DIME

Design and metocean: modelling and observations of extreme sea states for offshore renewable energies

Recommendations Report

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INFORMATION ABOUT THE DOCUMENT

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I.Introduction

The aim of the document is to produce a set of recommendations for the industry based on the DIME project results. The DIME project focused on improving the characterization of breaking waves in the context of slamming loads on offshore wind turbines design. In this regard, the DIME partners investigated the following research axes:

- The proposal of a new wave breaking criterion;
- The development of deterministic wave models for breaking and steep waves;
- The observation and parameterization of the statistics of breaking waves in storm conditions;
- The development of spectral wave models for the simulation of storm sea states;
- The characterization of slamming forces in the context of engineering studies.

This document is structured around 4 chapters that present the key results of the project and the recommendations that follow. The first chapter addresses storm waves hindcasting. After a comparison between two wave hindcast databases and in situ observations, it focuses on the evaluation of the capabilities of spectral models to represent storm conditions. It also provides an analysis and recommendations for directional and frequency spreading to be considered for storm sea states. The second chapter analyses on different phase resolving models' capabilities in representing the wave properties of interest for slamming loads assessments. The third chapter presents an analysis of slamming forces

assessment, applying engineering approaches, using fully nonlinear model outputs with a comparison to analytical solutions classically used in the industry, for the wave geometry and kinematics. Finally, the last chapter gives perspectives on the definition of the sea state and the design wave to be considered for the specific problem slamming forces on offshore renewable energy (ORE) systems.

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II. Extreme climatology

1 HOMERE/ANEMOC databases comparison

A study was conducted as part of the DIME project to compare the numerical sea state databases ANEMOC (Benoit *et al.*, 2008; Laugel *et al.*, 2014) established using the TOMAWAC model (Benoit *et al.*, 1997) and HOMERE (Boudière *et al.*, 2013), established using the WAVEWATCH III® model (Tolman, 2002; Ardhuin *et al.*, 2010). The study focused on the evaluation of statistical error metrics for several parameters, between the two numerical data sets on the one hand and between each numerical data set and the in-situ measurement data extracted from the directional buoy database of the CANDHIS network operated by Cerema on the other. The parameters were the significant wave height H_{m0}, the mean direction, the directional spread and the three wave periods T_{02}, T_p and T_e. The comparative study was conducted at nine control points along the coasts in the English Channel and the Bay of Biscay corresponding to the mooring points of the reference measurement buoys.

This study mainly focused on the ability of the models to correctly represent extreme events and their evolution. A comparative analysis of the most energetic sea states identified at nine sites in the Channel - Bay of Biscay domain covered by the databases shows that although the models can correctly reproduce these events on a synoptic scale, with good temporal synchronization, relatively large differences are observed in the distributions of the highest significant wave heights within the storms.

It is also noted that the trends in deviations between models and buoys vary from one site to another so that it is not possible to introduce a single correction law. This variability around the tails of the distribution of significant wave heights must be considered. It will have a significant influence on the level of confidence in the estimation of the 50- and 100-year return values extrapolated from these datasets.

In the analysis of the temporal evolution and persistence of strong events, it is also necessary to consider the potential simultaneous existence of wave systems with a dynamic significantly different from that of the wind sea. A study based on the evolution of partitioned wave systems that may coexist within these storms can help to clarify these temporal dynamics. The improvement of the representation of storm events by spectral models was one of the final objectives of DIME, as detailed hereinafter.

2 Recommendations on the forcings and physical parameterization of the WAVEWATCH III®

Ruju *et al.* explored in 2020 the performance of the spectral model WAVEWATCH III® (Tolman, 1990) to reconstruct storm sea states, in the Northeast Atlantic, up to the French Channel-Atlantic coast. The study focuses on the sensitivity of the results to wind forcing, known to be one of the main sources of error, and to the source terms that parameterize the physical processes of wind-induced wave growth, dissipation by breaking and friction on the bottom, and nonlinear energy transfers between spectral components.

This work focused on the winter of 2013-2014, known for the frequency and intensity of storms that agitated the area of interest, and used satellite and wave data for estimating model performance offshore and inshore, respectively. The model is based on a grid covering the globe with a regular mesh of 0.5 deg horizontal resolution, to capture waves in the offshore domain, forcing an unstructured grid covering the continental shelf and allowing to represent more finely the coastal processes affecting the wave transformation (friction on the bottom, refraction, etc...).

The evaluated wind fields are those from a compilation of satellite observations (Bentamy *et al.*, 2019) and the ERA reanalysis (Hersbach *et al.*, 2019). The conclusions of this work are as follows:

- Model performance generally decreases as one moves closer to the coast. The reasons put forward are the complexity of the coastal processes to be parameterized in the model and the quality of the associated forcings or input data (bathymetry and current in the first place), as well as local effects (orography, hydrography).
- With a given parameterization of the model, the use of winds from satellite data tends to increase the normalized bias. This is probably related to an underestimation of strong winds by the ECMWF reanalyses used to calibrate the model.
- Overall, the low frequency part of the spectrum is underestimated by the models or is not modeled correctly (presence of infra-gravity waves). Similarly, the contribution of the reflection of waves at the coast is not represented. We note that a parameterization exists in the WAVEWATCH III® model to capture these effects (Ardhuin and Roland, 2012; Ardhuin *et al.*, 2014).
- H_s values at the peak of storms are systematically underestimated (between 12 and 15%) in the open ocean and coastal areas.
- Increasing the temporal resolution of the wind (from 3h to 1h) only marginally (but positively) affects the model scores.
- In conclusion, as it stands, the combination of ECMWF winds and "TEST500" parameterization proposed by Filipot and Ardhuin in 2012 is the best alternative for simulating storm sea states using the WAVEWATCH III® model.

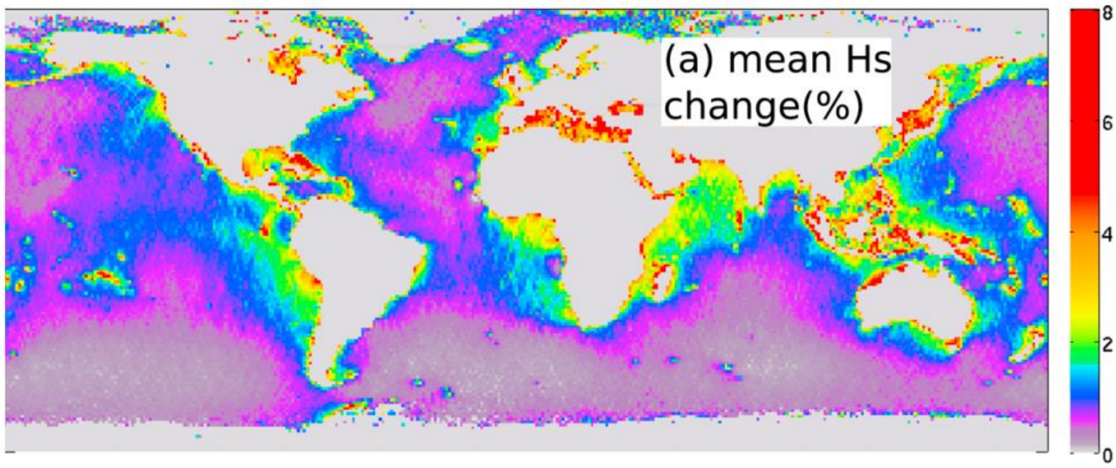

Figure 1. Effect of wave reflection at the coast on the significant height, H_s (from Ardhuin and Roland, 2012)

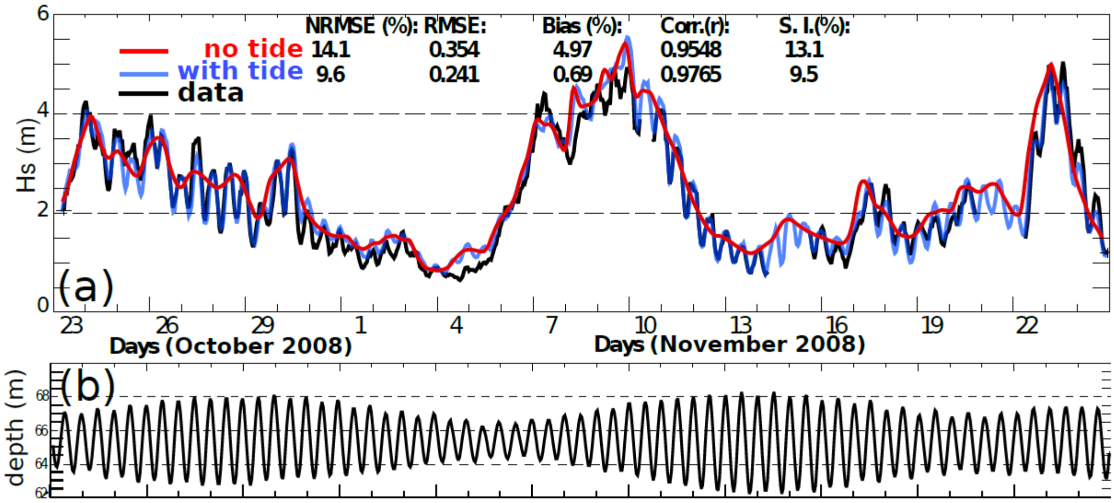

Figure 2. Sensitivity of wave forecasting by spectral model to the tidal current at buoy 62069 located at Pierres Noires, Brittany (from Ardhuin *et al.*, 2012)

3 Spectral shape in storm condition

The energy distribution within the sea states is classically represented by parametric functions describing the frequency-directional distribution of the wave energy density. These functions, or spectra, depend on several global parameters, including a wave height (significant height H_s or H_{m0}), a period (T_{02} or T_p), a wave propagation direction (mean direction θ_m or peak direction θ_p) and a directional spreading parameter (σ). These spectra are most often decomposed into a product of functions: a frequency spectrum and a characteristic function of the directional distribution:

$$S\,(f,\theta) = S\,(f).D(\theta) \quad \text{(A)}$$

The most used function to represent the spectral energy distribution is the JONSWAP spectrum (Hasselmann *et al.*, 1973) which introduces into the Pierson-Moskowitz formulation (Pierson Jr and Moskowitz, 1964) defined for established sea states, a supplementary parameter providing an additional degree of freedom on the spectral width of the energy density distribution. This spectral spread parameter, the peak enhancement factor γ, classically takes values between 1 (Pierson-Moskowitz, established wind sea) and 7 (narrow spectral band, most often associated with swell). A study was carried out in the DIME project aiming to evaluate the representativeness of extreme sea states by a JONSWAP spectrum and to specify the optimal values of the spectral spreading parameter γ for these extreme conditions. The study is based on the analysis of time series of spectra from the HOMERE database, at ten control points in the Channel and the Bay of Biscay. Nine points in intermediate to shallow water areas and one reference point offshore in deep water (see Table 1). The time series cover the period 1994-2019 (26 years).

3.1 Unimodal character of the extreme sea states

The JONSWAP formulation assumes that the considered sea state is unimodal, i.e., composed of a single wave system, resulting from the same atmospheric event, whether it took place locally (wind sea) or at a distance (swell). First, it is necessary to verify that the extreme events have a unimodal form. For this, we use the results of the partitioning data available in the HOMERE database. The wave systems identified by the model correspond to a wind sea and a maximum of five swells, classified by energy level. For the distribution of total significant heights, the distribution of significant heights of wind sea events alone, and the distribution of significant heights of unimodal swell events, the significant height values associated with the quantiles [0.25 0.5 0.75 0.95 0.98] are evaluated (Figure 3 top). The percentage of occurrence of unimodal sea states for these different quantiles is also evaluated considering, on the one hand, all unimodal sea states and, on the other hand, unimodal wind seas only and unimodal swells only. The criterion used to identify a unimodal wind sea state (respectively unimodal swell) is the strict criterion that the significant height of the wind sea partition (resp. the significant height of the primary swell) is equal to the total significant height of the sea state. An increasing evolution of the percentage of unimodal sea states with quantiles is observed on the ten control points (Figure 3 bottom). For the 0.98 quantile, unimodal sea state conditions represent about 80 % of the cases, varying globally between 70% and 90% depending on the site (Table 1, Figure 3 example of Groix site). Unimodal energetic sea states are mostly associated with wind seas, except at the ANGLET site, in the southeast of the Bay of Biscay, where swells dominate. Unimodal swell conditions in the Channel, east of Cotentin, are almost non-existent (less than 1%). We also note that on most sites the value of the significant wave height associated with the 0.98 quantile of wind seas alone is greater than the significant wave height established for this same quantile considering all sea states. The extreme sea states can therefore be considered as mostly unimodal with a distribution of strong significant wave heights more important within the unimodal wind seas.

3.2 Evaluation of the spectral spreading parameter γ

Various formulations are proposed in the literature to evaluate the spectral spreading parameter or peak enhancement factor γ as a function of different global parameters and of the ratio of the characteristic periods, mean period T_{02} and peak period T_p.

(DNV-GL, 2018)
$$T_{02} + Tp = \sqrt{(5+\gamma)/(10.89+\gamma)} \quad \text{(B)}$$

(Isherwood, 1987)
$$T_{02} + Tp = 0.0603 + 0.1164\sqrt{\gamma} - 0.01224\gamma \quad \text{(C)}$$

(Stansberg *et al.*, 2002)
$$T_{02} + Tp = 0.6673 + 0.05037\gamma - 0.006230\gamma^2 + 0.0003341\gamma^3 \quad \text{(D)}$$

Saulnier proposes a relation between the spectral spreading parameter γ and the peakedness factor Qp defined by Goda.

(Saulnier, 2013)
$$Q_p = 1.42 + 0.58\gamma - 0.016\gamma^2 \quad \text{(E)}$$

The variability observed in the estimation of the periods and in particular the ratio T_{02}/T_p for extreme sea state distributions did not allow to exploit these formulations in a satisfactory manner. For this study, we therefore choose to evaluate the spreading parameter γ by fitting JONSWAP spectra to the time series of frequency spectra in the HOMERE database, at each of the control points. We consider in these time series only the spectra of events whose significant wave height H_{m0} is higher than the value of the quantile 0.98 and identified as being unimodal. The fitting procedure minimizes the Normalised Root Mean Square Error (NRMSE) estimator evaluated over the entire frequency band, between the reference spectrum and the theoretical JONSWAP spectra of the same significant height and peak period and having γ values in the range [1 -7]. The mean spectral spread parameter and associated standard deviation are then evaluated for each site (Table 1). The γ values obtained range from 1.28 to 1.55 depending on the site considered. However, it was not possible to establish a correlation with the mean values of the other statistical parameters (mean significant wave height, mean peak period) or with the geographical location of the sites. The three highest values of γ are observed at the offshore reference point (W0035N455), at the ANGLET point in the southeast of the Bay of Biscay and at the COURSEULLES point along the East Channel coast (γ=1.55, γ=1.54 and γ=1.47 respectively). The plots of normalized spectra as a function of frequency scaled by a reference frequency (energy frequency f_e, peak frequency f_p and mean frequency f_{02} respectively) shown in Figure 4 highlight the variability of spectral shapes associated with extreme unimodal events. The spectra presented in this figure are scaled according to the following relation:

$$S_a\left(\frac{f}{f_{ref}}\right) = f_{ref}.S(\frac{f}{f_{ref}})/m_0 \quad \text{(F)}$$

with $$f_{ref} : f_e = 1./T_e \, , f_p = 1./T_p \, , f_{02} = 1./T_{02}$$

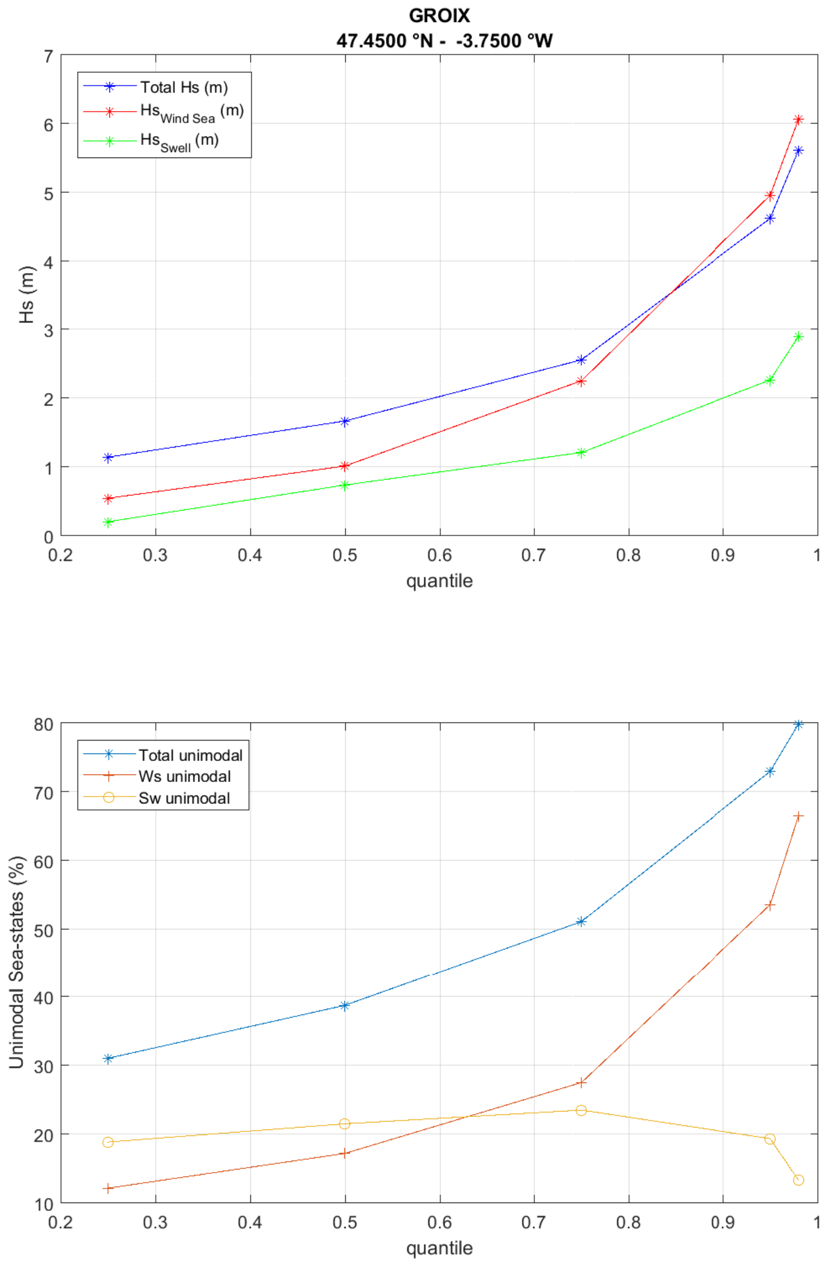

Figure 3. Distribution of unimodal sea state conditions. Top figure: Significant wave height associated with quantiles for the complete sea states (Total), the wind sea component and the set of swell components (Swell). - Bottom figure: percentage of occurrence of unimodal sea states: All unimodal sea states (Total), unimodal wind sea only (Ws), unimodal swell only (Sw)

Tableau 1. Identification of the spectral spread parameter in the Channel and Bay of Biscay

Site	Long.	Lat.	Depth (m)	H_{mo} QT0.98 all sea states (m)	H_{mo} QT0.98 wind sea (m)	H_{mo} QT0.98 waves (m)	Unimodal QT0.98 occurrence all sea states (%)	Unimodal QT0.98 occurrence wind sea (%)	Unimodal QT0.98 occurrence waves (%)	Gamma (average)	Gamma (standard deviation)	Directional spread (average)	Directional spread (standard deviation)
COURSEULLES	-0.5302	49.4712	29.3	2.16	2.24	0.73	68.47	68.39	0.09	1.47	0.303	26.74	3.31
CHANNEL	-0.4018	50.1169	49.9	3.59	3.69	1.27	78.24	78.24	0.00	1.36	0.207	25.90	4.35
SAINT-BRIEUC	-2.5422	48.8383	39.0	2.81	2.92	1.73	72.61	70.87	1.74	1.35	0.267	22.16	3.64
GROIX	-3.7350	47.4472	83.6	5.61	6.06	2.90	79.86	66.51	13.34	1.40	0.232	26.22	3.44
BELLE-ILE	-3.3046	47.3031	55.6	5.31	5.76	2.65	82.42	73.89	8.54	1.34	0.224	25.52	2.99
SEMREVO	-2.7858	47.2416	38.1	3.94	4.17	2.23	78.77	76.24	2.53	1.31	0.210	25.51	2.65
YEU	-2.3865	46.6777	36.0	4.71	5.15	2.45	82.92	77.93	4.99	1.28	0.184	24.20	2.60
CAP-FERRET	-1.4498	44.6557	53.3	4.69	5.29	2.55	85.80	68.70	17.10	1.44	0.250	23.78	2.18
ANGLET	-1.6082	43.5293	54.7	4.23	5.52	2.09	88.38	39.73	48.65	1.54	0.316	19.97	1.42
W0035N455	-3.4983	45.5221	1,855.9	6.21	6.53	3.17	74.55	56.52	18.03	1.55	0.291	26.96	2.71

Analysis of the distribution of the spectral spread parameter γ as a function of the mean directional spread σ (see WAVEWATCH III® User Manual) does not reveal any specific relationship between these two parameters. We observe that for the unimodal sea states of the strong events considered, this directional spread is relatively small, taking on the whole set of studied sites values ranging from 20 deg. to 35 deg.

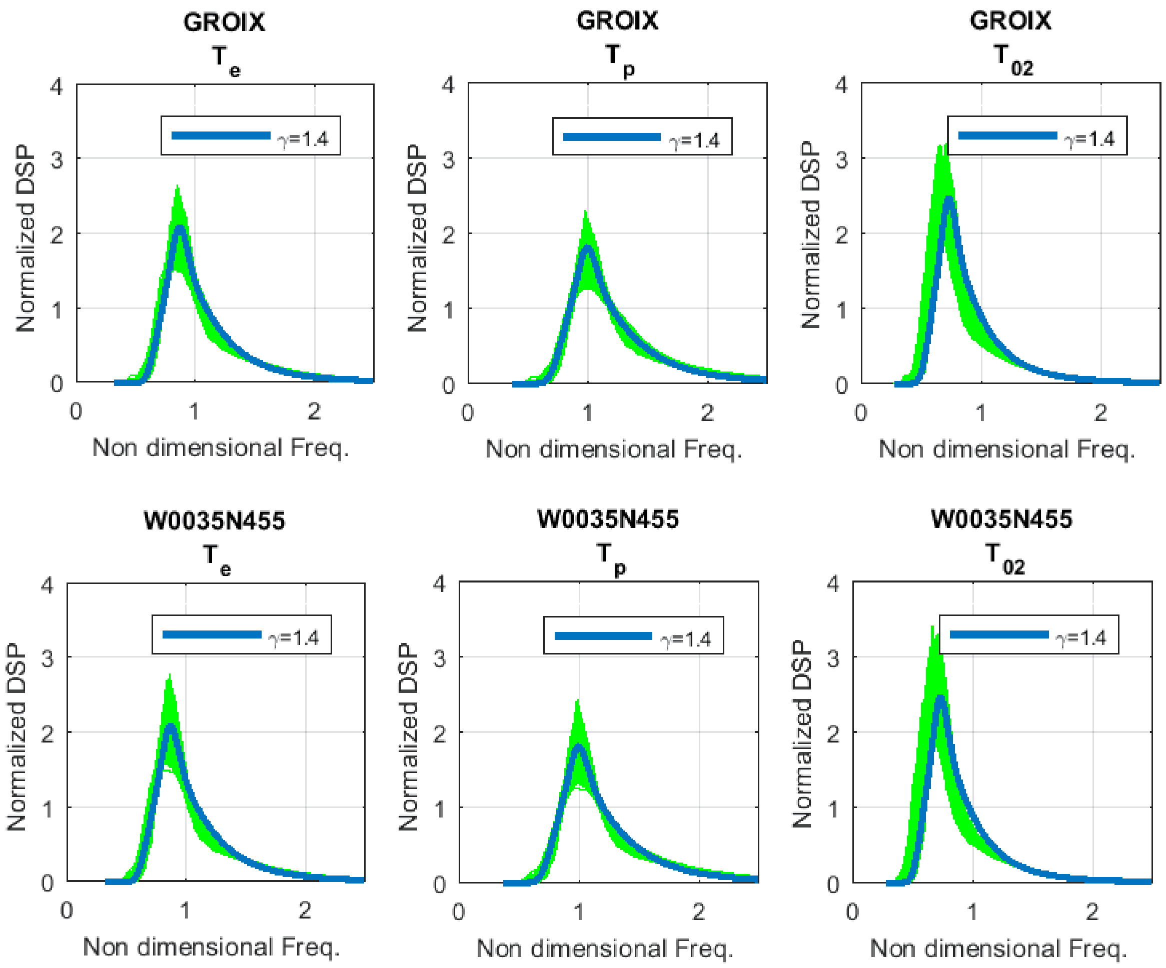

Figure 4. Distribution of normalized spectra for extreme events (Groix site (top) - offshore site W0035N455 (bottom)) as a function of frequencies scaled by f_e, f_p and f_{02} respectively

RECOMMENDATION 1
If the WAVEWATCH III® model is used to generate an hindcast to characterize the design conditions, the combination of ECMWF winds and "TEST500" parameterization is the best alternative to simulate the storm sea states.

RECOMMENDATION 2
In coastal areas, to reduce uncertainty in spectral model outputs, special attention must be paid to the quality of the following forcings: bathymetry, current fields, water levels and bottom roughness.

RECOMMENDATION 3
Sea states associated with extreme events are essentially unimodal wind seas. It is therefore necessary to ensure that the extreme sea state parameters selected for design studies are based on unimodal wind sea event statistics.

RECOMMENDATION 4
Under unimodal sea state conditions, the JONSWAP formulation allows for a realistic representation of the frequency distribution of the energy density within the extreme sea states. In this case, for the Channel and Bay of Biscay areas, a mean value of the frequency spread parameter of the order of 1.4 is recommended. The standard deviation associated with this average value is of the order of 0.25.

RECOMMENDATION 5
The sea states associated with extreme events unimodal wind seas, show relatively narrow directional spreads in the Channel and Bay of Biscay areas. A mean value for the directional spread of about 25 deg. is recommended. The standard deviation associated with this average value is about 3 deg.

III. Phase resolved simulations of breaking waves: tools developed and used in the DIME project and associated limitations

1 Fully nonlinear potential approached: the FNPM-BEM model

The DIME project was based on the FNPM-BEM (Fully Nonlinear Potential flow Model-Boundary Element Method) developed by Grilli and Subramanya in 1996. It is a model capable of reproducing a Numerical Wave Tank (NWT) in two dimensions. It solves for mass conservation by the BEM method and the kinematic and dynamic fluid properties are explicitly integrated at the surface, at computational nodes. The interior properties of the fluid can be derived explicitly from the quantities estimated at the free surface. This method allows to capture the nonlinear evolution of the waves until breaking, however the calculation stops when the jet touches the surface in front of the breaking crest.

The advantages of the code are:

- its computational cost: the simulation of a breaking wave takes a few minutes on a standard personal computer;
- the precision of the simulations, up to the crest overturning, which makes the code a tool that is certainly relevant for finely estimating the geometric and kinematic breaking waves properties.

Its drawbacks are the following:

- It is a research code that requires interaction with its developer, Pr. Stephan Grilli from the University of Rhode Island in USA for a proper application;
- The version tested was able to simulate 2D wave only (a 3D version exists see for instance Corte *et al.*, 2006);
- With the available version, the simulation stops at the first breaking wave: it is impossible to simulate irregular sea states, with several breakers. A version in development, including a dissipative term preventing the crest overturning, is under development (Grilli *et al.*, 2019).

2 Boussinesq approaches: the BOSZ model

The DIME project has supported the use and development of the BOSZ model, developed by Volker Roeber from University of Pau and Pays de l'Adour and introduced for example through Roeber *et al.* in 2010. The model had attracted the interest of the project partners for its ability to represent the kinematic and dynamic properties of three-dimensional irregular sea states in realistic configurations, i.e., at the scale of an ORE site. A thorough analysis proposed in Audrey Varing's thesis of the model's ability to capture fluid velocities in breaking crests has shown limitations of the model for this specific application.

The main limitation is that the physical equations are solved at mid-depth. In the case of very nonlinear waves in shallow water, the reconstruction of the vertical velocity profile up to the crest, based on parametric laws, is largely flawed. These results show that weakly dispersive Boussinesq approaches, even if they allow to capture the irregular character of waves in coastal and nearshore areas, are probably not a viable solution to capture the physical quantities of interest for estimating slamming loads, and in particular the velocity distribution in the crest and crest geometry.

An alternative FNPM code to that proposed by Grilli and Subramanya in 1996 has also been developed in the DIME project. The main advances are described by Papoutsellis *et al.* in 2019 and allow the simulation of two-dimensional regular waves on random bathymetries. A major difference from the code described in the previous section is the introduction of a dissipative term that allows the simulation to continue beyond breaking onset. Comparisons of observed and modeled free surface in the channel indicate that the code would be able capture the breaking waves asymmetry and skewness. Further efforts carried out outside of the DIME project by Simon *et al.* in 2019 demonstrated similar skill for irregular 2D waves over random bathymetries. However, the ability of the models to capture fluid velocities in breaking and nearly breaking wave crests has not been studied.

RECOMMENDATION 6
If the design wave can be approximated by a regular wave train, solitary wave, or wave packet, potential fully nonlinear models capture the information needed to estimate slamming forces.

RECOMMENDATION 7
While consideration of the irregularity of the design sea state is important, fully nonlinear approaches with dissipative terms are now available.

IV. Loading of a breaking wave on a bottom-fixed offshore wind turbine

An approach recommended in the codes DNV-42, DNV-GL-36, DNV-39 and used to evaluate the design forces on a wind turbine mast is the calculation of the kinematics of the design wave by the 5th order Stokes theory (Fenton, 1985) or high order stream function (Dalrymple and Cox, 1976). These two theories calculate the elevation and kinematics of a regular, symmetrical, non-linear wave on a flat bottom. The forces on the offshore wind turbine are then calculated by a classical Morison model. In the DIME project, we were interested in the differences in load that could be obtained according to the type of wave encountered by the wind turbine from a spilling (symmetrical) breaking wave to a plunging (asymmetric) breaking wave. We have identified in the different cases in the effort history, the "Morison" part inside the wave and the "Impact" part at the moment the wave hits the mast.

1 "Morison" loads vs "Impact" loads

To study the different effort histories, a wave from the FNPM - BEM (Fully Nonlinear Potential flow Model-Boundary Element Method) developed by Grilli *et al.* in 1989 was simulated. The goal was to have an extreme wave which evolves towards a plunging breaker. The forces created by this wave on a vertical cylinder representing a wind turbine mast, were analysed at different stages of the wave evolution before its breaking, this by positioning three virtual cylinders (Figure 5). The last position was chosen so that the wave and the mast meet at a time when the wave is close to breaking, presenting a vertical front at the top of the crest.

Two types of forces have been calculated using a strip theory method. A "Morison" type force, proportional to the square of the fluid velocities, non-zero as soon as the slice is completely immersed. An effort of the "Impact" type (Campbell and Weynberg, 1980), proportional to the square of the fluid velocity at the time of the strip entrance, effort very important at that precise moment (6 times the "Morison" force) then rapidly decreasing, to equal "Morison" when the slice is completely immersed.

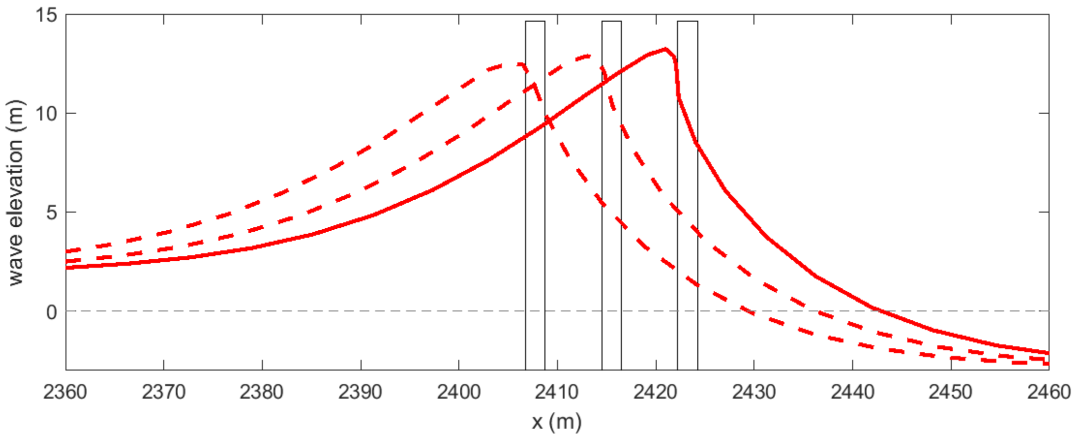

Figure 5. Wave shape at three different instants

What do we observe on the integrated forces on the height of the cylinder? When the wave crest reaches the first mast, the wave is already very steep, with a slope of 128% at the crest. However, the impact force remains very small (Figure 6a) and does not modify the maximum of the 1000 kN force history without consideration of impact.

On the other hand, on the last cylinder, the crest presents a vertical front, which induces a very high impact force (Figure 6b) which brings the maximum force to 1600 kN.

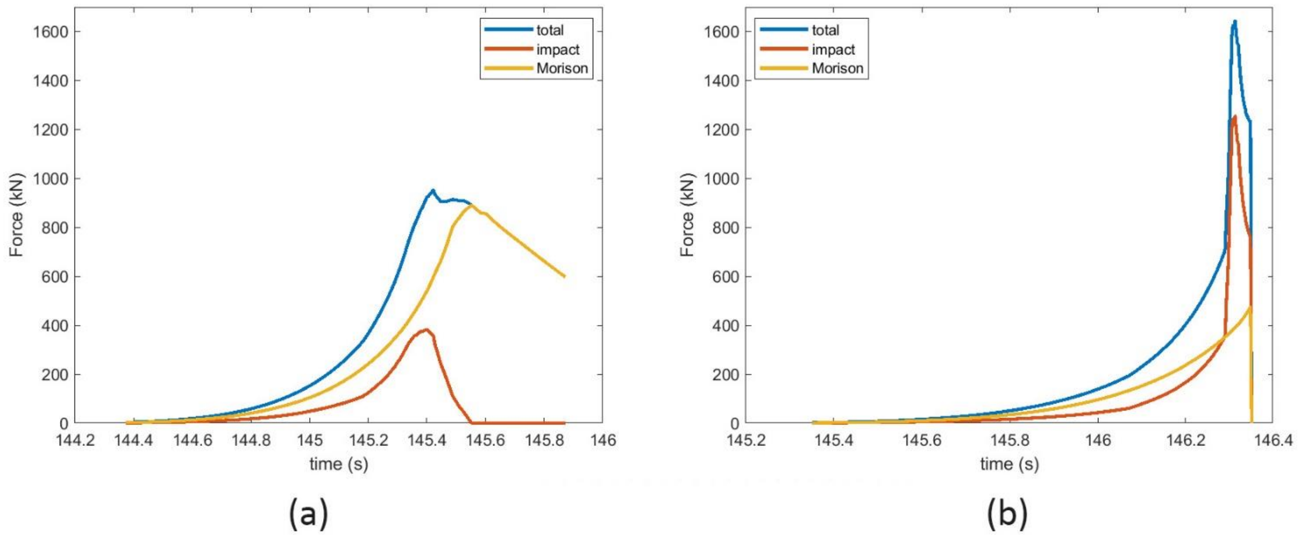

Figure 6. "Morison" loads, "Impact" load et total loads on the cylinder n°1 (a) and on the cylinder n°3 (b)

2 Comparison of force evolution using symmetrical and asymmetric waves

Given the analyses described above, it seems predictable that a symmetrical non-linear wave will induce very different efforts from those of a plunging wave. A wave with the same steepness ka = 0.096 and the same normalized water depth kd = 0.25 as the simulated wave was computed from the code of Clamond and Dutykh in 2018. The value of ka corresponds to 96% of the ka of a nearly breaking regular wave.

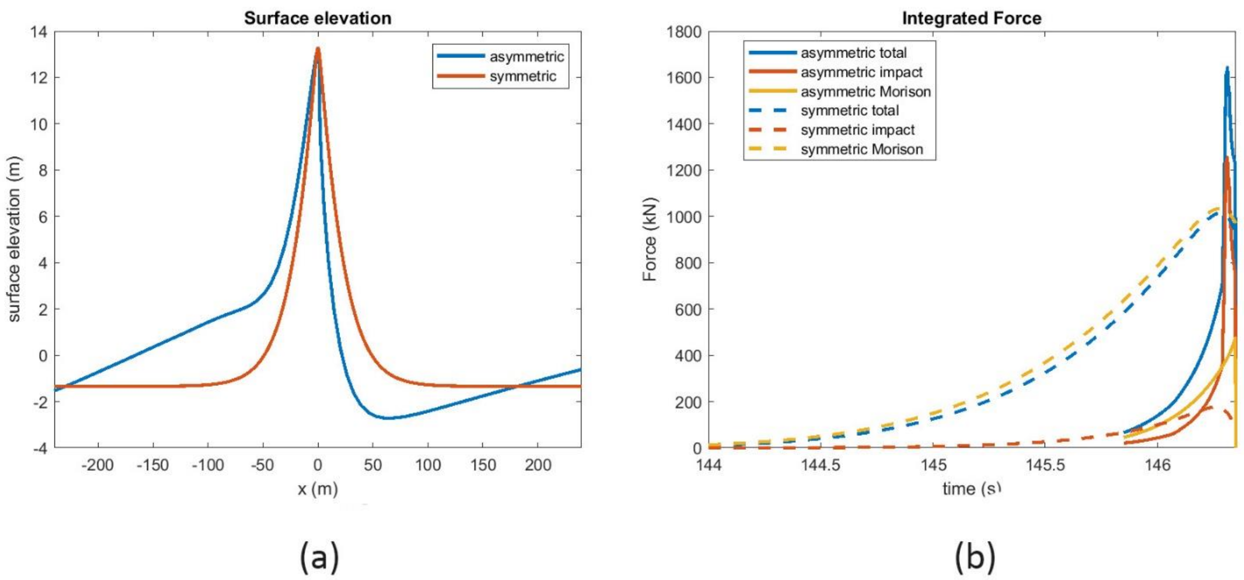

Figure 7. Symmetrical/asymmetric wave comparison, regarding free surface elevation (a) and load of the offshore wind turbine (b)

The two waves are shown in Figure 7a. One asymmetric, the other symmetrical at breaking onset. The forces generated on the mast are very different (Figure 7b), the force generated by the symmetrical wave, which has a much less steep front face, is progressive and dominated by the "Morison" effort, the effort generated by the asymmetric wave is very rough because it is dominated by the "Impact" effort. We can notice that the effort generated by the symmetrical wave is very close to the one obtained by the simulated wave on the mast 1 (Figure 7a). This suggests that if a vertical front does not appear at the wave crest, the approximation of the asymmetric wave by a symmetrical wave, obtained by a by a stream function method or other, is correct and gives similar efforts. As soon as a vertical front appears this approximation is no longer valid.

RECOMMENDATION 8
The presence of a vertical front at the wave crest makes the "Impact" type effort dominant. It is imperative, for a good evaluation of extreme loads, to characterize statistically the parameter describing the height of this front, associated with the other parameters, phase velocity, peak height.

RECOMMENDATION 9
The use of a symmetrical regular non-linear wave model is to be used if there are no waves with vertical faces in the sea state considered. In that case, the approximation of the efforts obtained by a regular symmetrical wave remains correct, even on strongly asymmetric waves.

V. Recommendation regarding the definition of the design sea states

The state of the art on this topic arguably corresponds to the paper by Paulsen, *et al.* in 2019 that focuses on the probability of slamming on bottom fixed wind turbine foundations in intermediate water depth. This work stems from the Joint Industry Projects (JIP) WiFi and WiFi II, which simulated basin design sea states with 5,000 to 15,000 waves per sea state.

In conclusion Paulsen, *et al.* in 2019, based on the analysis of modelled and observed surf probabilities, recommend considering the mean sea state steepness $R = \bar{k} H_s$ (with $\bar{k}$ the mean wavenumber) as an indicator to take slamming into account. They advise that slamming forces should be incorporated into the design for a steepness $R > 0.3$ for the design sea state. This result is mostly based on empirical findings and the generalization to other wave conditions and sites may be questioned. The following section presents a slamming probability model, in the framework of the DIME project. This approach represents an effort toward a more reliable and generic wave breaking statistics model.

1 Development of a new wave breaking statistics model

Analysing the past parameterizations of breaking statistics, including that of Paulsen, *et al.* in 2019, it appears that none of them accounts explicitly and jointly for: the stochastic nature of the waves, that must play a decisive role in the breaking process, especially in deep water, through group modulation effect, and the most widely accepted breaking onset criterion, i.e., the kinematic criterion.

The DIME project provided an alternative approach that allows to incorporate the two above-cited missing ingredients into a new wave breaking statistics parameterization presented by Stringari *et al.*, in 2021. The new wave breaking parameterization relies on the Gaussian theory-derived joint distribution of the phase velocity c and horizontal fluid velocity u, both quantities being estimated at local maxima (or local crests) in the space domain. This formulation $p(u, c)$ was derived by Marc Prevosto from Ifremer, and gives the breaking probability Q, by the following integration:

$$Q = \int_{u>Ac} \int_0^{\infty} p(u,c)\, dc\, du \qquad \text{(F)}$$

Here A is the breaking threshold above which Gaussian (linear) waves are supposed to break and adjusted to 0.24 by Stringari *et al.* in 2021.

2 Perspectives of methodology for the definition of the design sea state

The new wave breaking statistics model proposed in the DIME project provides a good basis to evaluate whether breaking wave are present in the 50-year sea states and decide whether slamming loads should be considered. However, there is no guarantee that the most severe slamming wave is carried by a sea state corresponding to the 50-year H_s return value. Indeed, the slamming severity is related to the crest speed, crest elevation and height of the crest vertical part (the so-called curling factor). Therefore, it seems important to draw effort toward the definition of a methodology that combines the breaking occurrences and the severity of the breaking wave to capture the most dangerous sea states, slamming-wise.

RECOMMENDATION 10
The definition of the design sea state and design wave for slamming efforts should be based on knowledge of sea state statistics. It may result in a different sea state/wave than the classical design conditions, defined in the sense of the highest wave height. The estimation of the wave breaking probabilities can be based on the work of Stringari *et al.* in 2021, developed in the DIME project.

RECOMMENDATION 11
A knowledge of the severity statistics of the breaking waves, combined with their occurrence statistics will be necessary to close the problem.

VI. Conclusions and perspectives

Based on the knowledge development provided by the DIME project, this report has allowed the emergence of a set of recommendations for the consideration of breaking waves loads in the design of ORE systems. They have been synthesised at the end of each chapter of this report. They address:

- the generation of wave hindcast database using spectral wave models;
- the spectral shape of extreme sea states;
- the numerical modelling of the design wave;
- the observation and modelling of breaking waves statistics;
- the limitation of the current engineering methods to assess the slamming loads on offshore wind turbines.

The DIME project had further opened perspectives in terms of barriers to be removed to further reduce uncertainties in the evaluation of slamming loads on offshore wind turbines. Among the most important challenges we note:

- the availability of numerical solution to simulate in arbitrary depths, irregular breaking waves;
- the generation of realistic extreme wave hindcast in coastal zones;
- the lack of reliable observations of statistics and properties of storm breaking waves for the validation of parameterizations and models;
- the definition of the severity of storm breaking waves (the curling factor) and its statistics.

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