computational effort, but will cause the results to have a significant error level in the 133 statistical estimates. Conversely, longer simulations may require more calculation time, 134 but the result will be closer to the true values of the stochastic process parameters.

135 In the wind industry, a simulation length of ten minutes has been considered 136 enough to ensure statistical independence and stationarity [7], and it is currently the 137 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 138 139 common practice in the offshore industry to consider simulation lengths between 3 to 6 140 hours for floating structures [14]. However, if the combined wind and wave loading is 141 considered, the assumption of stochastic independence for periods longer than one 142 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 148 149 was made by Haid et al. [16]. They analyzed simulation lengths between ten minutes to 150 six hours on an OWT supported by a spar-type structure (OC3 Hywind). This study 151 assessed ultimate loads but only in the short term, without applying any type of 152 extrapolation. No technique was applied to obtain some kind of statistical distribution of 153 the extreme values, instead, maximum single values extracted from time series were 154 averaged and then compared. The main conclusion of the study was that a simulation 155 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-overthreshold 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 shortterm 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. Theconclusions of this work indicate that the simulation length is not relevant.

167 Finally, Pillai et al. [19] studied the impact of simulation length on a semi-168 submersible OWT. In this work, no joint distribution of environmental parameters was 169 considered, and only a limited number of wind speeds were evaluated. The results were 170 based on a comparison of the maximum values of the time series, so no characterization 171 of the statistical distribution of the extreme values was made, nor any extrapolation 172 technique was applied. The authors concluded that simulations longer than ten minutes 173 are required to correctly capture the behavior of the system, in contrast to the results 174 found by Haid et al. [16].

Two things can be concluded from the previous paragraphs: there are 175 176 discrepancies among the conclusions of the studies and, there are aspects that have not 177 been taken into account in the current state of the art. The studies have been mainly 178 focused on extreme short-term loads, and only one of them has considered the 179 extrapolation of long-term loads. Also, the analyses have not contemplated fitting the 180 extreme values to a statistical distribution (e.g. Gumbel), this is because in some cases, 181 few stochastic realizations have been considered for the environmental conditions 182 analyzed, and in other cases, the averaging technique have been preferred by the 183 authors. Later, it will be seen that in this work it has been possible to cover these 184 pending aspects thanks to the use of the MECM, which has allowed focusing the 185 computational effort on a specific set of environmental conditions.

186 **b) MODELING UNCERTAINTY**

187

188 This uncertainty is related to the soil-structure interaction. For bottom-fixed 189 OWTs, this aspect is particularly relevant as there are large and direct connections 190 between the substructure and the seabed. The work required to avoid this type of 191 uncertainty is not easy. It is necessary to use more complete models that replicate the 192 physical phenomena with sufficient precision. Particularly, in this paper, we are 193 interested in the long-term extreme responses. Surprisingly, within the literature it is 194 rare to find studies that address the effect of the soil on extreme dynamic responses, 195 being the effects of the foundation model on the fatigue loads or the prediction of the 196 natural frequencies of the system the most addressed topics.

197 An early work that addressed the issue of extreme responses was performed by 198 Bush et al. [20]. In that research, a comparison of a rigid foundation versus a flexible 199 foundation based on the apparent fixity (AF) method was performed in a monopile 200 OWT. In this case, only one wind speed was analyzed and only the fore-aft bending 201 moment at the mudline was considered. Subsequently, this research was extended [21] 202 to include the coupled springs (CS) and the distributed springs (DS) foundation models. 203 Again, only the fore-aft bending moment at the mudline was analyzed for two wind 204 speeds. They concluded that the rigid model underestimates the extreme responses. 205 However, it is important to note that this study was guite limited, and although 150 206 stochastic realizations were performed for each wind speed, the results were mainly 207 based on statistical measures calculated from the samples. They did not fit an extreme 208 value probability distribution to the data obtained from the simulations to find the most 209 probable extreme response.

210 Considering the four foundation models mentioned in the previous paragraph 211 i.e. fully rigid, AF, CS, and DS; the last two are the most complex, but they are expected 212 to replicate the soil flexibility more accurately. However, using very complex models can 213 increase the computational effort required to complete the simulations. Thus, the same 214 problem that was observed with statistical uncertainty arises again. Therefore, it is 215 necessary to use a model that allows finding a trade-off between computational cost 216 and accuracy to reflect the soil-structure interaction. In this way, the most influential 217 aspects can be identified to delimit the domain of the different environmental variables, 218 which will deserve to be analyzed using more complex models at a later stage.

219 The simplest model to take into account the soil-structure interaction is the AF 220 model. Unfortunately, there are some problems with this method, since it is common 221 that only the diagonal terms of the stiffness matrix of the fictive beam are matched, and 222 the cross-coupling stiffness between the horizontal and rotational degree of freedoms 223 are neglected. Løken et al. [12] managed to solve this problem by considering a second 224 fictitious beam with different properties. This method is known as the Improved 225 Apparent Fixity (IAF) Method. The advantage of this model is that it is still simple as AF, 226 and can be properly implemented SubDyn module of FAST. The IAF provides a better 227 replication of the foundation conditions than a rigid model, but at the same time does 228 not increase the computational complexity dramatically. This is the model employed in 229 the present study.

230 ENVIRONMENTAL CONTOUR METHOD: TRADITIONAL AND MODIFIED231

232 Haver et al. [22] proposed the ECM as a practical approach for estimating long-233 term extreme responses by using short-term analysis. In general terms, the method can 234 be summarized in Eq. 1. In this expression, it is assumed that the short-term period is 235 one hour. **F** is the cumulative distribution function of the extreme value (ξ) of the 236 analyzed response X. Hereafter, U_W represents the mean wind speed at the hub height, 237 while **u**, **h**, and **t** represent the mean wind speed measured at 10 m above the still water 238 level, the wave height, and the wave peak period, respectively. The set $\{u_N, h_N, t_N\}$ 239 represents the most relevant environmental condition for a given return period **N**.

$$F_{X_{1 hr,N yr}}(\xi) \approx F_{X_{1 hr}|U_{W},H_{S},T_{P}}^{ST}(\xi|U_{N},h_{N},t_{N})$$
(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].

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

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.

260 To bypass that problem, Li et al. [25] proposed the MECM. It is based on the 261 widely accepted assumption that the long-term probability distribution of a response 262 can be extrapolated from the short-term distribution as short-term extreme values are 263 considered statistically independent in a short-term period e.g. one hour. Then, the 50-264 yr 1-hr extreme cumulative distribution function (CDF) can be written as Eq. 3. This 265 equation implies that the 50-yr extreme response can be found by estimating an 266 extreme response with a lower return period N₀. This procedure helps to bypass the 267 non-linearity on the limits of the operational range of the wind turbine. Since the return 268 period (N_0) will be lower than 50 years, it is necessary to apply an extrapolation to the 269 probability distribution between brackets to estimate the corresponding value of the 270 response at 50 years. This extrapolation is achieved by applying the exponent 50/N₀. 271 The expression between brackets can be found by applying the traditional ECM, Eq. 1,

then it becomes Eq. 4 but, considering the return period N₀. In this case, the extreme
response is calculated using one-hour short-term extreme distribution.

$$F_{X_{1 hr,50 yr}}(\xi) = \left[F_{X_{1 hr,N_{0} yr}}\right]^{50/N_{0}}$$
(3)

$$F_{X_{1 hr,50 yr}}(\xi) = \left[F_{X_{1 hr|U_{W},H_{S},T_{P}}}^{ST}(\xi|u_{N_{0}},h_{N_{0}},t_{N_{0}})\right]^{50/N_{0}}$$
(4)

274 Consequently, the MECM focuses on finding the return period N_0 in which the 275 maximum long-term extreme response is achieved. To reach this goal, many inner 276 environmental contours corresponding to wind speeds within the operational range of 277 the turbine need to be tested. The condition that provides the greatest response 278 among all the conditions tested will be the most important environmental condition or, 279 it can be also referred as the critical environmental condition. The return period that 280 corresponds to this important condition will be the return period required, N₀. A specific 281 procedure to apply the MECM to bottom-fixed OWTs under the combined action of 282 wind and wave can be found in [25].

283 LOAD EXTRAPOLATION

284

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.

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

290 As previously stated, it is necessary to have the 1-hr extreme probability 291 distribution for the extrapolation of 50-yr extreme responses using the MECM. This can 292 be achieved by running one-hour simulations or by using shorter simulations and then 293 applying an extrapolation to arrive at a one-hour level. For this purpose, extreme values 294 extracted from 10-min, 20-min, 30-min, and one-hour simulations are used to compare 295 the deviations in the most probable values of the fitted Gumbel distributions. After 296 extrapolation, the most probable value of the Gumbel distribution is given by Eq. 6. In 297 this equation, N₀ is the return period of the environmental condition (EC) tested. The 298 parameter \mathbf{r} will depend on the simulation length from which we have extracted the 299 extremes for fitting purposes. The value of r is 1, 2, 3, or 6 if the extremes for the 300 Gumbel fitting come from 1-hr, 30-min, 20-min or 10-min simulations, respectively.

$$Mo_{X} = \mu_{G} + \beta_{G} \cdot \ln(r \cdot 50/N_{0})$$
(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.

306 Considering that 2 dynamic responses, 12 environmental conditions, 2 different 307 foundation models, and 4 simulation lengths were analyzed, a total of 120 parameter 308 estimates were made. The goodness of fit is determined by the p-value obtained after 309 performing a hypothesis test based on Moran's statistic, which is implemented in WAFO 310 [27]. The criterion for accepting the parameter fit is that the calculated p-value is

311 greater than 0.05 (significance level). The higher the p-value, the better the goodness of 312 fit. Table 1 presents the number of parameter estimation cases grouped by the range of 313 the p-value obtained. It is observed that in 102 cases, out of a total of 120, the p-values 314 are higher than 0.10.

315 NUMERICAL MODEL

316

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.

334 For each wind speed, there will be an associated sea state and then, it is 335 necessary to set the values for the wave height (Hs), peak spectral period (Tp), and the 336 cut-off frequencies of the wave spectrum in the input files of FAST [32]. Wave profiles 337 are generated internally with HydroDyn [33] and using the JONSWAP spectrum with a 338 peak-shape parameter of 3.3. The heading wave direction is set to 0° and the water 339 depth is 20 m. The analysis time considered for incident wave calculations is 3630 s. 340 Additionally, one hundred simulations have been performed with different random 341 seeds for each environmental condition tested.

342 The monopile that supports the turbine has a diameter of 6 m and a thickness of 343 0.06 m, and it is considered fully constrained at the seabed for the first part of this work. 344 An important part of achieving accurate dynamic responses when considering wave 345 loading is to properly set the Morison coefficients for drag (C_D), added mass (C_A), and 346 pressure (C_P). The usual ranges for these values are: $1.5 \le C_P + C_A \le 2$ and, $0.6 \le C_D \le 1.2$, 347 according to [34]. For this work, the coefficients have been taken as CD=0.9, CA=0.75, 348 $C_P=1$, for a detailed explanation about the selection of these values the reader is 349 referred to [35] which is also supported by [36]. Other input parameters have been left 350 as they were defined in the NREL 5MW baseline. For the part of the analysis regarding 351 the inclusion of the soil flexibility, the IAF method has been taken into account, more 352 details of this model can be found in [12]. A scheme of these two fictitious beams with 353 three nodes can be seen in Fig. 1. Here, the lowest node (N_1) has a fully rigid condition. 354 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].

357 **RESULTS**

358

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/N₀, 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, 1hr 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.

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

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

a) Effects of simulation length

374

375 First, the trend of the most probable values extrapolated from extreme values 376 obtained from 10-min, 20-min, and 30-min simulations will be analyzed. All these values 377 have been extrapolated to the level of 1-hr. The trend for the FASF is shown in Fig. 2; it 378 can be also observed the most probable value obtained from one-hour simulations 379 fitting. As can be seen, the difference between the extrapolated most probable values is 380 small in comparison to the trend obtained with the one-hour simulations (black line 381 with diamonds). In the case of the FABM, Fig. 3, a slightly greater variation is observed. 382 In this case, the extrapolation obtained from 30-min simulations is the one that best 383 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

397 divergence for FASF becomes greater; being the extrapolation obtained from the 30 398 minutes simulations the one that comes closest to the value obtained from 1-hr 399 simulations. In the case of the FABM, Fig. 7, all extrapolations show a significant 400 deviation from the 1-hr case, but the extrapolation obtained from 10-min has the 401 largest difference. It can also be seen that both the 20-min and 30-min extrapolations 402 perform almost the same. Also, it is observed that the critical environmental condition 403 for 10 minutes simulations moves from 16.5 m/s to 17 m/s for the case of 20-min and 404 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).

412 **b) Effects of flexible soil**

413

414 In this section, the effects of considering the soil flexibility through the IAF soil 415 model on load extrapolation will be explored. For this analysis, 1-hr simulations are used

415 model on load extrapolation will be explored. For this analysis, 1-hr simulations are used 416 and extrapolation is applied to reach 50-yr levels. In Figs. 10 and 11, the trend of the 417 most probable values of the extreme responses in 1-hr can be observed for FASF and 418 FSBM, respectively. As it can be noticed, the difference between both curves is small. 419 Similarly, in Fig. 12 the relative errors for the FASF and the FABM are observed. In this

420 case, the comparisons are made between the response obtained considering the IAF
421 and the response obtained with the rigid foundation. So, an increase of up to about 3%
422 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 428 4%, and the FABM reaches up to 10% for 18 m/s where the critical mean wind speed is 429 found.

430 CONCLUSIONS

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432 One of the main concerns for the development of offshore wind energy is the 433 reduction of the LCOE. It has been identified that one of the ways to achieve this is to 434 control the level of uncertainty present in the initial phase of the projects that could 435 lead to changes in the current design processes and thus help to avoid over-436 conservative designs with excessive material. This would produce good and robust 437 predictions of the short- and long-term dynamic responses associated with specific 438 return periods. However, this is not an easy task, especially when dealing with extreme 439 responses, as it involves the simulation of several stochastic realizations for each 440 environmental condition. This implies the use of large computational resources, which 441 are not often accessible. So a mandatory step in this line of research is to find a trade-442 off between the accuracy of the results and minimizing the computational cost.

443 The present work has focused on the understanding of uncertainties in a 444 monopile OWT and, it has addressed the study of two issues of particular importance: 445 the simulation length (statistical uncertainty) and the foundation flexibility (model 446 uncertainty). In the initial part of this research, attention was focused on analyzing the 447 influence of the simulation length on the long-term extrapolation process of two types 448 of dynamic responses. From the review of previous research, it was seen that there is no 449 consensus on the minimum time to be considered in the simulations. Also, it was found 450 that in most of the papers, certain aspects had not been taken into account and that 451 could have influenced their conclusions. Among these aspects, which have been covered 452 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

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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.

505 The extreme value analysis was done based on one-hour simulations,
 506 since shorter simulations produce significant deviations when applying

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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.

521 The main finding of this research is that the inclusion of a flexible foundation in 522 the model leads to a shift of the critical wind speed, as well as an increase in the value of 523 the extrapolated response for the FABM. This wind speed is very important since it 524 allows restricting the short-term conditions to be considered when more accurate 525 techniques are required to find the value of the long-term extreme response, e.g. the 526 simplified long-term analysis (SLTA). An additional finding is that FASF and FABM are 527 found to be weakly sensitive to the inclusion of foundation flexibility in the short term, 528 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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670 671	Figure Captions List				
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		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			
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		with respect to most probable values from 1-hr simulations for the			
		FABM.			
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		level from simulations versus mean wind speed for FASF.			
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level from simulations versus mean wind speed for FABM.

Relative errors of the most probable values extrapolated to 50-yr level

- Fig. 8 with respect to most probable values extrapolated from 1-hr simulations for the FASF.
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Fig. 15Relative error of extreme response extrapolated to 50-yr level for FASF
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674 675	Table Caption List				
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	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].			
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Most probable 1-hr extreme



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Most probable 1-hr extreme



690 Most probable 1-hr extreme ■10min ■20min ■30min 6.0% 4.5% R.E. - FASF [%] 3.0% 1.5% 0.0% -1.5% -3.0% 11.4 12.0 14.0 16.5 17.0 18.0 20.0 10.0 16.0 22.0 24.0 25.0 Mean wind speed [m/s] 691 692



Most probable 50-yr extreme









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Most probable 1-hr extreme --Rigid --IAF 2.6 2.4 2.2 LASE [MN] 2.0 1.8 1.6 1.6 1.4 1.2 20 10 14 16 18 22 24 26 8 12 Mean wind speed [m/s] 710 711











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

7	2	1
1	3	T

Environmental Condition	Uw [m/s]	Hs [m]	Т _Р [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:

 $U_W=27.20 \text{ m/s} @10 \text{m} H_S=8.66 \text{ m} T_P=6.93 \text{ s}$

7	3	4
7	3	4

Beam	L [m]	D [m]	Thickness [m]	I [m ⁴]	E [N/m ²]
1	19.88	6.00	0.06	5.089	1.743x10 ¹²
2	5.00	6.00	0.06	5.089	1.388×10^{11}