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Verification through Accelerated testing Leading to Improved wave energy Designs

Deliverable 3.3

Description of UC1 hybrid testing platform

Version 1.0

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Executive Summary

Deliverable 3.3 aims to provide the necessary information for the setup of a hybrid testing methodology, using the novel approach of the VALID project and the AVL Model.CONNECT platform. The approach taken in the VALID project allows for metocean conditions to be included at higher fidelity and hence the subsequent wave-to-wire and load modelling to have enhanced fidelity.

The approach used in D3.3 provides an appropriate level of safety and reliability, representative environmental conditions over a device's life cycle. The focus of this task is on waves based on the VALID project requirements, and while they are site specific, the same process can be replicated for any location globally.

The site-specific conditions are analysed and used as primary inputs in the wave-to-wire model and the hybrid testing platform. The hybrid testing methodology, dependent on Model.CONNECT by AVL, can simulate one or several components, and can provide experimental data to the simulated models.

Project partner names

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- Fundacion Tecnalia Research and Innovation
- Corpower Ocean AB
- RINA Consulting S.p.A.
- Biscay Marine Energy Platform SA
- IDOM Consulting, Engineering, Architecture, S.A.U.
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1 Introduction

1.1 Background

Wave energy converters' (WECs) development is directly related to the advanced simulation tools being able to predict the behaviour. The response prediction is used for various phases of analyses and design. Developing a fairly accurate hybrid simulation tool for a WEC can be challenging in various aspects due to the presence of hydro-servo-elastic-geo interaction e.g. (*Marine energy - Wave, tidal and other water current converters - Part 101: Wave energy resource assessment and characterization (Technical Specification- IEC TS 62600-101:2015)*, 2015).

Understanding environmental conditions is the first step in any design process (S.C. Misra, 2016). The waves are recognized as a dominant load for WECs and establishing the design wave loads plays a crucial role. Continuous change in wave conditions, make it a more complicated phenomenon to be mathematically described and estimated (El-Reedy, 2015).

For defining the waves, metocean analyses should be conducted. Metocean is short-term meteorological and oceanographic. Metocean analyses provide the required environmental input or relevant metocean parameters for the design and operation of offshore structures (*International Standard International Standard- Metocean design and operating conditions*, 2005).

For the purpose of this project, the wave characteristics should be defined. The wave parameters in the proximity of the device can be established by the recorded wave data. However, in the absence of recorded wave data, hindcast data can be used. Hindcast data provide a high-resolution dataset over time and space.

Wave hindcasting refers to the estimation of wave parameters for past events. Consequently, statistical analyses can be conducted to estimate the extreme values for wave height and period. Statistical analyses include univariable and joint studies. A joint study is advised in standards due to the dependency of wave parameters.

1.2 Aim

This task aims to provide the required information for the setup of VALID hybrid test platform for wave-to-wire modelling. Defining the actions on an offshore structure is a major concern in analyses and design procedures. For defining the waves, metocean analyses should be conducted. Then the results should be statistically analysed and accurately interpreted to provide the pairs of wave parameters for the wave-to-wire modelling.

1.3 Methodology

To provide an accurate estimation of the expected actions on the device, and the extreme effects, the spectral parameters wave height and period should be defined from a contour approach. Otherwise, one-dimensional analyses can be used. Both techniques need historic wave data for statistical analyses. In absence of the continuous and reliable data for a site of interest, hindcast can be used (IEC, 2019).

For this project, user case 1 (CORPOWER OCEAN) has access to the extreme wave parameters needed for the VALID Hybrid Test platform. Therefore, the methodology here is generally described as being developed and applied to other user cases.

By developing a numerical model for hindcast, the wave parameters for the point of interest can be calculated. Like any differential equation, the development of the model needed a proper domain, boundary conditions, and defining the governing equations. The results should be validated and calibrated against the buoy measurements.

Moreover, statistical analyses should be conducted to provide an in-depth understanding of the provided information. The statistical analyses have two parts, one part is dedicated to investigating the uncertainties involved in the hindcasting and making the comparison with the buoy measurements.

The second part is used to provide an estimation of the extreme values for the return period of 50 years. Although, having joint variable analyses could provide a set of extreme values, conducting the univariable analyses ensure the validation of the joint probability and a better understanding of both wave height and period. Therefore, for this project, two sets of analyses have been developed univariable and joint studies of wave parameters.

2 Metocean conditions

The presence of metocean data in different life cycle analyses of offshore structures requires the development of an accurate assessments and estimation tools. It should be noted that metocean studies should be combined with energy resource assessment to assure that the device requirements are successfully met e.g. (ORSIG, 2015).

Metocean assessment can offer various wave parameters that can address the different requirements of various devices. The focus of the VALID project is on waves that act as important elements for dynamic loads, whilst they are governed by uncertainties that need to be quantified (Bai and Jin, 2016).

Wave conditions need to be accurately assessed in order to provide a proper design for the operation and prevent catastrophic situations. On the other hand, the correlation of extremes for different variables, should be considered to accurately represent environmental conditions and associated risks e.g. (Drago et al., 2015).

This subject becomes even more challenging for WECs, since they are expected to work in a harsh environment with higher risks for their survivability. The commercial viability of WECs is associated with the maximum operation and minimum downtime (Coe and Neary, 2014). As can be expected due to all the uncertainties involved, defining and categorizing extreme environmental conditions for a WEC is not a straightforward process.

The recommended extreme value (return waves) is associated with a return period of 50 years for energy converters e.g. (IEC, 2019). The required return period most of the time is much more than the available historical data, which give a rise to uncertainties (Neary et al., 2020).

For some WECs, the response of the device is amplified according to their specific dynamic characteristics rather than the extreme wave and consequently may cause high stress on the critical elements. Therefore, even the definition of the wave which should be considered for the analyses of the survivability of the device is ambiguous (Coe and Neary, 2014; Saeidtehrani et al., 2022b).

2.1 Life cycle metocean conditions requirement

Site conditions are any specific conditions that can influence the design of the structure for various lifecycle phases e.g. (DNV GL, 2018). The lifecycle phases of wave energy converter are shown in Figure 1 (inspired by (DNV GL, 2018; IEC, 2019)) .

Figure 1: Life cycle consideration, inspired by (DNV GL, 2018; IEC, 2019).

To provide an appropriate level of safety and reliability, representative environmental conditions for each life cycle should be considered. The focus of this task is on waves based on the VALID project requirements.

2.2 Integrated metocean analyses developed for the VALID project

The integrated metocean analyses are mainly constructed on three main elements of collection, management, and analyses of the data (ORSIG, 2015). For hindcasting wave parameters through a numerical wave model, several elements have to be defined. The procedure is summarized in Figure 2.

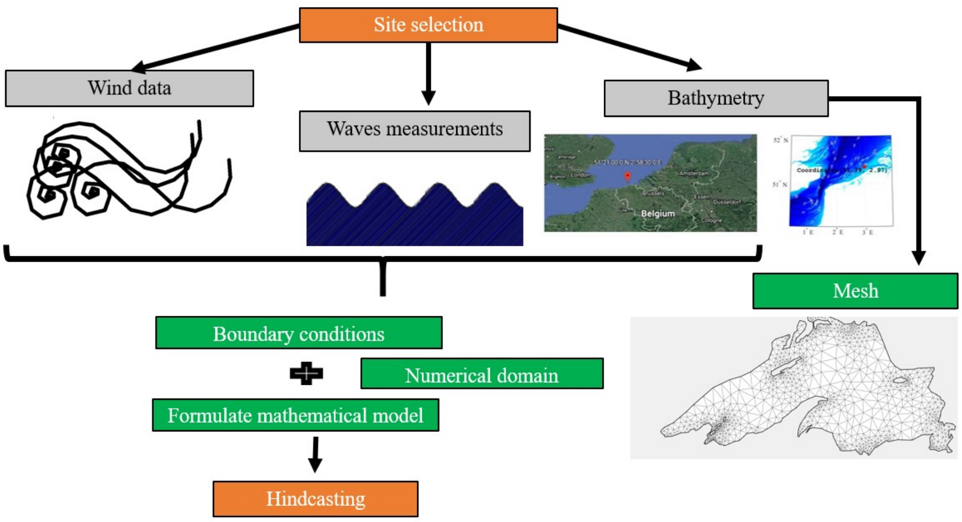

Figure 2: Integrated Metocean approach for VALID project- Hindcasting.

As it can be seen, the first stage after site selection is gathering and management of required data for creating boundary conditions and a numerical domain. In order to reduce climate uncertainties, quantify the wave energy resource, and quantify extreme conditions at least 10 years of data are necessary (Guillou et al., 2020; Ingram, 2011; Lavidas and Venugopal, 2018).

For this project, 20 years of data are considered, and relative conditions for wind and boundaries are obtained (Hans Hersbach et al., 2019). It is also essential to calibrate and validate the produced wave parameters with in-situ measurements, in order to quantify the accuracy of the results.

Although, numerical wave models have limitations, they are the only ones that can provide custom spatio-temporal data for effective decision-making in terms of energy resources and performance estimation (Lavidas and Polinder, 2019), (see Figure 3).

Wave models can be categorized as oceanic and coastal with various computational, efficiency, and accuracy demands. Over the years, various wave models are developed, one of the important distinctions in the wave models is the method for resolving the action balance density equation. The selection of wave model and hindcasting tool depends significantly on

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the application, computational resources, region, and engineering judgment which in turn depends on the user experience (Lavidas and Venugopal, 2018).

For the VALID project, the Simulating WAves Nearshore (SWAN) (*SWAN scientific and technical documentation Cycle III version 43.01*, 2022) is used. SWAN allows for implicit nearshore non-linear solvers and unlike its oceanic counterparts, it can estimate highly nearshore conditions such as depth breaking. Detailed explanations on developing the model in SWAN are provided in the following sections.

Figure 3: SWOT analysis for numerical wave modelling inspired by (Lavidas and Venugopal, 2018).

3 Site selection

The outputs of the hindcast are wave parameters both spectral and bulk variables such as significant wave height, peak period, peak direction, etc. Wave spectra can be provided in either variance or energy, for various locations.

Based on the proposed area by the user cases, the availability of nearby in-situ measurement buoys is investigated. According to the availability of data for validation and calibration, a domain for the hindcast is defined. The data from the buoys are used for the calibration and subsequent validation of the hindcast model. However, the insufficiency of buoys and the high cost of monitoring creates a big challenge in accurately defining the wave conditions (Lavidas et al., 2017) and further usage of the data for the hindcasting validation.

The three important variables in this project are wind, wave conditions, and bathymetry. The bathymetry of the domain is obtained and prepared as an input of a high-resolution unstructured grid for SWAN.

3.1 Wind

The wind is a random three-dimensional vector in space and time (Holthuijsen, 2007). Wave simulation is sensitive to wind data. The complexity of wind definition is dependent on the temporal, spatial, and geographic situation and the specific applications of the model (Lavidas et al., 2017). It was shown that wave results for the 1-h dataset have lower biases in comparison with the 6-h dataset (Lavidas et al., 2017). Therefore, for this project, a 1-hour interval at a fixed elevation above the mean sea surface for 20 years is used.

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3.2 Wave boundaries

The JONSWAP spectrum is used for wave boundaries which are derived from the joint North Sea wave project (JONSWAP) and can be considered for regions that limit the fetch like North Sea. The JONSWAP model is based on the observations along a 160 km profile into the North Sea (Hasselmann et al., 1973)

For this project, waves are described in a way that they cover all the boundaries of the domain for 1-hour intervals during the whole simulation. For each point, the significant wave height, peak period, mean wave direction, and wave spectral directional width are provided.

3.3 Model extend, grid size, set up data

Different meshing techniques can be used for the domain; however, unstructured mesh provides enough flexibility for meshing complex areas or around the coastlines. Although the unstructured mesh can be a combination of triangles and quadrilaterals, SWAN only accepts the triangles.

It is important to maintain a balance between high fidelity and computational needs. A higher refined mesh does not always imply a better hindcast, as the convergence condition by Courant–Friedrichs–Lewy has to be satisfied with a higher integration approach, which does not always translate into improvements in the hindcast. The mesh is developed for this hindcasting considering more accuracy in the coastal area and the region of interest.

The mesh should go through several optimizations to reach an efficient unstructured mesh. In general, we are looking for a high resolution in areas with a major change in bathymetry or evolution of waves.

3.4 Errors and uncertainties

The results are obtained by bi-linear interpolation in space from the computational grid if the exact coordinates do not coincide. However, output time is not interpolated; it is shifted to the nearest computational time level. To ensure that errors are reduced, the output times should match the time intervals (*SWAN scientific and technical documentation Cycle III version 43.01*, 2022)

Ideally, no errors occur by defining identical input, computational, and output grids; then no interpolation errors will be required. However, uniform spatial-temporal dataset is difficult to find. For the case study of this project, due to the specific bathymetry, the unstructured grid is defined, and the inputs are also different. Therefore, some interpolation will take place.

To obtain a reliable output, the input time windows should be defined in a way that coincides with the output, or be larger than the requested output time window (*SWAN scientific and technical documentation Cycle III version 43.01*, 2022). The output is presented as nearest to the computational time; otherwise stated, there is not any interpolation in time. Therefore, for increasing the accuracy the output time is chosen to coincide with the computational time level.

3.5 Computations

SWAN uses tri-linear interpolation from the given input grids; the output is obtained by bi-linear interpolation in space. Although SWAN is not directly governed by Courant stability criteria, the accuracy of the results depends on the time step especially when unstructured grids are used (*SWAN scientific and technical documentation Cycle III version 43.01*, 2022).

The lowest and highest frequency are selected to cover the 0.7 and 3.0 times the expected peaks. The expected peaks are averaged from the available wave measurements in the boundaries. The directional spreading for swell is also considered, which is reflected in 2^o direction resolution.

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3.6 Governing Equations

Overall information about sea surface can be captured from the wave variance spectrum or energy density $E(\sigma, \theta)$ (*SWAN scientific and technical documentation Cycle III version 43.01*, 2022). The general appearance of the wave can be inferred from the narrow or wide band of the spectrum (Holthuijsen, 2007), which in turn helps to specify the required level of sophistication for developing the wave-structure model.

The presence of wider or narrower frequencies based on the prerequisites of any particular WEC should be studied. The importance of the presence of various frequencies in the selection of the WEC device site is further studied in (Saeidtehrani et al., 2022b). Wave models estimate changes in action density N in Space and time as presented in the following equation:

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}}.\left[\left(\vec{c}_g + \vec{U}\right)N\right] + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

$\boldsymbol{S_{tot}}$ represents six main physical phenomena:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \quad (2)$$

These terms correspond to waves generated by wind, three and four-wave interactions, whitecapping, bottom friction, and depth-induced wave breaking. The last three terms represent wave energy dissipation. These terms are the nonlinear phenomena involved in the wave propagation problem.

Considering various sources of energy dissipation provides a more realistic while complicated simulation of the propagated waves. The effect of these phenomena is also dependent on the water depth. For example, in deep water, wave energy is only dissipated by breaking (white-capping) (Holthuijsen, 2007), while in shallow water, other interactions also come into effect.

From left to right, the first two terms basically describe the change of action density in time and space. The third and fourth terms represent the effects of shifting of radiation frequency and the refraction effects due to the mean current and depth changes, respectively.

4 Validation of the results

It was mentioned, that for the primary analyses, the domain should be selected in a way to have enough buoy measurements. These buoy measurements are used for the comparison and validation of the results. Buoy measurements can be considered as an independent reference for the validation of the hindcasting data.

It should be emphasized that there are a lot of restrictions for the validation of the results, due to the lack of buoy measurements for the whole year or the missing data in some hours. The other obstacle in the comparison is the difference in the time interval which could make a huge difference between hindcasting and measurements.

In most of the hindcasting validation, root mean square error (RMSE) and Scatter Index (SI) were provided as validation metrics e.g. (Alday et al., 2022; Chawla et al., 2013; Groenewoud and Hulst, 2016). However, for this study and for the goal of providing a better picture of the variability of the parameters, in-depth statistical comparisons methodology and information are provided and applied for the user case hindcasting. Therefore, apart from graphical representation, important statistical parameters should be also calculated. These parameters are compared for both wave measurements from buoys and hindcasting results.

To represent the range of values, the minimum and maximum of the data are calculated. As the most common basis for statistical analyses, mean, median, and Root Mean Square (RMS) are also provided and compared. The mean is the average of data, and the median is the value located in the middle of sorted-out data from the smallest to the largest. Root mean square is the square root of the mean value of all elements of a matrix of data.

Covariance (Cov) is also calculated between measurements and the hindcast:

$$\mathrm{cov(A,B)} = \frac{1}{N-1}\sum_{i=1}^{N}(A_i - \mu_A) * (B_i - \mu_B) \tag{3}$$

$$\mu_A = \frac{1}{N}\sum_{i=1}^{N} A_i \tag{4}$$

By calculating Cov for the matrix of hindcasting data and buoy measurements, a symmetric matrix is obtained which is also called a covariance-variance matrix. On contrary with covariance, variance shows the variation of a single variable. Variance provides an understanding of the dispersion of data in a data set. The diagonal elements of this matrix are the variances and the other arrays are the covariances. It should be noted that this metric does not assess the dependency between variables. Positive covariance shows that two variables tend to move together and in the same direction.

Other common statistical parameters for the validation of wave hindcasting are Root mean square Error (RMSE), Scatter index (SI), Mean Bias, and correlation coefficients.

Root mean square error (RMSE) (see Equation 5) calculates the errors between two sets of data, this provides a measure for comparing the data obtained from the model with measured data:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(Num_i - Buoy_i)^2}{N}} \tag{5}$$

RMSE shows how much the model fits with the observed data. The lower value of RMSE suggests higher accuracy. To get a further understating of the accuracy of the results, the Scatter Index (SI) is also calculated. SI also known as Normalized Root Mean Square Error (NRMSE) measures the relation of the RMSE to the average of measured data. As the mathematical description of SI suggested, it provides the percentage of difference with respect to the mean value of buoy measurements. Comparing the results with similar studies shows that hindcast results are in good agreement with the buoy measurements.

The correlation Coefficient (CC) represents the statistical relationship between two variables. This coefficient shows the linear relationship between two variables and how they vary together. The value of 1 for CC represents perfectly correlated data which is considered an unrealistic correlation.

5 Statistical data analysis and interpretation

According to standards, for the purpose of analyses and design procedures, extreme environmental conditions should be estimated (DNV GL, 2014; IEC, 2019). The extreme values can be obtained from the statistical data analyses.

The results from the hindcasting are used for the extreme value analyses as an independent variable and joint study. By study on the results of statistical analyses, a signal can be defined as input for the AVL tool. The procedure is shown in Figure 4.

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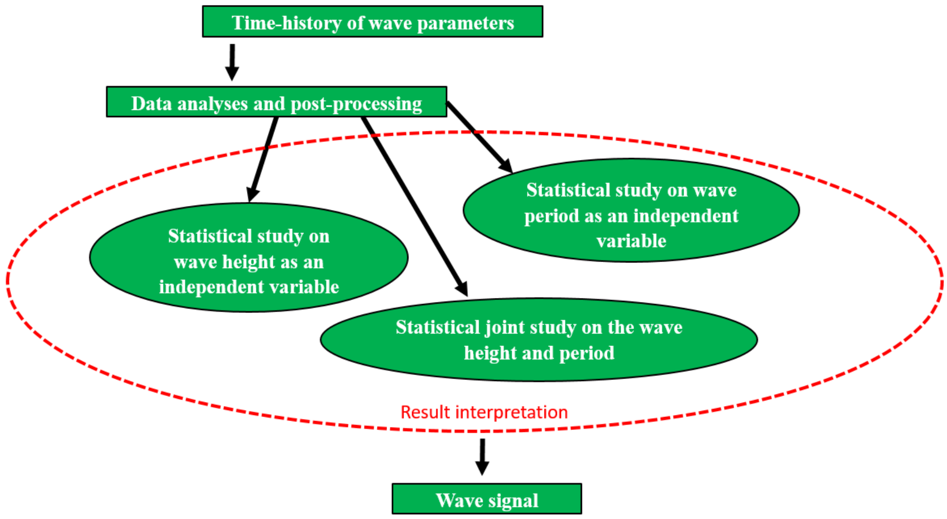

Figure 4: Application of hindcasting output.

5.1 Signal for wave-to-wire modelling

According to the requirement of an accelerated test, different wave signals can be provided as input for the analyses. The signal can be a simplified deterministic linear wave with the extreme values of wave height and period from the interpretation of the joint probability analyses and independent variable analyses.

The choice of the signal and their numbers are also dependent on the wave variance spectrum or energy density. This subject will be further discussed in the section on environmental wave modelling.

5.2 Extreme Value analyses

Statistical analyses are conducted to propose the proper mathematical model describing the data for interpretation and extracting the required information from the data e.g. (Putz, 2000). For studying waves, different methods are developed including total sample, annual maxima, and peaks over thresholds (POT) (Coles, 2001a; Mathiesen et al., 1994).

Each method has benefits and limitations. Two necessities of a statistical sample are independency and homogeneity which cannot be fully satisfied for the total sample method of extreme values (Y. Goda, 2000). Therefore, annual maxima and POT are used which could meet the prerequisites for finding the extreme values (Coles, 2001b; Y. ` Goda, 2000).

As has been explained in POT method the overall final filtered dataset is independent and identically distributed (iid) (Y. Goda, 2000). In this method, storm events above a certain threshold value are determined.
To find the best fit, different distribution functions are applied and the most proper one for the population is defined (Y. Goda, 2000). Here the threshold is set as a value of 99th percentile. Therefore, the threshold is equal to the value below which 99% of the data are found. For this project, the threshold is found, various probability distributions are fitted and the suitable fit for exceedances over the threshold is detected (hereafter called PKS).

5.3 Joint probability of wave height and period

It is advised to use the environmental contours as a common approach and representative of extreme joint probability (IEC, 2019). The reason is the correlation between wave parameters, which is ignored by the univariate approach. Environmental contours provide the extreme sea

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states required for the analyses and design procedure of marine structures (Eckert-Gallup et al., 2016).

The contours usually use the joint probability of significant wave height and peak period. Since it requires a sufficient amount of time, the hindcasting data can be used in absence of buoy measurements (Eckert-Gallup et al., 2016; IEC, 2019).

There are multiple definitions and various methods to compute a contour (Haselsteiner et al., 2017). Here the IFORM approach as a design practice is utilised. IFORM originates from the structural reliability methods. In this method, it is essential to know the probability of exceedance to find the corresponding response level. The failure probability is estimated by the following equation:

$$p_F = \frac{1}{365 \times (\frac{24}{t_s}) \times T_r} \tag{6}$$

$$r_r = 1 - p_F \tag{7}$$

In this equation, t_s is the time interval of recorded data. Hindcasting simulation results are set hourly, so t_s is one hour. T_r is the return period, which according to the standards, it was considered 50 years. Considering 50 years return period, the failure probability is calculated.

By using the inverse of the cumulative normal distribution function, the corresponding value of a circle with radius β is estimated for the failure probability (p_F). All the pairs with a specified tolerance that belong to the circle are considered target joints. Therefore, tolerance in accepting the pairs plays a crucial role, which indicates 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. (Haldar, 2019).

Lognormal distribution of *Tp* is correlated to *Hs* by defining the relation between *Hs* and the distribution parameters. A correlation was found between each lognormal parameter and *Hs*.

$$\mu(LnTp) = a_1 + a_2 Hs^{a_3} \tag{8}$$

$$\sigma(LnTp) = b_1 + b_3 \exp{(b_3 Hs)} \tag{9}$$

Various time steps should be chosen to figure out the suitable one. It should be noted that the interval directly affects the number of peak events, for this reason, a time interval of two to four days is suggested (Mathiesen et al., 1994). Here, based on sensitivity analyses, 72 hours have been selected for the application of the tool to the user case hindcasting data. Nonlinear least square with 95% confidence bounds is used for finding a_i and b_i, i=1,2,3.

It must be noted that the time step defines the range of the data in each classification. It is also known as binning data that directly affects the predictive model. Binning data in 72 hours, means having 72 data in each bin. Considering 175200 data (20 years X 365 days X 24 hours), it provides a very small while accurate binning.

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. The graphical representation also shows the measure of spread. Although the parameters (a_i and b_i) were found to find the nearest fit between Hs and the lognormal parameters, it captures the central tendency, and there are still some data extended in various directions than the fitted curve.

The procedure for finding the environmental contour is explained in more detail in (DNV GL, 2014; Kim, 2020).

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For the application, the contour is generated from 1420 points. To get a clear picture of pairs of wave parameters, the data classification should be conducted. Simplified data bining or subranging over a range of data has been done which specifies values fall into a given interval.

6 WAVE-TO-WIRE MODEL

Developing a fairly accurate hybrid simulation tool for a WEC can be challenging in various aspects of hydro-servo-elastic-geo interaction (Saeidtehrani et al., 2022a). The expected challenges in the development of the simulation tool are presented in Figure 5.

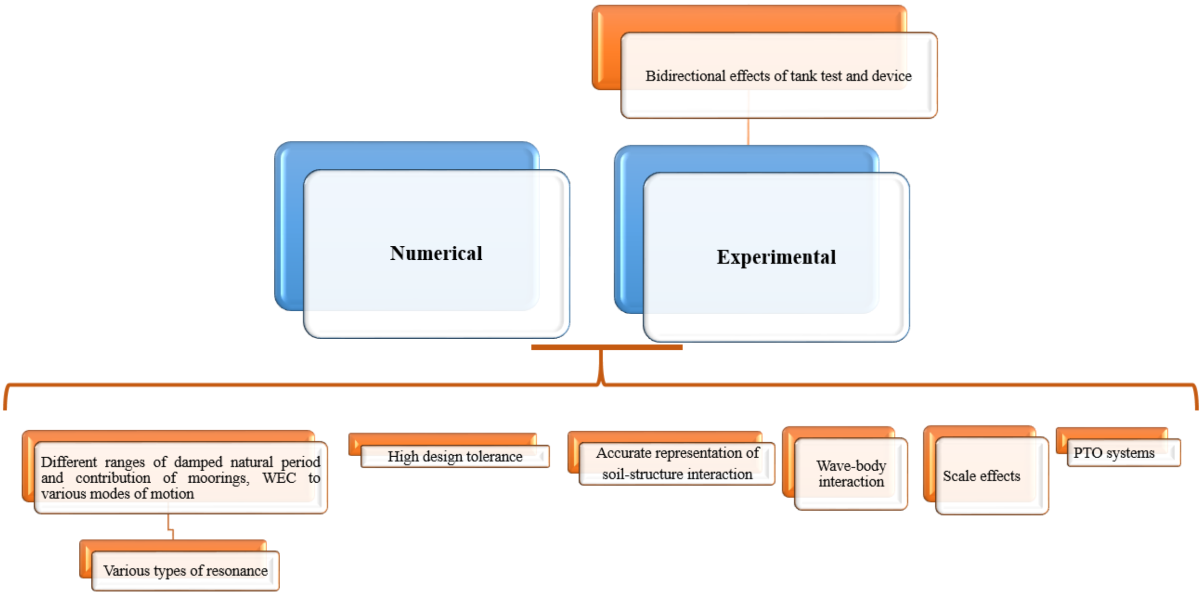

Figure 5: Main challenges in developing simulation tools for WEC (Saeidtehrani et al., 2022a)

One of the critical parts of the simulation of WEC behaviour is the representation of wave-body interaction. Most of the limitations are due to the usage of the old theories which are now utilized for a new generation of marine structures such as WECs. On the other hand, computationally demanding tools cannot be always a good solution for the industry. Especially during the operation procedure that it is critical to assess and compare the data for possible faults or malfunctions.

The wave-structure interaction for oscillating WECs, especially under moderate to harsh environmental conditions, is highly nonlinear (Saeidtehrani, 2021a; Saeidtehrani and Karimirad, 2021) and, therefore, the development of a fairly accurate simulation tool while decreasing the computational/time efforts (Folley et al., 2012) is still ongoing (Folley, 2016; Yu, 2017). Some of the expected phenomena that can make the simulation of wave-body interaction difficult are presented in Figure 6.

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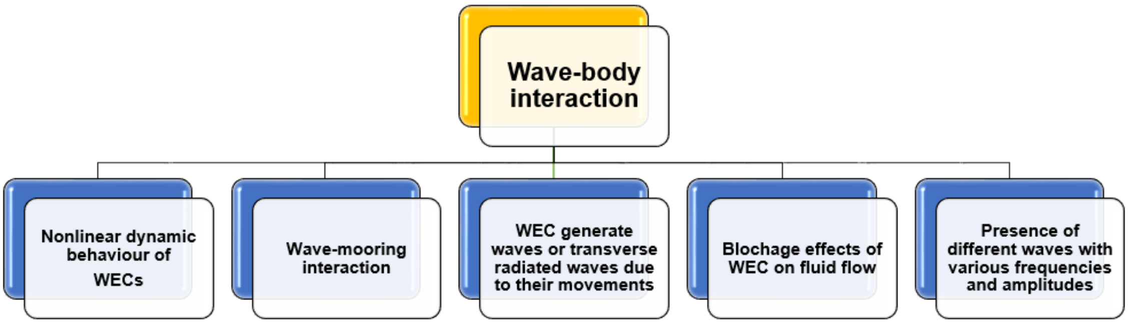

Figure 6: wave-body interaction challenges (Saeidtehrani et al., 2022a).

Various PTO families are also under development for different WEC concepts. Due to the diverse dynamic loading patterns and the variability of renewable energy resources, the cost-effective PTO design is a difficult task. An accurate reproduction of PTOs in experimental tests is also complex due to the variety of unscaled friction effects e.g. (Têtu, 2017) and the downscaling of electrical systems and components.

These various uncertainties from the test setup to power estimation are the challenging sources in experimental tests (Giannini et al., 2020).

The required blocks to make the hybrid model incorporate the soil-structure-wave interaction model, PTO model, and accelerated test data which are explained in the following sections. Generally, by using some simplified models the interactions between different parts are captured. However, in any kind of modelling thorough understanding of the phenomena involved makes a much clear decision on the simplified approaches. Therefore, due to the importance of soil-structure-wave interaction model description is split into two parts of wave-structure and soil-structure.

6.1 Wave–structure interaction models

Wave-structure interaction models extend from the most simplified to the more advanced CFD models which simulate the fluid motions and their influences on other phenomena (Tu et al., 2018).

For WEC devices, CFD is used to represent the WEC structure-wave interaction. The model can be developed depends on the desired level of complexity and the reliability of the approaches and models. For selection of the appropriate CFD model, Reynolds number, is generally accepted as a key factor (Faltinsen, 1990). Reynolds number is a dimensionless quantity which can be used for determining flow regimes and patterns.

Known flow regimes can be approximately tabulated as follows:

Table 1. Reynolds number and flow regimes (Faltinsen, 1990).

Subcritical	$Re < 2 \times 10^5$
Critical	$2 \times 10^5 < Re < 5 \times 10^5$
Supercritical	$5 \times 10^5 < Re < 3 \times 10^6$
Transcritical	$Re > 3 \times 10^6$

The theoretical estimation of the Reynolds number and the fluid flow regimes can be used to select a suitable CFD model. However, it should be noted that for WEC devices, the shape and the movement of the device can significantly affect the fluid flow behaviour. These effects cannot be reflected in the general formula of Reynolds which is calculated for the length of the body (Saeidtehrani, 2021b).

Based on the primary assessment and the engineering judgement, the complexity level of the model is defined. It should be highlighted that for different life cycles (Section 2.1), various levels of complication may be required.

The most complicated model simulates the direct Navier-stokes equations which can represent the diverse kind of fluid flows (Pope et al., 2000; Svendsen, 2006). However, the vast information for turbulent flows from the direct approach can be considered impractical for engineering applications (Pope et al., 2000).

Therefore, it would be possible to assume that the flow field (u) includes local oscillations (u') and a time-averaged part (U) (Pope et al., 2000) to make further simplifications.

Similar to the simulation of the fluid flow behaviour, the structural part can have different levels of complexity. The model can encompass a simplified idealized model representing dynamic movement and the general behaviour or most complicated simulating various components and their interaction.

6.2 Soil-structure interaction models

The station-keeping system for floating bodies is another major topic in the development of simulation tools and design of floating concepts. The station keeping system can be a passive, active, or combined passive-active system based on the principle of providing the restoring force (Gao and Moan, 2009). Typical foundation and mooring response assessment include several steps and the response analysis procedures, which can vary from static to dynamic, are the topic of several guidelines (DNV GL, 2017) and studies (Karimirad et al., 2015).

7 Numerical models for the hybrid testing platform

This section describes a methodology to connect different parts of the model by the use of a co-simulation platform. This platform is used for the implementation of hybrid testing to integrate the physical and virtual models. This platform is called IODP (integrated and open development platform) which acts as a communication layer to effectively exchange information from the above-mentioned elements of wave-to-wire modelling (see Section 6).

It should be emphasised that the integration of models based on various software is a challenging task. Therefore, a co-simulation environment is introduced which has the advantage of interchangeability utilizing the best possible simulation tools along the development process. The co-simulation platform Model.CONNECT couples simulation tools like Matlab/Simulink (Mathworks, 2022) with OrcaFlex (Orcaflex, 2022). The schematic Figure 7 represents the connection between different modules representing the hybrid testing platform. The modules include the block simulating PTO, accelerated test data, and soil-structure-wave interaction model by using a co-simulation platform.

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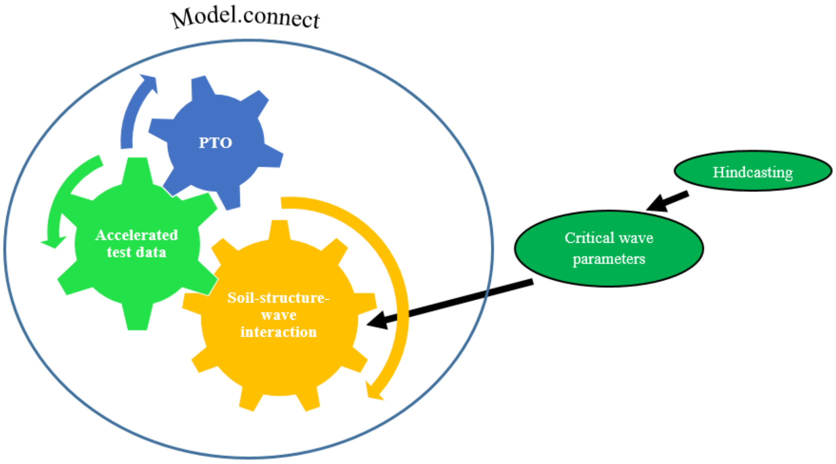

Figure 7. Numerical model configuration.

The connection of the blocks in Model.CONNECT is shown in Figure 8. The 'Buoy' block, an Orcaflex model, is responsible for simulating soil-structure-wave interaction. The wave hindcasting results are used for the simulation in this block. The PTO block is simulating the mechanics and electrics of the power converter, controlled by a separate submodel 'Controller'. A so-called boundary condition server can be used to provide experimental data to the simulation models.

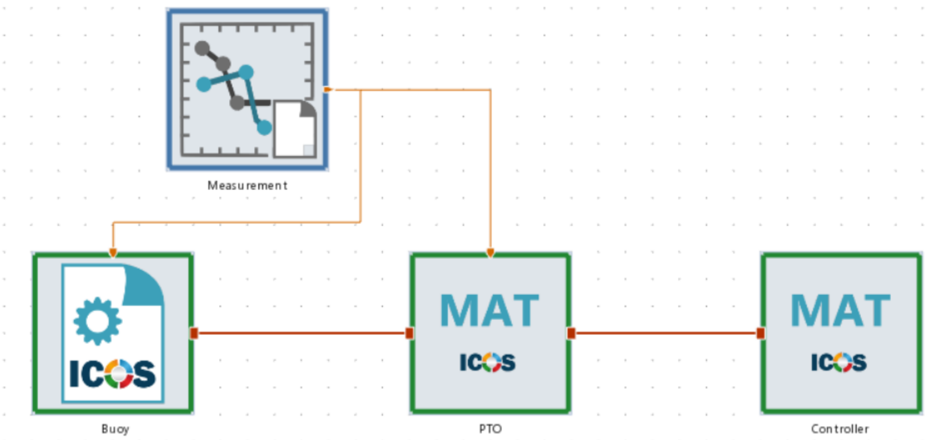

Figure 8: Exemplary system-layout of Corpower WEC in Model.CONNECT.

8 Conclusions

This task aimed to provide all information for the VALID Hybrid Test Platform which encompasses gathering the ocean conditions to setting up the wave-to-wire model.

In the process of modelling, it is mandatory to use various levels to provide enough understanding of the system. For the specific needs of each user case, high-fidelity models should be used. These models can bring better knowledge of the scale effects or other sources of uncertainties that can affect the prediction of the device and critical subsystems' behaviour.

For wave-to-wire modelling, it is essential to provide inputs with sufficient accuracy. Wave conditions need to be assessed to provide a proper design for the operation and prevent catastrophic situations. On the other hand, the correlation of extremes for different variables should be considered to accurately represent environmental conditions and associated risks e.g. (Drago et al., 2015).

Since the development of hybrid testing is focused on extreme loads, it needs probabilistic analyses of long-term data. However, in the absence of the measured data, the standards advised to use hindcasting.

By developing a numerical model, the wave parameters for the point of interest can be calculated. Like any differential equation, the development of the model needs a proper domain, boundary conditions, and defining the governing equations. The governing equation is the spectral energy balance equation over a spatial grid.

There are different sources of errors that could affect the reliability of the numerical model. Some of these errors in connection with the hindcasting model were discussed and a suitable approach to tackle them was explained. Mesh sizes, solver time step, and boundary conditions are the possible sources of errors to name but a few.

However, since user case 1 (CORPOWER OCEAN) has already access to the environmental inputs for the VALID Hybrid Test Platform, the step for hindcasting and finding the extreme wave parameters were skipped. Therefore, this deliverable only provides the methodology to set up the wave-to-wire simulation in which the wave data and the required steps for hindcasting were also explained in detail.

Then, the wave input can be used for the hydrodynamic simulation. The hydrodynamic solver will be connected to the AVL. AVL provides a platform to connect different sources of information from numerical results and experimental tests to conduct VALID Hybrid Test.

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9 Nomenclature

Abbreviations

CC	Correlation coefficients
Cov	Covariance
Hs	Significant wave height
Min	Minimum
Max	Maximum
PkDir	Peak wave direction
RMS	Root mean square
RMSE	Root mean square error
SI	Scatter index
Tm01	Mean absolute wave period
Tp	Peak period
Var	Variance

Variables

a_i	Fitting coefficients
b_i	Fitting coefficients
β	Radius in the U-space
cg	group velocity
c_σ	Propagation velocity in spectral space, frequency
$c\theta$	Propagation velocity in spectral space, direction
Hs	Significant wave height
N	action density
POT	Peaks over thresholds
p_F	Failure probability
r_r	Reliability
Re	Reynolds number
σ	frequency
S_{tot}	non-conservative source/sink term
S_{in}	wave growth by the wind
S_{nl3}	three-wave interaction
S_{nl4}	four-wave interaction
$S_{ds,w}$	whitecapping
$S_{ds,b}$	bottom friction
$S_{ds,br}$	depth-induced wave breaking

θ	propagation direction
t	Time
Tr	Return period
ts	Time interval of recorded data
U	Current
x	x-Space

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