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ENVIRONMENTAL EXTREME CONDITIONS FOR A WAVE ENERGY CONVERTER: AN INTEGRATED WAVE-STRUCTURE APPROACH

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ABSTRACT

The process of finding values of extreme waves and their impacts on wave energy converter (WEC) responses, depends on both wave resources and WEC dynamic characteristics. A wide range of waves can influence the reliability of operation and survivability of a WEC. In this paper, a methodology is described to find specific values of wave heights and periods that can be critical for a flap-type WEC, through the use of an integrated wave-structure approach.

The goodness of the fit is studied and the corresponding return periods for ranges that a selected WEC is mostly operating are evaluated. Further discussions for engineering applications and making a clear understanding of the extreme and operational conditions of the WEC are also provided. The critical wave characteristics are defined based on power production and the significant change in the nonlinear dynamic behavior of the device in various ranges.

The WEC behavior is represented by an experimentally validated numerical tool considering the nonlinear behaviour of a flap as single and in an array. The study aims to provide insights in the expected behavior and loading on the WEC, affecting its reliability, considering potential catastrophic wave return values that correspond to their power production phase. The finding can be used for determining both efficient operations and limiting environmental conditions or weather windows.

Keywords: Wave energy converter, wave-structure interaction, wave contours, extreme environmental analyses

NOMENCLATURE

a_i	Fitting coefficients
b_i	Fitting coefficients
β	Radius in the U-space
Hs	Significant wave height
μ	Log-normal distribution parameter
POT	Peaks over thresholds
p_F	Failure probability
σ	Log-normal distribution parameter
Tp	Peak wave period
Tr	Return period
ts	Time interval of recorded data
θ	Flap rotation
r_r	Reliability

1. INTRODUCTION

Surveying and resource assessments are the primary steps in the market stationing of marine renewable energy [1]. The wave characteristics of the installation site affect the devices' design and efficiency [2].

The wave-induced loads are a major aspect of design, and so the selection of design waves is considered the starting step in designing marine structures [3]. Ocean waves as important dynamic loads while highly uncertain need to be accurately assessed in order to provide a proper design for the operation, whilst preventing catastrophic situations.

However, the irregularity of waves, makes this estimation process uncertain and difficult [4]. This fact leads to developing simplified while fairly accurate methods for estimating design waves [5].

The process became even more complicated for its application in the WEC industry. Defining and categorizing the extreme environmental conditions for a WEC is not a straightforward process.

Standards recommend the extreme wave height with a return period of 50 years for energy converters e.g. [6]. The required return period is most of the time much more than the available historical data which give a rise to the uncertainties involved [7].

The devices with flexible or highly nonlinear dynamic behavior, expand the range of the critical waves. The critical environmental condition makes the maximum response in the device [8]. For some WECs, the response of the device is amplified in waves rather than the extreme wave and consequently may cause high stress on the critical elements.

This study connects resource characterization with the structural responses to investigate the suitability of a candidate site for a specific WEC device both in terms of extreme waves and efficient operation.

In this study, first, a proper site based on the required depth (below 15 meters) for a flap-type WEC for the primary design is selected. Then the range of the periods corresponding to the efficient operation of the device is selected.

From the previous studies on a flap-type WEC a range of critical periods were found and classified [9]–[11]. It was shown that in a specific range of incoming wave periods, the amplification of the response could happen.

The time series of significant wave height and period in the candidate site is studied to find the most suitable fit for each variable. Different methods for studying the extreme wave height and the operational wave height are used, and the differences and accuracy of the methods are explained. Then the procedure is conducted for the wave period. Based on the selected wave periods, the return periods of the waves in the candidate site are estimated.

The extreme values corresponding to the 50 years return period by using both univariate and bivariate methods are studied for the candidate site. A bivariate study is conducted by using the environmental contours to investigate the dependency of wave height and period. This is conducted because sea waves as important dynamic loads while highly uncertain can be better represented by joint distribution of wave period and height [12]. It should be noted that the environmental contours concept is based on defining the extreme condition [13].

The proposed procedure can be used for site selection of any WEC type by tailoring the procedure according to the needs and physical requirements.

For the return period of operational condition, 10 years is selected as a minimum return period considering the rate of change [14] and for extreme value 50 years is considered based on standards recommendations e.g. [6].

2. MATERIALS AND METHODS

2.1 Device concept operation

This section provides the information on WEC Concept, its operation, and critical wave characteristics that could affect the nonlinear dynamic behavior of the device.

The WEC is a nearshore flap-type hinged to the seaward horizontal surface of a vertical breakwater as it was patented and proposed for the port of Piombino in Southern Tuscany [15], [16]. **Figure 1** shows different sections and views of the 1:40 scale of the proposed WEC device encompassing five flaps hinged to the breakwater.

2.2 Critical wave characteristics for the WEC

For the design of WECs not only the highest wave height is of interest but also different windows of wave periods that can make various kinds of resonance or amplification in the response are important [9], [17].

Tuning dynamic characteristics of the WEC in primary design stages could help to increase the response to the dominant expected wave resource, increasing the hydrodynamic efficiency, and delivering less energy as PTO to the system [18], [19].

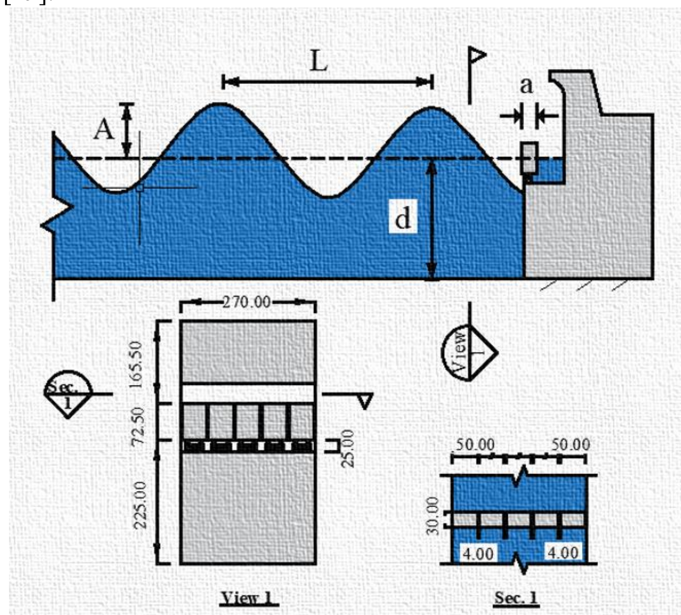

Figure 1: WEC CONCEPT

Based on previous experimental and numerical studies on five flaps working in an array, it was found that the device has higher power performance with a tuned system for a range of periods [9]–[11].

As it can be seen in **Figure 2**, maximum responses of the flaps are observed in response to Hs equal to 0.05 m and the range of periods between [0.7, 1.0] s due to the all nonlinearities involved [9].

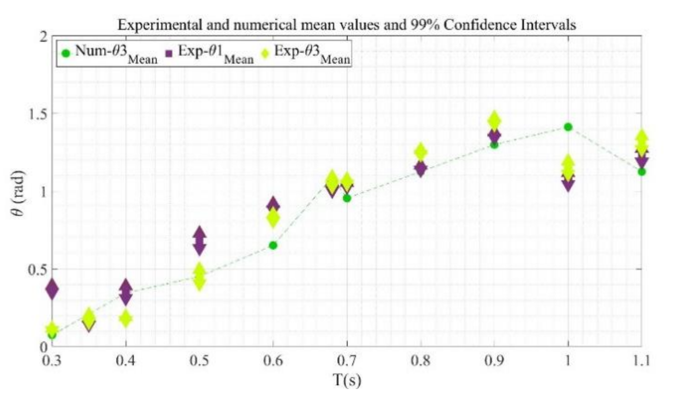

Figure 2: EXPERIMENTAL AND NUMERICAL MEAN VALUES AND 99 % CONFIDENCE INTERVALS OF EXPERIMENTAL RESULTS

The scaled range of periods and significant wave height in **Figure 2** are based on the wave characteristics Tp∈[3.5 6.3] s and Hs=2 m of the port of Piombino that was considered as the proposed high energy place for the installation of the device in the primary studies [15].

For the sake of clarity, only the response of Flap 1 and 3 for experimental studies and Flap 3 for numerical studies are shown in **Figure 2**. Flap 1 is the flap at the one edge of the array and Flap 3 is the middle flap. It is shown in previous studies that due to the symmetry of the numerical simulation, the responses of all flaps follow the same pattern to a specific wave height and period [9], [11].

Thus, it is safe and more illuminative to only represent one flap's response in which Flap 3, a middle flap, is chosen as a representative of an array of flaps. However, in experimental simulation, due to the construction effects, and the small change in the gaps between the flaps, the response of Flap 1 and 3 has slight differences [9], [11].

It is expected that by increasing the amplitude of response, the power can be increased [17]; this topic for the specific Flap-type WEC is studied and the device was further tuned in terms of distance from the breakwater to make the maximum response and power to the incoming wave [10].

The range of periods [0.7, 1.0] s in the scale model (**Figure 2**) in which the device shows the maximum response corresponds to the periods [4.4, 6.3] sec in real sites. In the next section, based on the depth and the wave characteristics, that the device is proposed in the first place [15], [20], another site is proposed and studied in terms of the extreme and operational wave characteristics.

2.3 Site selection

In reliance on the requirement of the device, shallow water have been selected for the study. A code is developed in Matlab [21] to read the bathymetry suitable for the implication of the device. Accordingly, the following location is selected for the study (see **Figure 3**, [22]), assuming that the device can be implemented in this region.

Figure 3: MAP [19] AND BATHYMETRY

The dataset used have been extracted from the North Sea Wave Database [23]–[27]. The NSWD is a calibrated, validated database that encompasses 38 years of metocean and spectral information (1980-2018), developed by using the SWAN model with modified nearshore parametrization, whitecapping and wind growth [28], [29]. The next section describes the methodology for statistical analyses of wave parameters for the candidate site.

2.4 Methodology

This section provides a brief review of the studies and research methods that are used for studying the candidate site wave parameters in correlation with the Flap-type WEC (see **Figure 4**).

As seen in **Figure 4**, by selecting a proper site, the statistical study on wave parameters is initiated. The joint distribution is used for investigating the dependency of the wave parameters for extreme waves; while the univariate study is used for both operational and extreme waves.

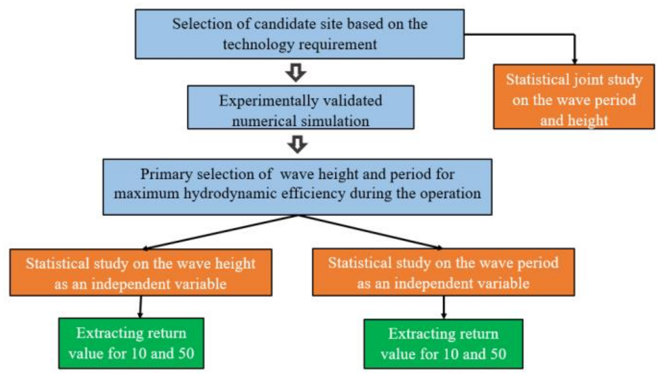

Figure 4: METHODOLOGY FOR THE STATISTICAL STUDY OF WAVE PARAMTERS IN CONNECTION WITH EXTREME VALUES AND OPERATIONAL EFFICIENCY

3 RESULTS AND DISCUSSION

3.1 Statistical analyses of Wave significant height

The statistical analyses are used to propose the mathematical model describing the data for a more convenient interpretation and extracting the required information from the data e.g. [30].

Different methods are generally used for studying wave samples including total sample, annual maxima, and peaks over thresholds (POT) [31], [32]

Each method has benefits and its limitations. Two necessities of a statistical sample are independency and homogeneity which cannot be fully satisfied for the total sample method when the studies are focused on the extreme values [3]. Therefore, other methods such as annual maxima and POT are investigated for finding the extreme values which could meet the prerequisites of independency [33], [34].

3.1.1 Peaks-Over-Threshold method (POT)

POT identifies storm events above a certain threshold value, whilst ensuring the overall final filtered dataset is independent and identically distributed (iid) [3]. A common practice to find the best fit is to apply different distribution functions and find the most proper one for the population [3].

Here the threshold is defined as a value of 99^{th} percentile which is equal to the value below which 99% of the data are found. This value corresponds with Hs equal to 3.17 m for the candidate site.

An algorithm is developed in Matlab [21] to step by step follow the procedure from finding the threshold to creating a probability distribution and detecting the suitable fit for exceedances over the threshold (hereafter called PKS).

Figure 5 shows POT with a minimum time step of 72 hours, which are chosen to guarantee the independence of the samples.

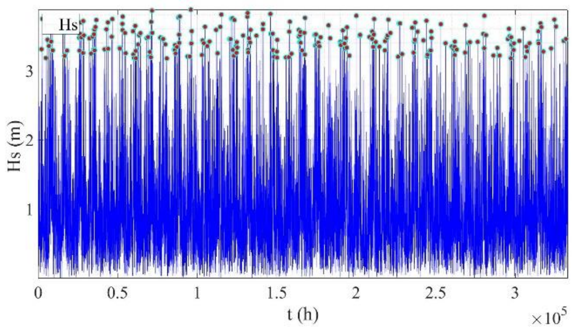

Figure 5: PEAKS OVER THRESHOLD METHOD APPLIED ON THE DATASET

The cumulative distribution function and the corresponding return periods obtained from the distribution functions fitted to the Peaks over thresholds are represented in **Figure 6**. Upon finding the best fit, the extreme return period of the wave height is estimated by using the distribution function and at the corresponding probability [3].

DistName	Return_Period	Return_Values
"Normal"	50	3.7218
"LogNormal"	50	3.7261
"2- Parameters Weibull"	50	3.7212
"3- Parameters Weibull"	50	3.7187
"2-Parametrs Generalized Pareto"	50	3.7637

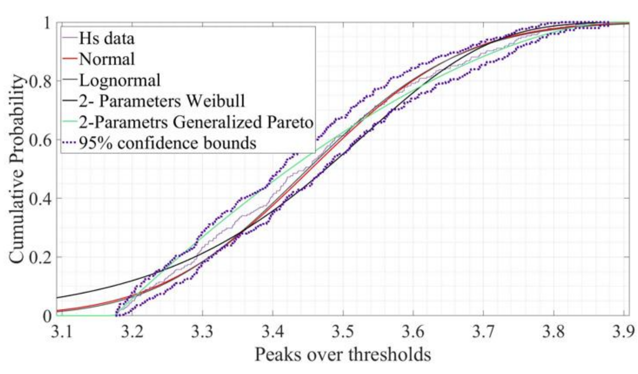

Figure 6: CUMULATIVE PROBABILITY AND DIFFERENT FITTING DISTRIBUTION FOR PKS ALONG WITH RETURN PERIOD OF 50 YEARS AND CORRESPONDING RETUEN VALUE FOR PKS

It should be noted that Weibull distribution can be considered as generalized extreme value distribution with its corresponding parameters [35]. The 2-parameter Generalized Pareto remains in the confidence interval for the whole dataset above the threshold; though the return value estimated from the different distribution has a negligible difference.

By this method, the extreme of the wave height can be estimated for the specific return period. The provided data cover 38 years which can provide a highly accurate benchmark for calculating an extreme for 50 years return period.

As previously mentioned, the device was found to effectively operate at wave heights of 2 m [9], [11]. So by focusing the study on less than 2 meters we can find its probability from the cumulative probability based on the total sample. In the next sections, the maximum and mean over years are presented; then by using the fitting distribution over the whole data, the probability of return value for 2 m is investigated.

Since the desired wave height for operation is less than the threshold, the limitation of the total sample method in the case of independency and homogeneity is not of concern.

It should be emphasized that the total sample method is not recommended for finding the extreme values; in which the requirements of independency and homogeneity are not fulfilled. However, for finding the return value over limited years and under the threshold, it is possible to use the total sample method. Since it considers all values, and for values under the threshold the possibility of dependency which for waves can happen during storms does not come into account.

3.1.2 Annual maxima method

The annual maxima method acquires the largest significant wave height in each year. Although this approach considers limited data and ignores the fluctuation of data in a year e.g. [36], it can give a rapid understanding of the change of waves during the years. The maximum and mean value of the significant wave height over 38 years for the candidate site is depicted in **Figure 7**.

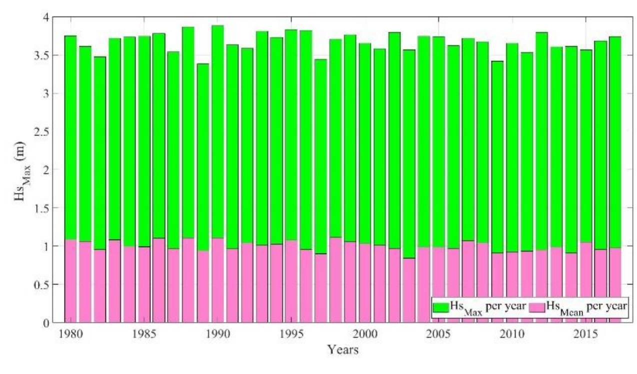

Figure 7: ANNUAL MAXIMA METHOD, AND MEAN VALUES FOR Hs

As it can be seen in **Figure 7**; although the maximum value per year is more than 2 meters, the mean value does not cross the 1.5 meters. Therefore, further statistical analyses could help the possibility of the waves with more than 2 meter wave height.

3.1.3 Total sample method (Initial distribution method)

In this method, the data are cumulatively analyzed, and different distribution functions are fitted to the data. A code is developed in Matlab [21] to find the best fit and the required parameters by maximum likelihood method for Hs data.

DistName	Return_Period	Return_Values
"Normal"	10	1.8682
"LogNormal"	10	2.0835
"2- Parameters Weibull"	10	1.9124
"3- Parameters Weibull"	10	1.9101

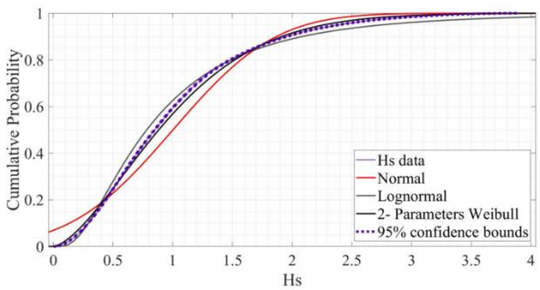

Figure 8: CUMULATIVE PROBABILITY AND DIFFERENT FITTING DISTRIBUTION FOR TOTAL SAMPLE Hs, ALONG WITH RETURN PERIOD OF 10 YEARS AND CORRESPONDING RETUEN VALUE FOR TOTAL SAMPLE OF Hs

Weibull can be considered as the best fit for this set of data. From the cumulative distribution for the whole time series, it is expected that the return period for wave height more than 2 meters will be around 10 years with a 90% probability.

3.2 Statistical analyses of Wave period

3.2.1 Peaks-Over-Threshold method (POT)

The same procedure for wave height is repeated for the wave Period of the dataset, lognormal distribution was found that provide the best fit for peaks over the threshold. Threshold as a value corresponding to 99% quantile is 11.01 s. the return value for 50 years return period for different distribution is presented in **Table 1**.

Table 1: Return value corresponding to 50 years return period

DistName	Return_Period	Return_Values
"Normal"	50	14.398
"LogNormal"	50	14.335
"2- Parameters Weibull"	50	14.816
"3- Parameters Weibull"	50	14.816
"2-Parametrs Generalized Pareto"	50	15.2

3.2.2 Total sample method

The same approach for studying the cumulative data is used for the wave period (see **Figure 9**). As is shown, Lognormal provides a better fit with 95% confidence interval.

DistName	Return_Period	Return_Values
"3- Parameters Weibull"	10	7.8951
"Normal"	10	7.7439
"LogNormal"	10	7.9615
"2- Parameters Weibull"	10	7.8977

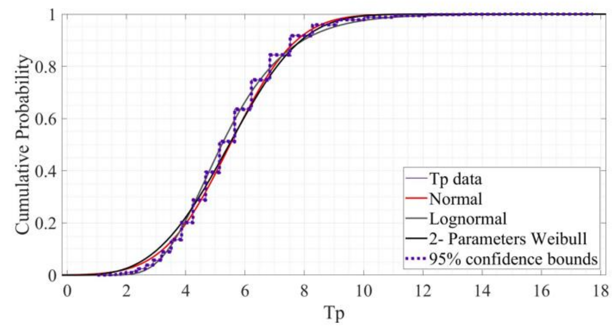

Figure 9: CUMULATIVE PROBABILITY AND DIFFERENT FITTING DISTRIBUTION FOR TOTAL SAMPLE Tp

The estimated return value for 10 years shows that the probability of having waves with the period beyond 7 seconds is more than 90% which fulfills the requirement for the optimized energy conversion.

3.2.3 Annual maxima method

Figure 10 shows the results for the annual maxima method in which the mean value is almost half of the maximum value in each year. Although, the mean value is around 6 s with insignificant changes during the years; the maximum values have a variance of almost 60 % during the years from the maximum of 17.74 s to a minimum of 11.02 s.

The same routine has been conducted to find the minimum period over the years. As shown in **Figure 11**, the minimum period swings from 1.0 s to 1.5 s; which corresponds to a 46 % change in the minimum period. From the previous section on studying the whole sample and the annual maxima method, it can be expected that the upper bound period requirement for efficient operation in the candidate site is satisfied.

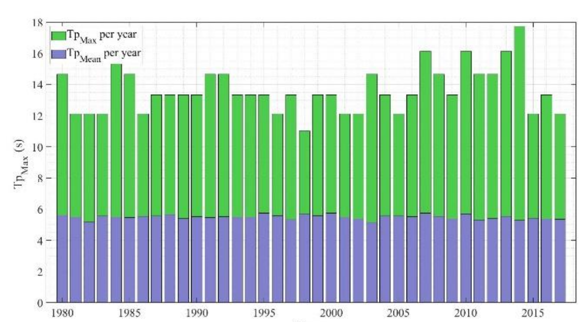

Figure 10: ANNUAL MAXIMA METHOD, AND MEAN VALUES For Tp

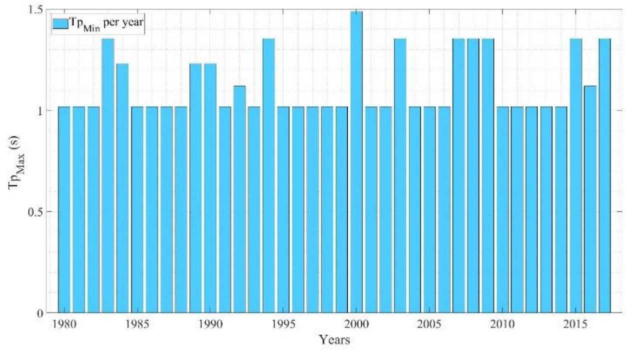

Figure 11: MINIMUM VALUES OF TP

Studying the time series of Hs and Tp, as independent variables can enlighten the statistical understanding; however, the joint probability of the two variables considering the dependency of one variable to the other would be more precise. In the next section, the joint probability of the Hs and Tp is studied.

3.3 Joint probability distribution of wave period and amplitude

For a return period of 50 years, it is advised to use the environmental contours as a common approach and representative of joint probability [6]. There are multiple definitions and various methods to compute a contour [37]. Here the IFORM approach is utilised, which originates from the structural reliability methods, and can be efficiently used for marine structure application [38]. In this approach, it is essential to know the probability of exceedance to find the corresponding response level.

The failure probability can be estimated by the following equation:

$$p_F = \frac{1}{365\times(\frac{24}{t_s})\times T_r} \quad (1)$$

$$r_r = 1 - p_F \quad (2)$$

In this equation, t_s is the time interval of recorded data, and T_r is return period. So considering 50 years return period, the failure probability is calculated.

For the failure probability found, the corresponding value of radius β is estimated by using the inverse of the Cumulative Normal Distribution Function:

$$\beta = CDF_N^{-1}(r_r) \quad (3)$$

All the pairs that belong to the circle are considered as target joints. Here the tolerance of finding the pairs plays a crucial role.

Although the change in β with various return periods is insignificant, the tolerance in accepting points that belong to the circle with the radius equal to β can make a crucial change. This can indicate the uncertainty involved in the IFORM method.

Simultaneously, the dependency of wave period distribution to wave height should be defined. It is widely acknowledged that lognormal for the conditional term and Weibull for the marginal distribution of Hs can provide a good fit e.g. [12]. This was also confirmed by the finding of this study on a specific location, in which Weibull and lognormal provide a better fit for the data as explained in Section 3.1.3 and 3.2.1.

Lognormal distribution of Tp is correlated to Hs by defining the relation between Hs and the distribution parameters. The correlation found between the parameters and Hs.

$$\mu(LnTp) = a_1 + a_2 Hs^{a_3} \quad (4)$$

$$\sigma(LnTp) = b_1 + b_3 \exp(b_3 Hs) \quad (5)$$

The scatter diagram and the fit for Hs and lognormal parameters are shown in **Figure 12**, with results being time step sensitive, various time steps have been chosen to figure out the suitable one for the analyses. Finally, 72 hours have been selected. Nonlinear least square with 95% confidence bounds is used for finding a_i and b_i, i=1,2,3.

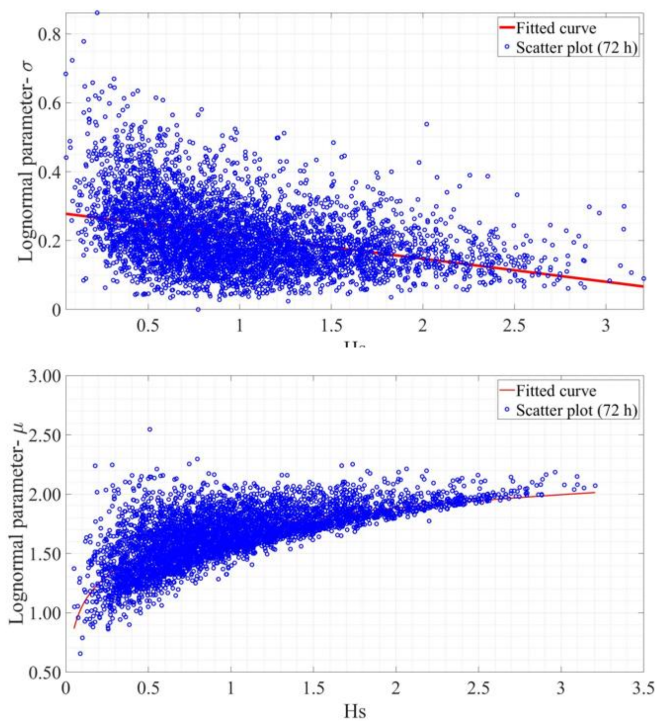

Figure 12: FITTED CURVES OF LOGNORMAL PARAMETERS- μ AND σ

Albeit the proposed fits can mathematically describe the dependency of wave period parameters to wave height, the spread of data can induce another source of uncertainties.

This conditional term for Tp based on Hs will be further studied in a future work, and will aim to decrease the uncertainties involved. The procedure for finding the environmental contour is explained in more detail in [13], [39]. The pairs of Hs and Tp for 50 years are found and depicted on the scatter diagram of Hs and Tp (**Figure 13**).

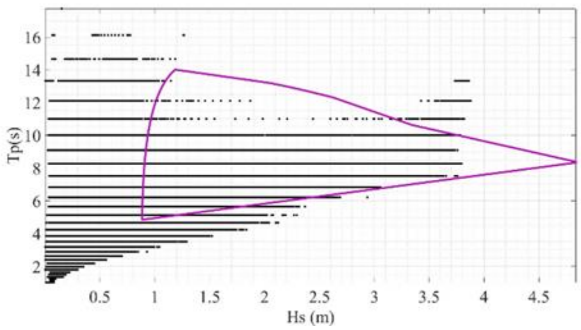

Figure 13: ENVIRONMENTAL CONTOUR FOR 50 YEARS

4 CONCLUSION

This paper investigates the critical wave parameters for operational and extreme conditions of a flap-type WEC. Expected changes in the wave height and peak period over the years (based on a 38 year dataset) by using different univariable methods, showed that the maximum and minimum wave period have 60 % and 46 % difference, respectively.

The return period of 10 years for considering the changes in years is selected to find the corresponding return value of wave period and wave height. The estimated return value for 10 years is 1.9 m and 8 s which satisfies the minimum wave height and upper bound of the period for higher hydrodynamic efficiency.

From the univariable POT method, the return value of Hs, and Tp is beyond 3.7 m and 14.8 s for 50 years return period. The environmental contour also confirms these results while overestimating the maximum wave height.

It was also observed that the environmental contour is so sensitive to the number of pairs extracted from the circle with β radius in U-space and the defined tolerance.

Future work will focus on studying and comparing the suitability of different candidate sites and reducing the uncertainties on finding a hot spot for the operation of the flat type WEC.

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