

Article

CFD Study of a Novel Wave Energy Converter in Survival Mode

Cassandre Senocq^{1,*}, Daniel Clemente^{2,3}, Mailys Bertrand¹, Paulo Rosa-Santos^{2,3,*}
and Gianmaria Giannini^{3,4,*}

¹ SeaTech School of Engineering, University of Toulon (UTLN), 83957 La Garde Cedex, France; mailysbert83@gmail.com

² Department of Civil Engineering and Georresources, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal; daniel_r_clemente@outlook.com

³ Marine Energy and Hydraulic Structures Research Group, Interdisciplinary Centre of Marine and Environmental Research (CIIMAR-LA), University of Porto, Port of Leixões Cruise Terminal, Av. General Norton de Matos s/n, 4450-208 Matosinhos, Portugal

⁴ Marine Energy Lab, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

* Correspondence: cassandresenocq1@gmail.com (C.S.); pjrsantos@fe.up.pt (P.R.-S.); ggiannini@ciimar.up.pt (G.G.)

Abstract

Harnessing Europe's strong wave energy could support net-zero emissions goals, but extreme ocean loads still make wave energy expensive and delay the rollout of commercial wave-energy converters (WECs). To address this, the twin-floater CECO WEC has been redesigned into a single-pivot device called the Pivoting WEC (PWEC), which includes a passive duck diving survival mode to reduce extreme wave impacts. Its performance is evaluated using detailed wave simulations based on Reynolds-Averaged Navier–Stokes (RANS) equations and the Volume-of-Fluid (VoF) method in OpenFOAM-olaFlow, which is validated with data from small-scale (1:20) wave tank experiments. Extreme non-breaking and breaking waves are simulated based on 100-year hindcast data for the case study site of Matosinhos (Portugal) using a modified Miche criterion. These are validated using data of surface elevation and force sensors. Wave height errors averaged 5.13%, and period errors remain below 0.75%. The model captures well major wave loads with a root mean square error down to 47 kN compared to a peak load of 260 kN and an R^2 up to 0.80. The most violent plunging waves increase peak forces by 5 to 30% compared to the highest non-breaking crests. The validated numerical approach provides accurate extreme load predictions and confirms the effectiveness of the PWEC's passive duck diving survival mode. The results contribute to the development of structurally resilient WECs, supporting the progress of WECs toward higher readiness levels.

Keywords: marine renewable energy; wave energy; WEC; numerical modeling; OpenFOAM; extreme wave-load assessment; survivability; pivoting wave energy converter



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1. Introduction

Meeting net-zero targets requires a major rethink of where the world's energy comes from. The International Energy Agency's 2023 Net-Zero Roadmap still sets 2050 as the deadline for carbon-neutral energy [1]. Meanwhile, the European Green Deal aims for at least a 55% cut in emissions by 2030 and full climate neutrality by 2050 [2]. At the same time, electricity demand continues to rise; it reached a new record in 2023 at 29,471 TWh, which is an increase of 627 TWh compared to the previous year [3]. Ocean

waves, a virtually unexplored and renewable resource, can help balance ambitious electricity supply targets with increasing demand whilst diversifying the energy mix. The global gross theoretical wave power potential is estimated at roughly 3.7 terawatts [4], which is already comparable to the world's average electricity demand. Along Europe's Atlantic coast, the resource is especially strong: the west coast of Portugal sees average annual wave power values of around 40 kW per meter of wave crest [5], making the country one of the continent's key energy "hotspots." But beyond the sheer magnitude of the wave energy resource, functionality is crucial for power grid integration (i.e., an aspect related to how and when this energy can be practically be supplied). Indeed, wave energy can be predicted reliably several days in advance [6] and often reaches its peak when solar power is low, making it a natural complement to solar generation [7]. The predictability of wave energy also helps smooth out the variability of wind power, contributing to a more stable and balanced energy system. In short, harnessing even a small portion of this reliable, high-density energy source could assist ongoing decarbonization efforts whilst ensuring sufficient electricity supply.

Wave-energy technology is remarkably varied: over 6400 patents have been filed worldwide [8]. Yet, only a small number of these designs have reached full-scale for sea trials. In general, wave energy converters fall into three main hydrodynamic categories: oscillating water columns, overtopping devices, and wave-activated bodies such as point absorbers, attenuators, and surge flaps [9]. These systems also differ by location: some are fixed to the shore, others are mounted on the seabed in shallow waters, and others float offshore in deeper waters. Each setting influences the WEC-wave interactions, device accessibility, conversion performance and the overall cost [10]. Several prototypes highlight the range of wave energy technologies. On the shoreline, Spain's Mutriku breakwater plant features 16 oscillating water column chambers with a total capacity of 259 kW and has produced over 3 GWh since it began operating in 2011 [11]. Offshore, the Pelamis P1, an articulated attenuator, enabled the world's first wave farm in 2008 with three 750 kW machines (2.25 MW total) connected to the grid at Aguçadoura, Portugal [12]. WECs, such as the EcoWavePower, Oyster, and WaveRoller devices, located on or near the shore, have the advantage of requiring shorter power transmission lines and are easier to maintain due to their proximity to the shore. This makes them favorable candidates for earlier development over offshore devices.

Despite the aforementioned milestones, wave energy deployment remains limited. By the end of 2023, 13.3 MW of wave energy had been installed in Europe since 2010, but only about 1 MW was still operating [13]. A key barrier is cost, as the levelized cost of wave electricity in 2020 ranged between 0.35 and 0.85 USD/kWh [14]. This was about seven times higher than the average cost of new offshore wind projects commissioned that same year, which was estimated at 0.084 USD/kWh [15]. A closer look at these costs reveals that capital expenditures (CAPEX) dominate the levelized cost of electricity (LCOE), while operating costs (OPEX) are smaller but still significant [14]. The high costs are largely due to the challenges of survivability, as shown by field experience [16]. Failures such as the withdrawal of Pelamis P1 after technical issues [12], the shutdown of Oyster-800 (Aquamarine Power Ltd., Edinburgh, UK) in 2015 after testing [17], and storm damage to CETO-4 in 2014 [18] highlight how extreme ocean loads lead to overengineered structures, unexpected downtime, and investor hesitation. In short, reducing LCOE requires modeling tools that can accurately predict the complex, non-linear forces acting on devices, allowing for lower yet more reliable safety margins without compromising structural integrity. This need sets the foundation for the CFD-based approach introduced in the next section.

The hydrodynamic modeling of a wave-energy converter (WEC) typically begins with linear potential-flow theory [19]. In this approach, dynamic equations and

forces are described using Newton's second law and the Cummins formulation, which via convolution terms allow including the hydrodynamic effect of the device's past motion [20]. The hydrodynamic coefficients needed for these type of models are rapidly calculated using boundary-element methods based on solving a potential-flow domain. Recent comparative studies of this approach applied to WECs evaluate open-source tools (e.g., NEMOH v2.0, HAMS v3.2, Capytaine v1.4.0) and their computational trade-offs against commercial alternatives [21,22]. However, potential-flow theory does not account for viscosity and cannot reproduce the strongly non-linear interactions that dominate during large body motions/free surface elevation amplitudes in energetic seas [23]. As a result, large safety margins are still used when designing for near-breaking [16], motivating the use of nonlinear and high-fidelity Computational Fluid Dynamics (CFD) to capture these extreme phenomena. Beyond the study of WECs, CFD has also proven its versatility in other engineering contexts, offering the ability to capture viscous dissipation and turbulence while reducing reliance on costly experimental campaigns and thereby shortening research duration and development costs. For instance, it has been successfully applied to analyzing hydraulic energy losses in complex pipeline and fitting configurations [24], demonstrating its capability to resolve intricate hydrodynamic processes and energy dissipation mechanisms. Building on this broader foundation, Reynolds-Averaged Navier–Stokes (RANS) simulations coupled with Volume-of-Fluid (VOF) schemes have been employed in the marine field to resolve the air–water interface and strongly non-linear effects. Such approaches are increasingly validated for the survivability assessment of WECs under extreme sea-states [25,26]. The applicability of OpenFOAM to the study of WECs, including the modeling of steep and breaking waves, has been confirmed by several recent studies [27,28]. This has particularly been demonstrated through the use of specialized open-source tools such as waves2Foam [29], IHFoam [30], and olaFlow [31]. Because full CFD simulations remain computationally expensive, a targeted strategy is to select extreme wave conditions directly from long-term hindcasts and reproduce only those in RANS–VOF models, keeping costs manageable while providing high-fidelity survival load estimates needed to optimize design margins and lower the levelized cost of energy [25,32].

This study focuses on the Pivoting WEC (PWEC), which is a redesigned version of the original CECO WEC [33,34] developed at the Faculty of Engineering of the University of Porto (FEUP). PWEC, in contrast to CECO (translating WEC), consists of a rigid flap-shaped floater that swings around an upper hinge and activates a rotational-like power-take-off (PTO), which is placed above the waterline for easier maintenance. The hinge and PTO are attached to a fixed structure. An initial assessment of the PWEC was carried out using a time-domain potential-flow framework based on the Cummins equation with no CFD employed at this stage [35,36]. Thanks to the simpler structure and dry PTO, the design promises a 28% reduction in capital costs and could shorten the expected payback time by roughly 2.5 years [35]. The key innovation of this device is the introduction of a passive duck diving survival mode, which was specifically designed to limit the loads experienced by the device during storm conditions [36]. It was found that this mode could significantly reduce the floater's exposure to wave forces and structural loads by up to 65% during storms. This preliminary finding justifies the motivation for more accurate numerical modeling of the present study, which is aimed at testing the survivability under non-linear waves loading conditions.

The primary objective of this study is to develop a high-fidelity CFD model to evaluate extreme loads on a PWEC using a fully viscous approach based on RANS–VOF simulations implemented in olaFlow. The novelty of the work lies in the numerical modeling of a new PWEC concept, which is aimed at supporting the structural design process through accurate hydrodynamic load predictions. This, positively, enables the development of

resilient wave energy converter structures while minimizing the risk of overengineering. The passive duck diving survival mode of the PWEC involves locking the flap-shaped floater in a submerged position beneath the wave crest during storm conditions, thereby significantly reducing the loads acting on the device. The proposed CFD framework is intended not only to assess the performance of this specific WEC configuration but also to be applicable to similar nearshore devices. Additionally, the study seeks to validate the effectiveness of the survival strategy in mitigating extreme wave-induced forces, enhancing structural integrity, and promoting the long-term viability of wave energy as a dependable renewable energy source.

The paper is divided into three main parts: Materials and Methods, which outlines the PWEC concept, site conditions, and the CFD modeling approach; Results, which presents simulation outcomes and validation against experimental data; and Discussion and Conclusion, which interpret the findings in terms of structural resilience and the effectiveness of the passive duck diving survival mode under extreme wave conditions.

2. Materials and Methods

2.1. Description of the PWEC

The PWEC is a near-shore wave energy device designed to harness the kinetic energy of ocean waves, as shown in Figure 1. It uses a single floater that pivots around a joint fixed above the water, which is supported by a rigid structure anchored to the seabed. Under operational conditions, the floater oscillates in response to waves, and this motion is transmitted to a rotary generator positioned at the pivot point. The conversion of mechanical energy into electricity is achieved through a compact, above-water mechanical setup. By placing the mechanical components above the water surface, the PWEC offers practical advantages in terms of accessibility while also lowering installation and maintenance requirements compared to traditional submerged systems.

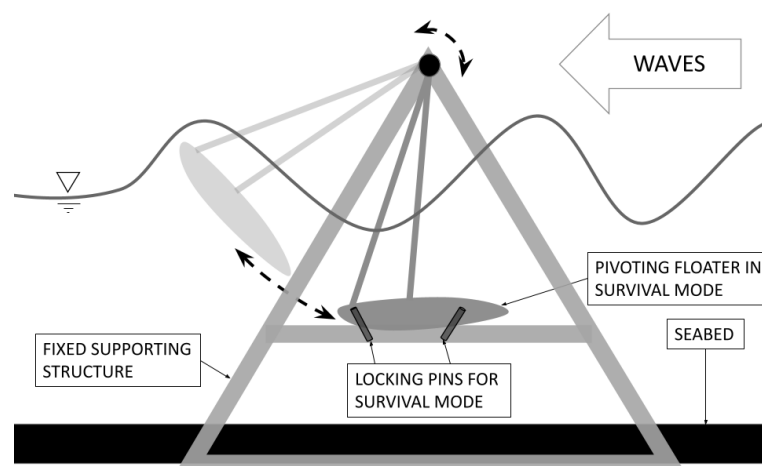


Figure 1. Schematic of the PWEC in passive duck diving survival mode [36].

The PWEC's ability to withstand extreme wave conditions was a key consideration in its design, which is why a dedicated passive duck diving survival mode was included. This mode, inspired by the duck-dive technique used by surfers to pass beneath breaking waves and avoid their full force, submerges the floater and locks it in a low-profile position beneath the wave crest using electrically controlled pins. Combined numerical simulations and 1/20 scale physical tests show that this configuration can reduce total hydrodynamic loads by up to 65% compared to normal operation [36]. This significant load reduction allows for lighter locking pins, a more streamlined support frame, and ultimately, tighter safety margins across the entire structure.

2.2. Deployment Site and Environmental Conditions

The full-scale PWEC prototype is being studied for potential deployment off the coast of Matosinhos, Portugal (coordinates: 41.17830° N, −8.71047° W). The device is developed to operate and withstand realistic Atlantic Ocean wave conditions. For such scope, a wave resource matrix based on 44 years of wave observations at the deployment site is shown in Figure 2.

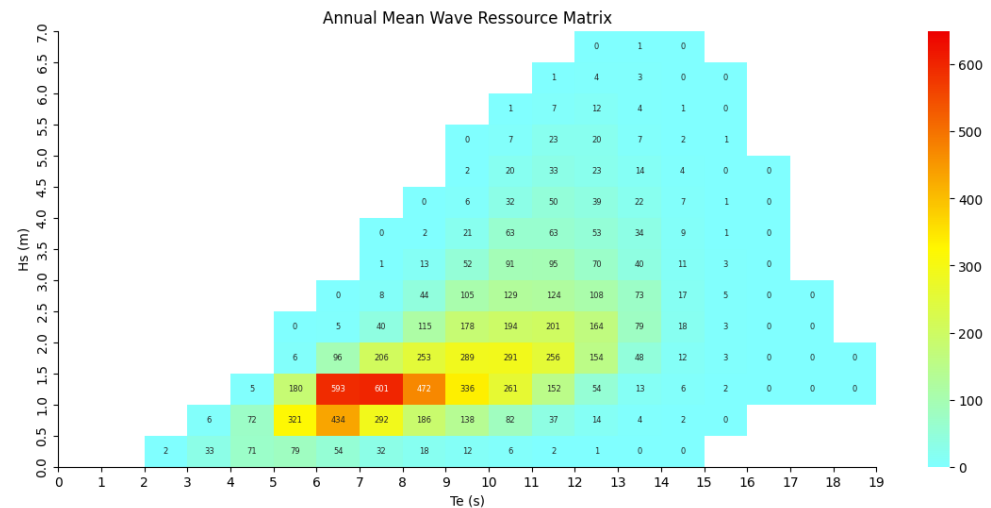


Figure 2. Mean annual wave resource matrix at the Matosinhos deployment site.

To assess the long-term survival capability of the WEC, it is essential to characterize the most extreme sea states it may encounter over its operational lifetime. To this end, a Block Maxima (BM) sampling method was employed by selecting the annual maximum significant wave heights (H_{m0}) from the past 44 years. However, for the purposes of distribution fitting, only the first 43 years were considered, as the most recent value appeared anomalous. Although it could not be definitively confirmed as an outlier, its exclusion led to improved H_{m0} estimates. These maxima were then used to fit a Generalized Extreme Value (GEV) distribution, allowing us to extrapolate the probability of future extreme sea states [37]. Based on this modeling, spectral significant wave heights expected over a 100-year period were estimated. The GEV model produced three representative cases: a central estimate, a lower prediction bound, and an upper prediction bound. Figure 3 shows the evolution of H_{m0} over 100 years for these three scenarios. The upper bound represents the reference survival conditions the PWEC must endure, serving as a basis for structural integrity assessment and design validation.

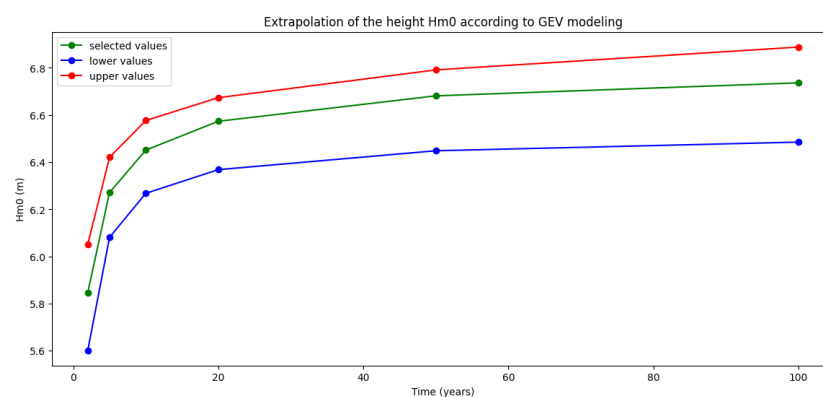


Figure 3. Extreme sea states derived from 100-year return period analysis using GEV modeling.

2.3. Numerical Setup

Three-dimensional (3D) numerical simulations were carried out using OpenFOAM-10, an open-source CFD platform, coupled with the olaFlow library, which is specifically adapted for simulating wave propagation and interactions with stationary structures. Only the floater was represented in this study to reduce computational costs (in terms of simulation time and memory requirements) and to simplify the geometry. The floater was modeled as a rigid, fixed body to analyze the passive duck diving survival mode of the PWEC (submerged fixed floater), matching the operational scope of the olaFlow solver.

The flow is described by the incompressible, multiphase Navier–Stokes equations and is discretized with the finite-volume method:

$$\nabla \cdot u = -\frac{1}{\rho} \frac{d\rho}{dt} \quad (\text{continuity}) \quad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \otimes u) = -\nabla p + \nabla \cdot [\mu(\nabla u + \nabla u^T)] + \rho g + \sigma \kappa \nabla \alpha, \quad (\text{momentum}) \quad (2)$$

The density and viscosity depend on the volume fraction α : $\rho(\alpha) = \alpha \rho_\ell + (1 - \alpha) \rho_g$ and $\mu(\alpha) = \alpha \mu_\ell + (1 - \alpha) \mu_g$. The term $\sigma \kappa \nabla \alpha$ comes from the Continuum-Surface-Force formulation for surface tension [38].

To capture the air–water interface, the Volume-of-Fluid (VOF) method solves a transport equation for α , as shown in Equation (3).

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha u) + \nabla \cdot [\alpha(1 - \alpha) u_r] = 0, \quad (3)$$

with $u_r = C_u \|u\| n$ sharpening the interface. The MULES limiter maintains $0 \leq \alpha \leq 1$ while conserving mass [39,40].

The pressure–velocity coupling is addressed through the PIMPLE algorithm, which is a hybrid approach that merges SIMPLE under-relaxation with PISO pressure corrections. By combining the stability of SIMPLE with the time accuracy of PISO, this method is particularly effective for transient multiphase simulations [38,41].

In all simulations, three outer correctors, two pressure correctors, and one non-orthogonal corrector were applied per time step, in line with best practices suggested by Wolf Dynamics [42], to ensure numerical stability and convergence, particularly for strongly coupled flows, large domains, or when using meshes with non-orthogonal cells.

2.3.1. Computational Domain

The computational domain was designed to provide adequate space for generating and propagating waves, as well as for capturing their interaction with the structure, whether in breaking or non-breaking conditions. In the streamwise direction, the domain length was set to six or eight times the incident wavelength plus the length of the floater: six times for model validation cases, which involve a set of regular waves [43] used for model validation, and eight times for extreme wave cases, in which waves are more likely to break and potentially generate strong reflections [44]. In all cases, the position where waves were generated was selected based on a preliminary analysis of the wave field in order to observe the exact target wave characteristics at the point of the WEC. A uniform bottom slope of 4° , approximately the bathymetry slope existing at the case study site, was applied consistently across all scenarios independent of the wave regime. This setup ensures that the free surface at the shoreline remains below the top of the slope under all wave conditions, effectively mimicking a beach profile. The 4° inclination encourages gradual changes in wave shape, concentrates wave energy through shoaling, and allows waves to break naturally when conditions favor it [45].

In the transverse direction, the domain width was set to half a wavelength plus the floater's width, allowing the development of a single wave crest without interference from lateral boundaries [46]. In the vertical direction, the domain height was defined as 20 m or 30 m depending on the wave amplitude to provide adequate clearance above the free surface. This configuration kept the wave fully contained within the computational domain and contributed to stable tracking of the interface throughout the simulation.

Figure 4 shows the schematic of the overall computational domain used in the simulations.

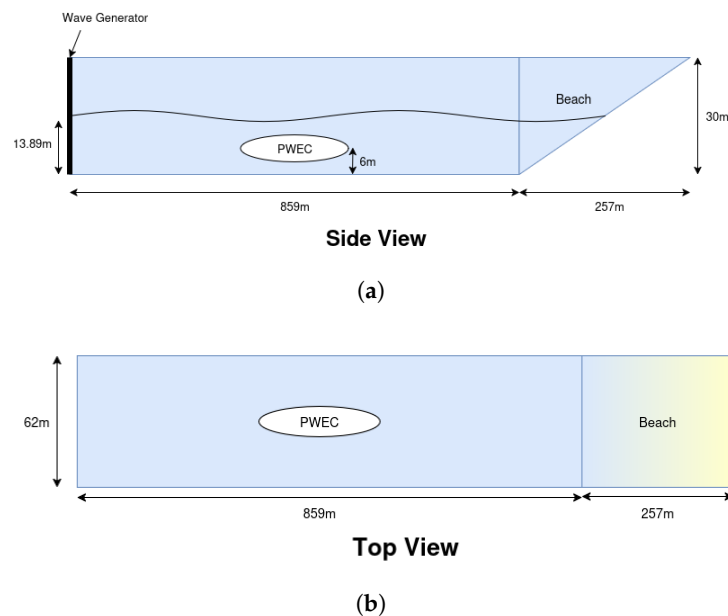


Figure 4. Schematic views of the computational domain: (a) side view and (b) top view, showing the largest dimensions employed in the study.

Table 1 summarizes the different wave tank dimensions used in this study.

Table 1. Wave tank dimensions for the test cases.

Case ID	Case ID	X Length (m)	Y Length (m)	Z Length (m)
Regular wave validation	V1	725	47	20
	V2/V3	1007	71	20
Extreme wave campaign	E1/E2/E3	908	49	30
	E4/E5/E6	1116	62	30

2.3.2. Mesh Generation

The mesh was generated through a two-step process: first, a coarse base grid was created using blockMesh, which was followed by local refinement with snappyHexMesh (OpenFOAM v10). This method provided precise control over mesh density in key areas while preserving overall computational efficiency across the domain.

Refinement was particularly focused on the free surface and the floater, as shown in Figure 5. Following classical mesh design criteria to ensure an accurate resolution of wave elevation and interface dynamics, the mesh in the vertical direction near the surface was refined to achieve a resolution of $\Delta z \leq H/10$ [47]. In the horizontal direction along the wave propagation axis, a spatial resolution of $\Delta x \leq \lambda/40$ was enforced to resolve wave steepness and phase speed accurately according to recommended practices [48].

Additional refinement levels were applied to the floater to capture pressure gradients and flow separation. In accordance with the fixed survival configuration studied in this

work, a refinement level of 4-4 (base level plus four layers of local refinement) was applied to the floater surface. This configuration was selected based on prior mesh sensitivity analyses to ensure the convergence of hydrodynamic forces while limiting computational cost.

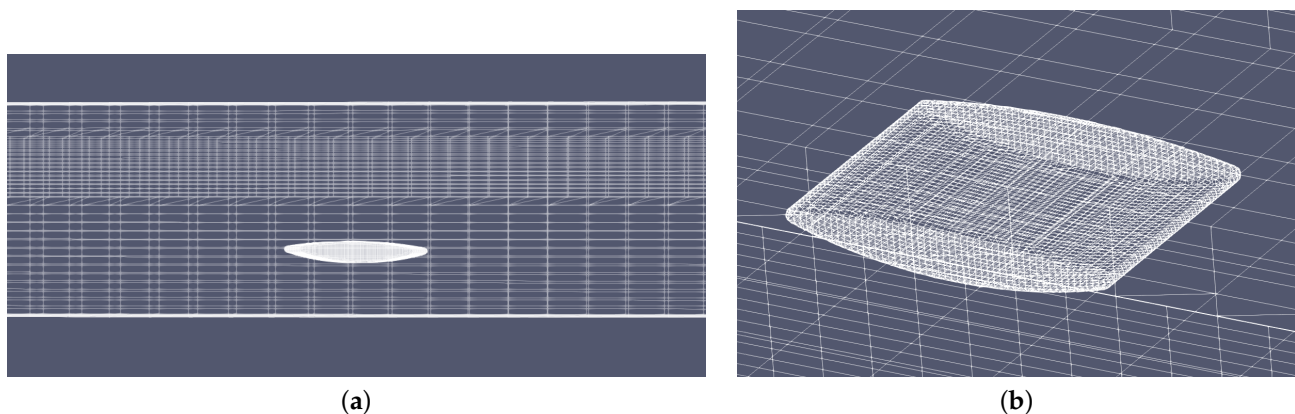


Figure 5. Mesh refinement near the free surface and floater: (a) overall mesh distribution, (b) close-up of the floater.

2.3.3. Boundary Conditions

To ensure valid waves generation and numerical stability, a set of tailored configurations and boundary conditions were implemented. Specific settings included wave absorption parameters to avoid wave reflections and track the water surface. Table 2 summarizes the boundary conditions used for each domain boundary and their respective purposes.

Table 2. Summary of boundary conditions for wave simulation.

Boundary	Boundary Condition	Description
Inlet	waveVelocity, waveAlpha (from olaFlow)	Controls incoming wave characteristics (velocity and phase fraction)
Outlet	waveAbsorption2D	Absorbs outgoing wave energy to reduce reflections and avoid interference
Lateral sides	symmetryPlane	Assumes negligible lateral flow, supports single wave crest across the domain width
Bottom (seabed)	No-slip wall	Accounts for frictional effects due to the sloping seabed
Top (free surface)	Atmospheric pressure outlet	Allows free movement of water surface and air phase exchange

This boundary setup was chosen to closely mimic real hydrodynamic conditions in wave–structure interaction simulations while reducing numerical issues like artificial reflections or energy build-up at the edges of the domain.

2.3.4. Temporal Discretization

To maintain numerical stability throughout the simulations, two Courant number limits were enforced: one for the overall flow (maxCo) and another for the volume fraction field (maxAlphaCo), which were both capped at 0.5. In areas where the flow changed rapidly, particularly near the interface or during strong wave impacts, a minimum time step ($\Delta t_{min} = 1 \times 10^{-6}$ s) was used to avoid solver divergence. The time integration itself was accomplished using the implicit Euler method, which, although first-order accurate, proved reliable when dealing with sharp gradients and non-linear wave behavior.

2.3.5. Interface Capturing

The air–water interface was accurately captured using the VOF method along with the MULES (Multidimensional Universal Limiter for Explicit Solution) algorithm. To maintain a sharp interface and limit numerical diffusion, the MULES settings were adjusted to $nAlphaCorr = 3$, $nAlphaSubCycles = 2$, and $cAlpha = 2$. These parameters, respectively, control the number of correction steps, the number of sub-cycles within each time step, and the intensity of interface compression. This configuration follows guidance from the Wolf Dynamics OpenFOAM guiding materials [42], which recommend 3 or more alpha corrections for highly transient flow, high-Reynolds-number, or high-CFL-number flows, as well as using 2 or more sub-cycles when applying explicit MULES. In addition, interface sharpening was enhanced by activating the term $div(phi_{rb}, alpha)$, which improves the capture of steep wave fronts, particularly in strongly non-linear and breaking wave scenarios [42].

2.3.6. Turbulence Modeling

Turbulence modeling is adapted to the wave regime: for non-breaking waves, a laminar flow assumption is applied, while for breaking or post-breaking conditions, a RANS approach with a standard $k - \epsilon$ turbulence closure is used. This combined approach ensures adequate resolution of wave dynamics while keeping the simulations efficient in both regular and highly non-linear wave conditions.

2.4. Post-Processing Strategy for Free Surface Elevation

To verify the accuracy of wave generation and ensure consistency with target wave conditions, a post-processing approach was implemented to extract and analyze the free surface elevation from the numerical domain.

Measurements were performed at multiple probe locations spaced every 25 m along the wave propagation direction, starting from $x = 25$ m. These locations covered the first three wavelengths of the domain. To ensure that the wave field remained unaffected, the floater was intentionally excluded from the simulation during this validation phase.

At each probe point, the free surface elevation was reconstructed from the multiphase VOF field by identifying the vertical position where the phase fraction $\alpha = 0.5$, corresponding to the air–water interface. When this threshold was crossed between adjacent cells, a linear interpolation was used to estimate the interface position.

Each simulation ran for a little over 10 wave periods, ensuring that a sufficient number of waves were available for the analysis. The surface elevation signal was then post-processed using a Python (v3.10) script to detect wave crests and troughs and estimate individual wave heights and periods.

Since experimental data of the free surface were not available, a theoretical sinusoidal wave profile was constructed as a reference for validation, using the wave input parameters defined in the waveDict file, notably the target period and amplitude. The relative errors on wave height and period can be computed using Equation (4).

$$\text{Relative error (\%)} = \frac{|\text{Measured value} - \text{Reference value}|}{|\text{Reference value}|} \times 100 \quad (4)$$

where the measured value is the OpenFOAM simulated wave height/period and the reference value is the target sinusoidal input value. The comparison was intended to validate the consistency of the wave generation system with its own configuration rather than against experimental measurements.

2.5. Hydrodynamic Force Extraction and Analysis

In order to complement the free surface elevation analysis and further validate the numerical model, a dedicated post-processing approach was implemented to evaluate the hydrodynamic forces exerted by waves on the floater.

To carry out this part of the validation, the total wave-induced forces acting on the floater were monitored and analyzed. Specifically, the focus was placed on the horizontal (F_x) and vertical (F_z) components of the global hydrodynamic force, which are directly relevant for evaluating the structural loading in survival conditions.

The force signals were extracted using OpenFOAM's built-in post-processing utilities. In particular, the forces function object was employed to compute both pressure and viscous contributions over the entire surface of the floater. This method relies on the integration of the surface stress tensor over the patch corresponding to the floater surface.

Force data were sampled throughout the simulation with a temporal resolution of 0.05 s (20 Hz), providing sufficient resolution to capture the full temporal evolution of the load signals. The resulting time series F_{total} reflects the dynamic interaction between the incoming wave field and the structure, including all non-linearities due to wave steepness, viscous effects, and, where relevant, wave breaking.

As in the free surface elevation validation, simulations were run for more than 10 wave periods to ensure statistical convergence and robustness of the results. The obtained force histories were then post-processed using a Python script to extract key statistical indicators (mean, maxima, error assessment) and enable direct comparison with experimental measurements when needed.

2.6. Miche Criterion for Extreme Waves

This study aims to study the highest breaking and non-breaking waves at a water depth of 13.89 m (depth at location 41.178303° N, −8.71047° W). To carry out the analysis, the modified Miche criterion was used to determine the limiting wave conditions and distinguish between waves that break and those that do not. This criterion offers a theoretical estimation of the maximum wave height before breaking, taking into account both wave steepness and water depth, as shown in Equation (5) [49].

$$H_{\text{max}} = \gamma \cdot \lambda \cdot \tanh\left(\frac{2\pi h}{\lambda}\right) \quad \text{with} \quad \gamma = 0.142 \quad (5)$$

The Miche criterion is widely used in coastal and ocean engineering due to its simplicity and relevance, especially in intermediate water depths where both depth-induced and steepness-induced breaking can occur [50]. Compared to its original form, the modified criterion offers better accuracy in practical applications, making it more suitable for realistic CFD simulations. Because of its ability to define a theoretical upper limit for wave height before breaking, it is particularly useful for establishing reference conditions for numerical simulations.

In the simulations, the breaking waves were modeled using a wave height input equal to $1.1 \times H_{\text{max}}$ given by the modified Miche criterion, not because a wave can stably exceed this limit in practice, but to intentionally surpass the theoretical breaking threshold and ensure that breaking would occur within the computational domain. For the non-breaking waves, a height of $0.75 \times H_{\text{max}}$ was selected, as heights as high as $0.8 \times H_{\text{max}}$ still led to marginal breaking.

The premature wave breaking, even below the theoretical threshold, may occur by several factors. First, the modified Miche criterion offers an idealized estimate of the breaking limit without considering transient effects, turbulence, or energy dissipation. As a result, it may fail to accurately predict the onset of breaking under realistic, non-ideal

conditions involving shear effects or reflections. Additionally, numerical instabilities or slight overshoots in wave amplitude caused by the generator can trigger marginal breaking. Numerical dissipation, turbulence, and implicit viscosity modeled within OpenFOAM's RANS or VOF frameworks may further destabilize the wave prematurely. Mismatches in the velocity field phase can also promote crest overturning. These factors highlight the challenges of accurately capturing wave breaking in CFD and emphasize the importance of carefully configuring the simulation setup.

2.7. Previous Experiment

A physical modeling campaign was conducted at FEUP's Hydraulics Laboratory in the $28\text{ m} \times 12\text{ m} \times 1.2\text{ m}$ ocean basin. The experiments used the four-paddle feature of the wavemaker system (tests' channel width $\approx 3.07\text{ m}$) and a still water depth of $h = 0.6\text{ m}$. A simplified 1:20 scale PWEC physical model (shown in Figure 6a,b) under Froude similitude was used, following established scaling and experimental recommendations [51]. This experiment aimed to validate the concept and quantify loads in three configurations: operational (moving), standard locked, and a passive duck diving survival mode. The floor-anchored model was built from a welded steel frame with a bicycle fork pivot and a hydraulic disc brake to emulate a tunable PTO, which was calibrated by dry oscillation tests.

The PWEC model was positioned along the central axis of the basin, providing a symmetric lateral clearance of approximately 1.54 m from each sidewall to minimize wall effects. Longitudinally, the center of the model was located about 2.50 m from the dissipative beach (upstream) and 2.00 m from the wave maker (downstream). This placement was selected to reduce both lateral and end reflections, ensuring a quasi-two-dimensional incident wave field in the interaction zone with the PWEC.

The instrumentation included four resistive wave probes for free-surface elevation measurement (sampling frequency 128 Hz ; accuracy $\pm 1\text{ mm}$), an optical motion-capture system with three Qualisys IR cameras (sub-millimetric precision, 200 Hz), and, in survival tests, a horizontal load cell mounted out of the water to improve signal quality (capacity 10 kg ; resolution 0.01 N). Operating condition control methods involved calibration of the PTO damping through dry oscillation tests, the continuous monitoring of wave probe base-lines, and motion tracking synchronization with wave generation signals. All instruments were periodically calibrated according to the manufacturers' guidelines [36].

Tests under regular waves ($T = 8\text{--}16\text{ s}$; $H = 4\text{ m}$ at full scale) and irregular waves ($T_p = 10\text{--}18\text{ s}$; $H_s = 4\text{ m}$) showed good repeatability (RAO variability $< 10\%$) and confirmed the effectiveness of the passive duck diving survival mode with reductions in horizontal load of up to $\approx 65\%$ compared to operational functioning ($\approx 40\%$ vs. the standard position). For the scope of the present study, a set of regular tests results, of such an experimental campaign relative to the passive duck diving survival mode configuration, is considered for validation purposes. These experimental results provide the basis for validating the OpenFOAM/olaFlow CFD simulations presented in this paper.

To enhance the reliability of the dataset, an uncertainty analysis was performed considering sensor resolution, calibration drift, repeatability of trials, and wave maker control accuracy. Following standard procedures for hydrodynamic experiments, the combined expanded uncertainty for free-surface elevation was estimated at $\pm 2\%$, while motion-capture displacement errors remained below $\pm 1\text{ mm}$. Load cell measurements showed an uncertainty of $\pm 3\%$ under dynamic conditions [36]. These quantified uncertainties are reported to strengthen the validation of the numerical simulations.

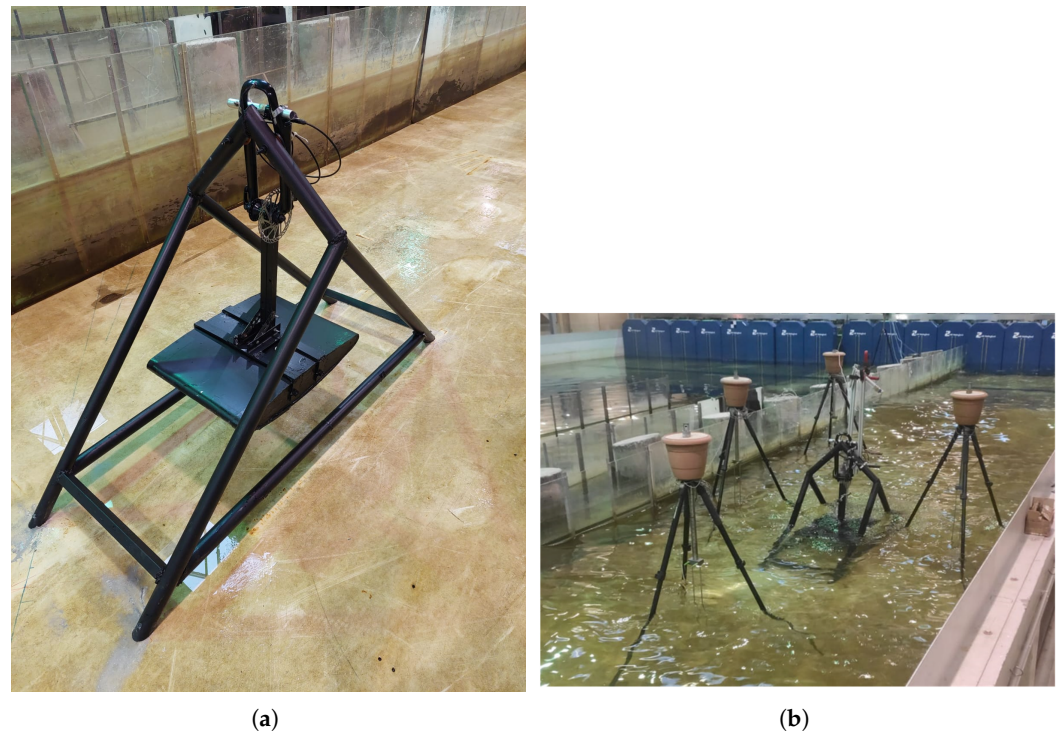


Figure 6. PWEC physical model: (a) assembled in the wave tank channel (no water), and (b) during load tests and wave probes.

2.8. Test Matrix

The numerical study involves two parts: regular wave validation with three cases and extreme wave tests using two wave periods ($T = 8$ s and $T = 10$ s), as shown in Table 3. For the extreme wave campaign, two regimes were simulated per period: non-breaking at $0.75 \times H_{\max}$ and breaking at $1.10 \times H_{\max}$. Wave loads were extracted at three floater positions: a non-breaking location (near the inlet), the breaking point, and a post-breaking location downstream.

Table 3. Test matrix.

	Case ID	T (s)	Regime	H (m)	λ (m)	Floater Position
Regular wave validation	V1	8	Regular	4.0	75.85	1 λ from wavemaker
	V2	12	Regular	4.0	122.89	1 λ from wavemaker
	V3	12	Regular	3.0	122.89	1 λ from wavemaker
Extreme wave campaign	E1	8	Non-breaking ($0.75 H_{\max}$)	6.78	79.77	$x = 25$ m (from inlet)
	E2	8	Breaking ($1.10 H_{\max}$ input)	9.94	79.77	At breaking point ($x \approx 87$ m)
	E3	8	Post-breaking ($1.10 H_{\max}$ input)	9.94	79.77	50 m downstream of breaking point
	E4	10	Non-breaking ($0.75 H_{\max}$)	7.64	105.81	$x = 25$ m (from inlet)
	E5	10	Breaking ($1.10 H_{\max}$ input)	11.20	105.81	At breaking point ($x \approx 105$ m)
	E6	10	Post-breaking ($1.10 H_{\max}$ input)	11.20	105.81	50 m downstream of breaking point

3. Results

3.1. Model Validation

Before applying the numerical model to extreme wave conditions, a preliminary validation was carried out to ensure that the simulation framework could accurately reproduce simple and controlled wave scenarios. The objective was to assess whether the model could generate realistic free surface elevations and compute consistent global forces on the fixed floater within acceptable uncertainty. These two criteria were chosen for their direct relevance to the quantities of interest in passive duck diving survival mode analysis.

3.1.1. Free Surface Elevation

As part of the model validation process, the accuracy of the free surface elevation was assessed using a set of regular wave cases, as shown in Figure 7. The red dots indicate the detected wave crests, while the green dots correspond to the identified troughs. These values were used to calculate individual wave heights and periods in the post-processing analysis. This step was designed to verify whether the numerical wave generation system could produce wave profiles that closely matched the input conditions defined in the simulation setup, particularly in terms of wave height and period.

The results are presented for three regular wave cases: two with a constant wave height $H = 4$ m and wave periods $T = 8$ s and $T = 12$ s, and one with a wave height $H = 3$ m and a wave period $T = 12$ s. For each wave, the location that exhibited the best agreement with the theoretical input, based on amplitude and period estimation, was identified from the previously recorded surface elevation signals. This optimal position corresponded consistently to a distance of exactly one wavelength from the wavemaker, and it was selected as the floater location for subsequent simulations.

The main characteristics derived from the analysis for each wave case are summarized in Table 4.

Table 4. Wave generation performance for regular wave test cases.

	Input Wave Parameters		Wave Characteristics			Relative Error		
	H (m)	T (s)	H _{mean} (m)	H _{max} (m)	H _{min} (m)	T (s)	H _{meanerror}	T _{error}
V1	4.0	8.0	3.73	4.69	3.02	7.99	6.75%	0.13%
V2	4.0	12.0	4.22	4.90	3.51	12.01	5.50%	0.08%
V3	3.0	12.0	2.82	3.00	2.64	12.02	6%	0.17%

The relative errors are small: on the order of 10^{-3} for the wave period and 10^{-2} for the mean wave height, indicating excellent reproduction of the period and moderate deviations in mean height (only slight underestimation for V1 and V3 and slight overestimation for V2).

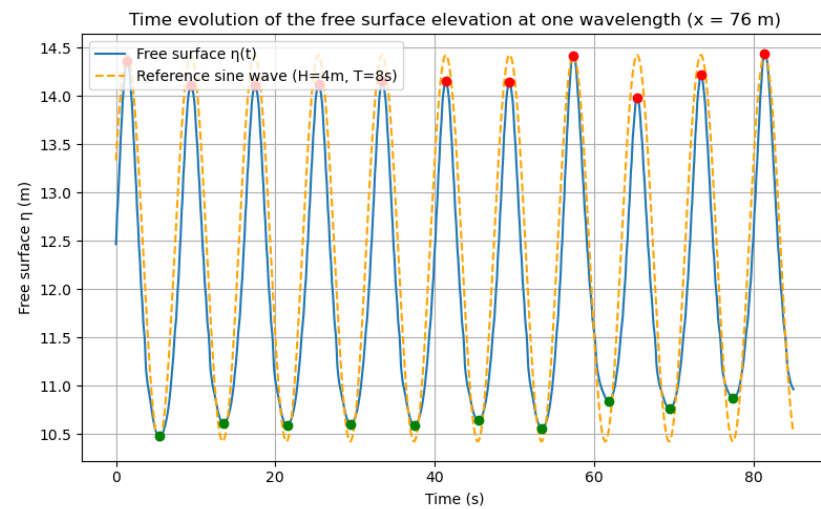
3.1.2. Global Force Comparison

To evaluate the reliability of the numerical predictions, a specific comparison was conducted between the simulated hydrodynamic forces and those measured experimentally. Regular wave conditions were used to ensure a controlled environment in which wave loads on the floater could be accurately assessed.

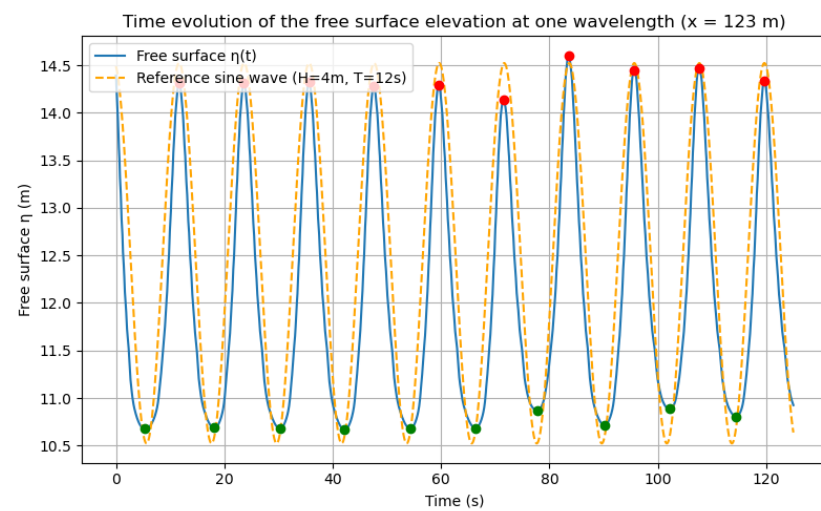
The reference signals for comparison were obtained from experimental measurements carried out under the same wave conditions used for the free surface elevation validation. These measurements served as a baseline to assess the agreement between the simulated and physical responses of the floater. In this context, the comparison focused on the overall shape, amplitude, and timing of the force signals. Because physical wave trains take minutes to fully develop and stabilize in the experimental basin, the experimental data were temporally shifted to isolate the steady portion of the response. The numerical force signals were compared only to this stable interval.

Results are presented for the same wave cases as the free surface elevation: two cases with a wave height $H = 4$ m and wave periods $T = 8$ s and $T = 12$ s, and one case with a wave height $H = 3$ m and a wave period $T = 12$ s.

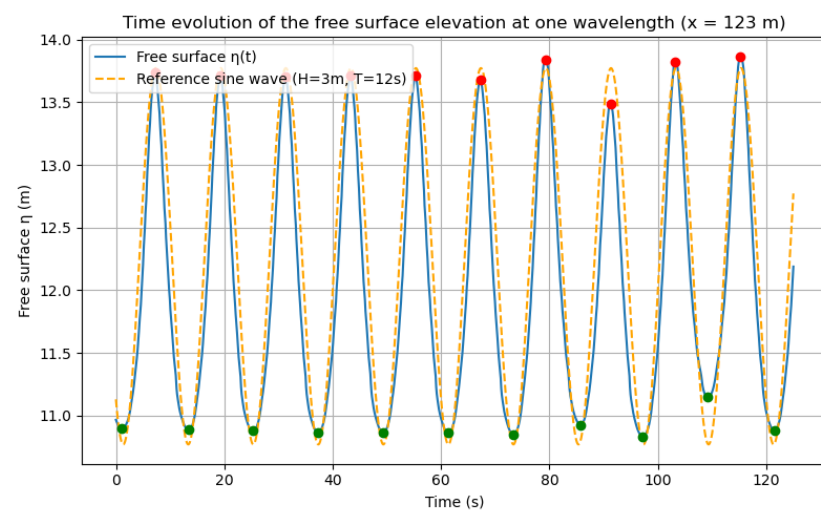
Figure 8 presents the comparison between the simulated and measured force signals for these wave conditions.



(a) Non-breaking



(b) Breaking



(c) Post-breaking

Figure 7. Time series of free surface elevation $\eta(t)$ for three regular wave cases: (a) $H = 4$ m, $T = 8$ s; (b) $H = 4$ m, $T = 12$ s; (c) $H = 3$ m, $T = 12$ s.

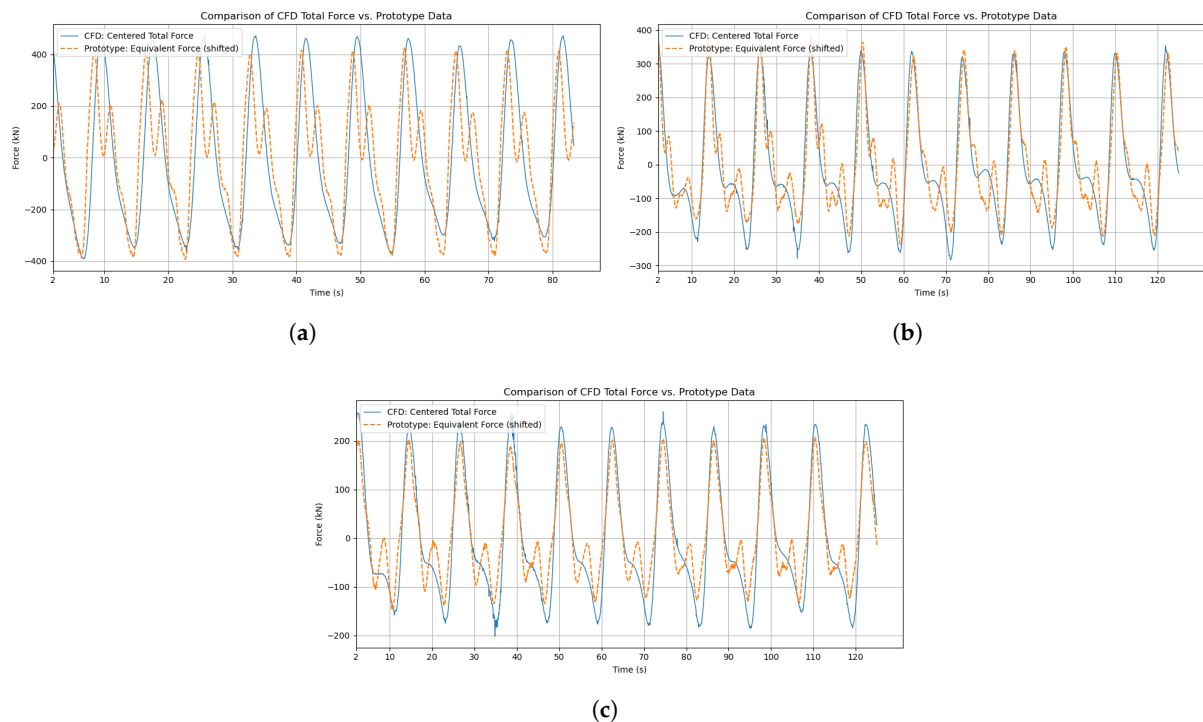


Figure 8. Hydrodynamic force time series $F(t)$ for three regular wave cases: (a) $H = 4$ m, $T = 8$ s; (b) $H = 4$ m, $T = 12$ s; (c) $H = 3$ m, $T = 12$ s.

Quantitative metrics were then computed to assess the level of agreement between the simulated and experimental force signals. Table 5 summarizes the key statistical indicators mean, minimum, and maximum force values, as well as the error metrics (RMSE, MAE, and coefficient of determination R^2), for each regular wave case.

Table 5. Force simulation performance for regular wave test cases.

	Wave Parameters		Type	Comparative Statistics			Error Assessment		
	H (m)	T (s)		Mean (kN)	Min (kN)	Max (kN)	RMSE (kN)	MAE (kN)	R^2
V1	4.0	8.0	CFD	−7.00	−390.78	472.12	179.12	138.18	0.40
			Prototype	−3.66	−393.95	424.11			
V2	4.0	12.0	CFD	−2.50	−281.57	368.02	66.53	56.40	0.80
			Prototype	3.98	−235.83	383.39			
V3	3.0	12.0	CFD	−0.49	−201.79	259.57	47.45	40.29	0.75
			Prototype	5.72	−145.16	208.29			

3.1.3. Discussion

The CFD framework shows good performance in capturing the incident wave field with mean wave height errors staying below 7% and wave period differences under 0.2% across all three regular wave cases (V1–V3). These results emphasize the importance of accurately representing wave kinematics when predicting hydrodynamic loads. However, achieving this accuracy becomes increasingly difficult as wave steepness rises, making steep waves particularly challenging to model. In the steepest test case, W1 ($H = 4$ m, $T = 8$ s), the wave-height error is 6.8%, which corresponds to a relatively low coefficient of determination ($R^2 = 0.40$) and a global force RMSE of 179 kN compared to a peak load of 472 kN. In contrast, for the milder wave in case W2 ($H = 4$ m, $T = 12$ s), the wave-height error drops to 5.5%. This leads to a much better fit ($R^2 = 0.80$) and a significantly lower RMSE of 67 kN compared to a peak load of 383 kN. These comparisons show a pattern: the accuracy of load predictions is closely linked to the accuracy of wave height reproduc-

tion. A reduction of just 1% in wave-height error can cut the RMSE by nearly half. This trend is also seen when comparing W1 and W3: W1's 6.8% error results in an RMSE of 179 kN compared to a peak load of 472 kN, while W3, with an error closer to 5%, has an RMSE of only 47 kN compared to a peak load of 260 kN. Overall, the data suggest a consistent relationship: for each 1% improvement in wave-height accuracy, the global force RMSE tends to decrease by about 40–50%. Most of the remaining discrepancies are mainly due to limits in spatial resolution. Although the numerical mesh follows Jacobsen's criterion for capturing the free surface, it tends to smooth out the sharp wave crests. This smoothing leads to an overestimation of the peak hydrodynamic forces. In addition, some of the modeling choices contribute to the observed differences. The rigid-body assumption ignores any structural flexibility, and the use of the RANS turbulence model does not account for higher-order viscous or unsteady effects, both of which can reduce the accuracy of load predictions. Within the tested conditions (wave heights up to 4 m, periods between 8 and 12 s and a water depth of 12 m), the CFD-VOF framework delivers reliable estimates of first-order hydrodynamic loads, making it suitable for early-stage design work. However, beyond this range, especially in very steep or breaking wave scenarios, the accuracy may decrease. In such cases, better spatial resolution and more advanced turbulence models may be required.

3.2. Extreme Wave Analysis

Numerical tests were conducted to estimate the maximum breaking wave height (H_{max}) for wave periods ranging from $T = 5$ s to $T = 20$ s. The results show a noticeable rise in wave height as the period increases. However, from $T = 12$ s onward, OpenFOAM was no longer able to compute the wave. None of the wave generation models available in OpenFOAM were able to produce a valid solution for such high-energy swell conditions. The following points have to be mentioned, following the initial test results.

- Wave generation models based on linear theory, like Stokes I, and weakly non-linear ones, such as Stokes II and III, are fundamentally unsuitable for extreme waves due to their inability to capture strong nonlinear effects, particularly near the breaking threshold.
- Although the stream function method is generally effective for modeling steep and non-linear waves, it is based on the assumption of deep water conditions, where the water depth is large compared to the wavelength. For example, at a wave period of $T = 12$ s, the wavelength can be estimated using the linear wave dispersion relation in deep water:

$$\lambda = \frac{gT^2}{2\pi} \approx \frac{9.81 \times 144}{2\pi} \approx 224.7 \text{ m}, \quad (6)$$

To satisfy deep water conditions, the depth should be at least half the wavelength, i.e., 112.35 m, which is way above the 13.89 m in the present study, making this method inapplicable in this context.

- Among the available non-linear wave theories, the cnoidal wave model proved valid up to a wave period of $T = 9$ s. Beyond this point, the simulations systematically failed: floating-point exceptions were triggered, which was likely due to numerical instability in the elliptic function computation at low non-linearity or when transitioning out of the shallow water regime.
- Similarly, the Stokes V wave model was able to produce valid solutions up to $T = 10$ s, after which the simulation failed due to a lack of convergence in the wave field generation step. The non-convergence of the Stokes V solver is typically caused by excessive wave steepness or the inability of the model to maintain the correct

phase relationship between the free surface elevation and the velocity field in strongly non-linear regimes.

Table 6 summarizes the wave parameters used in the simulation campaign along with the applicability of the Stokes V and cnoidal models for each wave period.

Table 6. Validity of the Stokes V and cnoidal models as a function of period T and maximum wave height Hmax.

Parameters	T = 5 s	T = 6 s	T = 7 s	T = 8 s	T = 9 s	T = 10 s	T = 11 s	T = 12 s	T = 13 s	T = 14 s	T = 15 s
Hmax (m)	5.32	6.92	8.15	9.04	9.7	10.18	10.55	10.83	11.06	11.24	11.38
StokesV	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
Cnoidal	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No

Due to the mentioned constraints, the Stokes V model was selected, focusing on wave cases with periods of T = 8 and T = 10 s, for which the model remained valid and stable. These two wave periods are representative of distinct sea states. Waves with a period of 8 s tend to be shorter, steeper, and more energetic at a local scale, and they are typically formed by regional winds or nearby storms. Waves with a period of 10 s are longer and more developed, which is typical of storm conditions observed during autumn and winter.

Since this study aims to investigate both the highest non-breaking and breaking wave conditions, two cases were considered for each wave period. One corresponds to a non-breaking wave, with a wave height set to 75% of the theoretical breaking limit Hmax, and the other corresponds to a breaking wave, with the wave height set to 110% of Hmax, in accordance with the modified Miche criterion and CFD limits. The parameters for these cases are summarized in Table 7.

Table 7. Wave parameters used in the extreme wave simulation campaign.

T (s)	Wavelength λ (m)	Breaking Limit Hmax (m)	Wave Height Used in Simulation (m)
T = 8 s	79.77	9.04	75% of Hmax (non-breaking): 6.78
T = 8 s	79.77	9.04	110% of Hmax (breaking): 9.94
T = 10 s	105.81	10.18	75% of Hmax (non-breaking): 7.64
T = 10 s	105.81	10.18	110% of Hmax (breaking): 11.20

Notably, even at 75% of the theoretical breaking limit Hmax, the resulting wave heights (6.78 m for T = 8 and 7.64 m for T = 10 s) exceed or closely match the 100-year maximum return period of 6.91 m. This confirms that the wave conditions selected for simulation represent sea states at or beyond the most extreme events expected at the site. As such, the analysis covers realistic extreme waves exerting limit hydrodynamic loads that the PWEC may probably experience during its installation lifetime.

3.2.1. Verification of Numerical Generated Extreme Waves

In order to confirm the accuracy of wave reproduction under extreme conditions, an analysis of the free surface elevation was conducted. For each wave period (T = 8 s and 10 s), two representative wave cases were examined: one non-breaking case and one breaking case, corresponding, respectively, to 75% and 110% of the theoretical breaking wave height as defined by the modified Miche criterion. To verify the accuracy of the wave generation itself, the surface elevation signal at x = 5 m was compared to a reference sinusoidal wave profile constructed from the target amplitude and period. For the non-breaking cases, the reference wave was built using 75% of Hmax. For the breaking cases, although a wave height of $1.1 \times H_{\max}$ was used as input in the simulation to intentionally induce breaking, the reference sinusoidal profile was constructed using Hmax only, since

this value represents the maximum stable wave height before breaking. In all six cases, the simulated waveform closely matches the theoretical signal, confirming that the generated wave is consistent with the input specifications. Figures 9 and 10 show the comparison at $x = 5$ m for all cases.

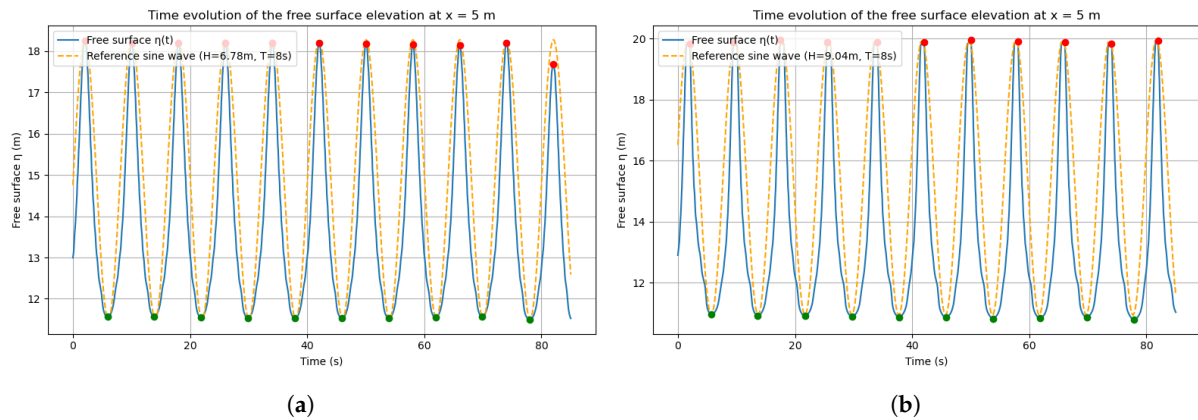


Figure 9. Time series of free surface elevation at $x = 5$ m for two wave cases $T = 8$ s : (a) non-breaking; (b) breaking.

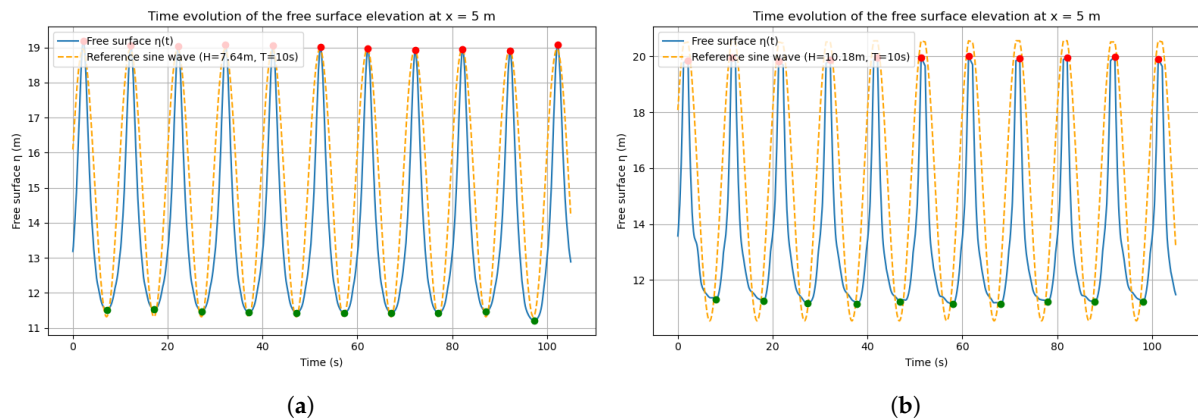


Figure 10. Time series of free surface elevation at $x = 5$ m for two wave cases $T = 10$ s : (a) non-breaking; (b) breaking.

Table 8 summarizes the main characteristics derived from the analysis for each wave case:

Table 8. Wave generation performance for extremes waves.

	Input Wave Parameters		Wave Characteristics			T (s)	Relative Error	
	H (m)	T (s)	H_{mean} (m)	H_{max} (m)	H_{min} (m)		$H_{\text{meanerror}}$	T_{error}
E1	6.78	8.0	6.60	6.72	6.19	7.99	2.65%	0.13%
E2/3	9.04	8.0	9.06	9.15	8.97	8.06	0.22%	0.75%
E4	7.64	10.0	7.58	7.89	7.43	10.01	0.79%	0.10%
E5/6	10.18	10.0	8.75	8.86	8.66	10.01	14.05%	0.10%

Additionally, for each simulation, the free surface elevation $\eta(t)$ was recorded at three key locations along the wave propagation direction: at 5 m, 100 m, and 200 m from the wave generation boundary for $T = 8$ s, and at 5 m, 150 m, and 300 m for $T = 10$ s. This allowed for tracking the wave evolution and identifying breaking onset. Figures 11 and 12 present the surface elevation over time for the non-breaking (left) and breaking (right) cases at $T = 8$ s and 10 s.

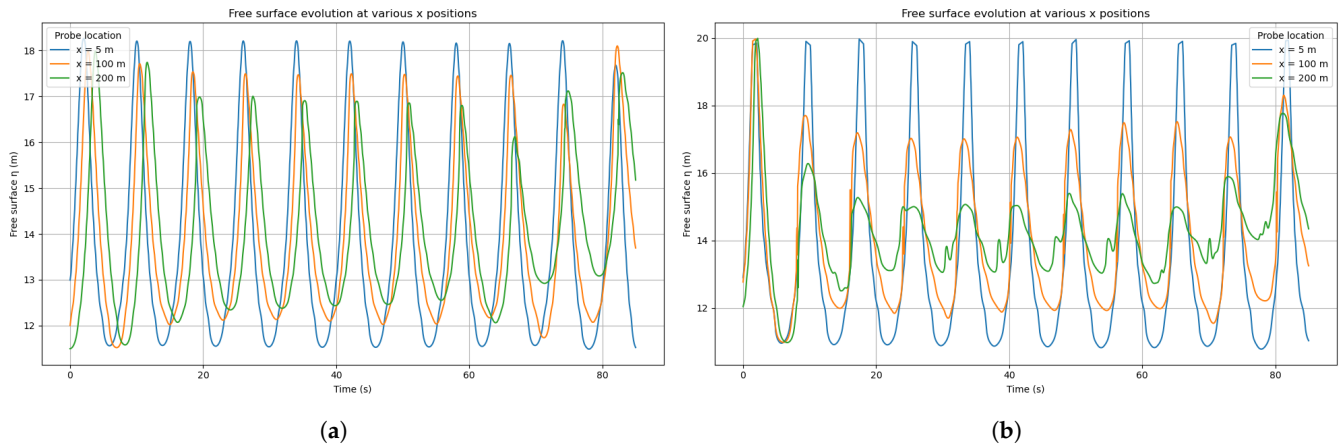


Figure 11. Free surface elevation over time recorded at multiple locations along the wave tank for wave period $T = 8$ s: (a) non-breaking case, measured at $x = 5$ m, 100 m, and 200 m; (b) breaking case, measured at the same locations.

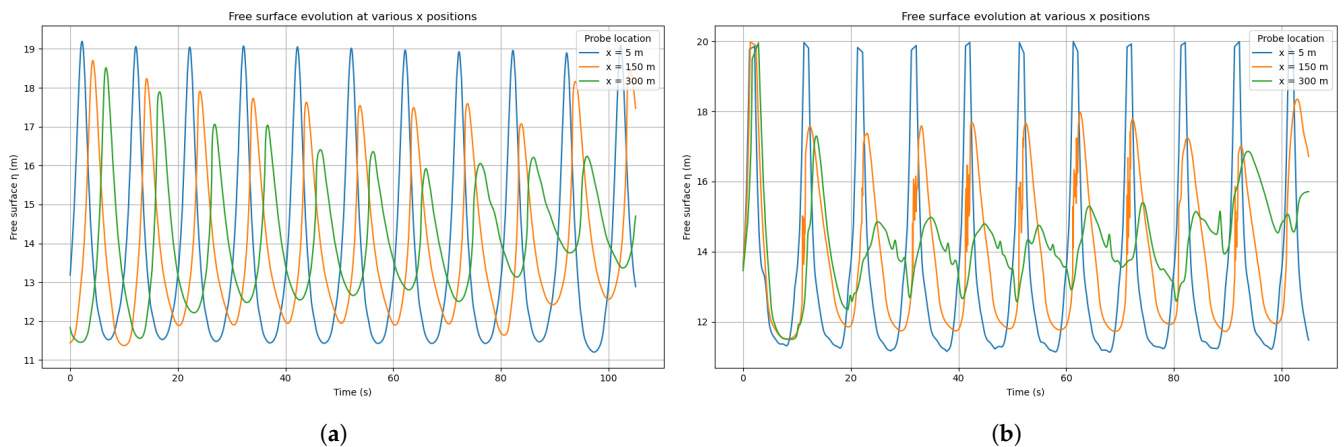


Figure 12. Free surface elevation over time recorded at multiple locations along the wave tank for wave period $T = 10$ s: (a) non-breaking case, measured at $x = 5$ m, 150 m, and 300 m; (b) breaking case, measured at the same locations.

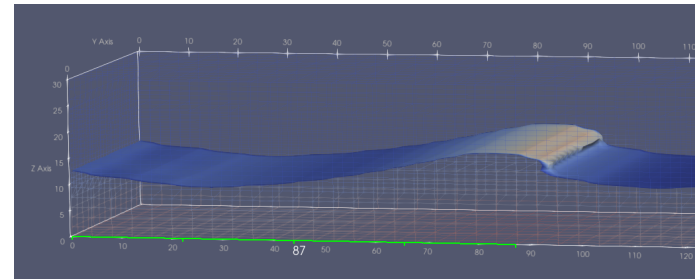
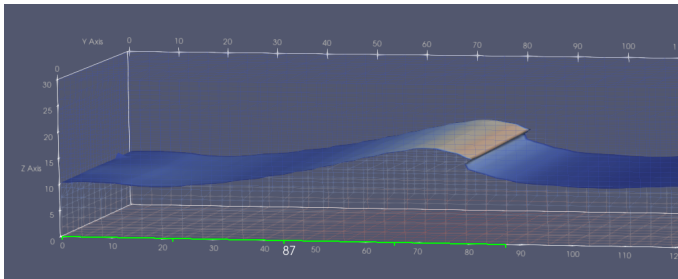
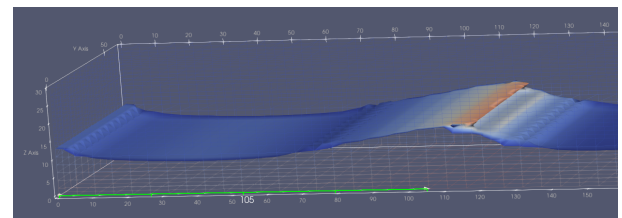
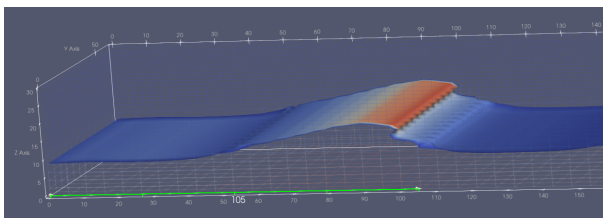
In the non-breaking case (a), the waveforms remain regular across all probe locations, maintaining their shape as it propagates. A decay in amplitude can still be observed, which may be attributed to numerical dissipation caused by the VOF method and to shoaling-related energy redistribution resulting from the sloped seabed. In contrast, the breaking case (b) shows significant deformation and amplitude decay beyond 100 m, indicating the onset of wave breaking.

Visual inspection of the numerical simulations using ParaView confirmed that in all breaking cases, wave breaking consistently initiated between 50 m and 150 m from the inlet. For each case, the precise location at which the wave broke was identified using ParaView, and this point can be used as a reference for further analysis, as shown in Figures 13 and 14. In these figures, the color scale represents the velocity magnitude at the free surface.

Table 9 summarizes the identified breaking points for each wave period used in the study.

Table 9. Breaking conditions for the two extreme wave periods assessed.

Wave Period T (s)	Breaking Wave Height (m)	Breaking Location (m)
8	9.94	87
10	11.20	105

**Figure 13.** Temporal evolution of wave breaking for the case with $T = 8$ s, visualized in ParaView. Each image corresponds to a different time instant, showing the progression of the wave crest as it deforms and breaks at $x = 87$ m.**Figure 14.** Temporal evolution of wave breaking for the case with $T = 10$ s, visualized in ParaView. Each image corresponds to a different time instant, showing the progression of the wave crest as it deforms and breaks at $x = 105$ m.

3.2.2. Global Forces Analysis

To assess the hydrodynamic forces exerted on the structure under extreme wave conditions, the floater was placed at specific positions along the wave propagation direction, depending on the wave regime.

For non-breaking waves, the floater was positioned 25 m from the wave generation boundary. This location was selected because, due to the high energy content of these waves, amplitude decay occurs relatively quickly, and placing the floater closer than one full wavelength allows for a more accurate assessment of the unattenuated wave impact. For breaking waves, two positions were analyzed: one at the breaking point previously identified using visual inspection in ParaView and a second 50 m further downstream. This configuration ensures that for each wave period, three scenarios were evaluated: before, during, and after wave breaking, offering a thorough view of the force evolution across the wave field.

Figure 15 shows the three configurations used to analyze the hydrodynamic loads on the PWEC along the wave flume.

For each of these six cases, the horizontal and vertical force components acting on the floater were extracted from the numerical simulations. The resulting time series are presented in Figures 16 and 17 for wave periods $T = 8$ s and $T = 10$ s, respectively. Each figure displays both the hydrodynamic force signals and the corresponding free surface elevation at the floater location, allowing a direct comparison between wave shape and structural loading. The three subplots per figure represent different floater positions relative to the breaking zone: the non-breaking case, the position at the onset of breaking, and a location 50 m downstream of the breaking point. This layout illustrates how wave

transformation due to shoaling and breaking influences the force dynamics experienced by the device.

To complement the time series analysis, Figure 18 presents a comparison of the maximum hydrodynamic forces and wave heights experienced by the floater under the three wave conditions: non-breaking, breaking, and post-breaking, for the two wave periods studied. The bar charts show the peak values extracted from each simulation case, providing a concise overview of how wave transformation influences the intensity of the wave–structure interaction.

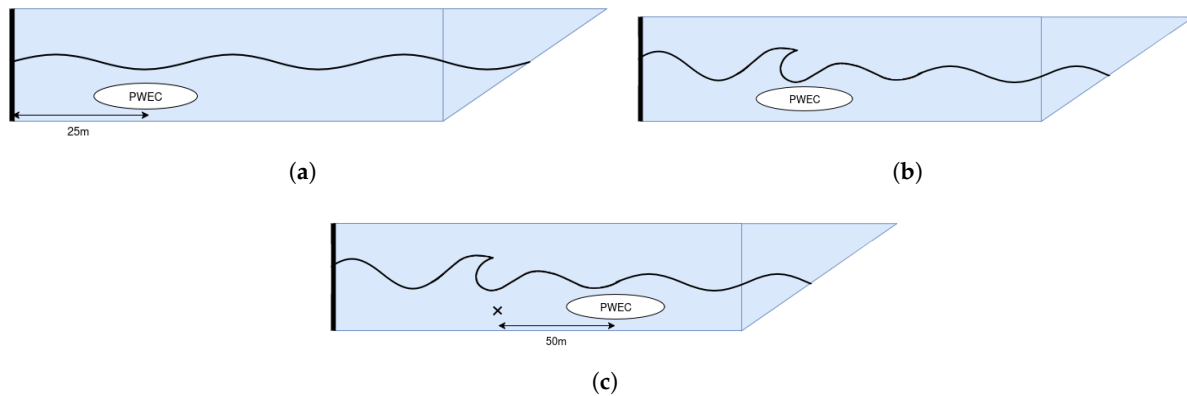


Figure 15. Schematics of the three cases studied: (a) PWEC 25 m from the wavemaker under non-breaking conditions, (b) PWEC exactly at the breaking point, and (c) PWEC 50 m downstream of the breaking point.

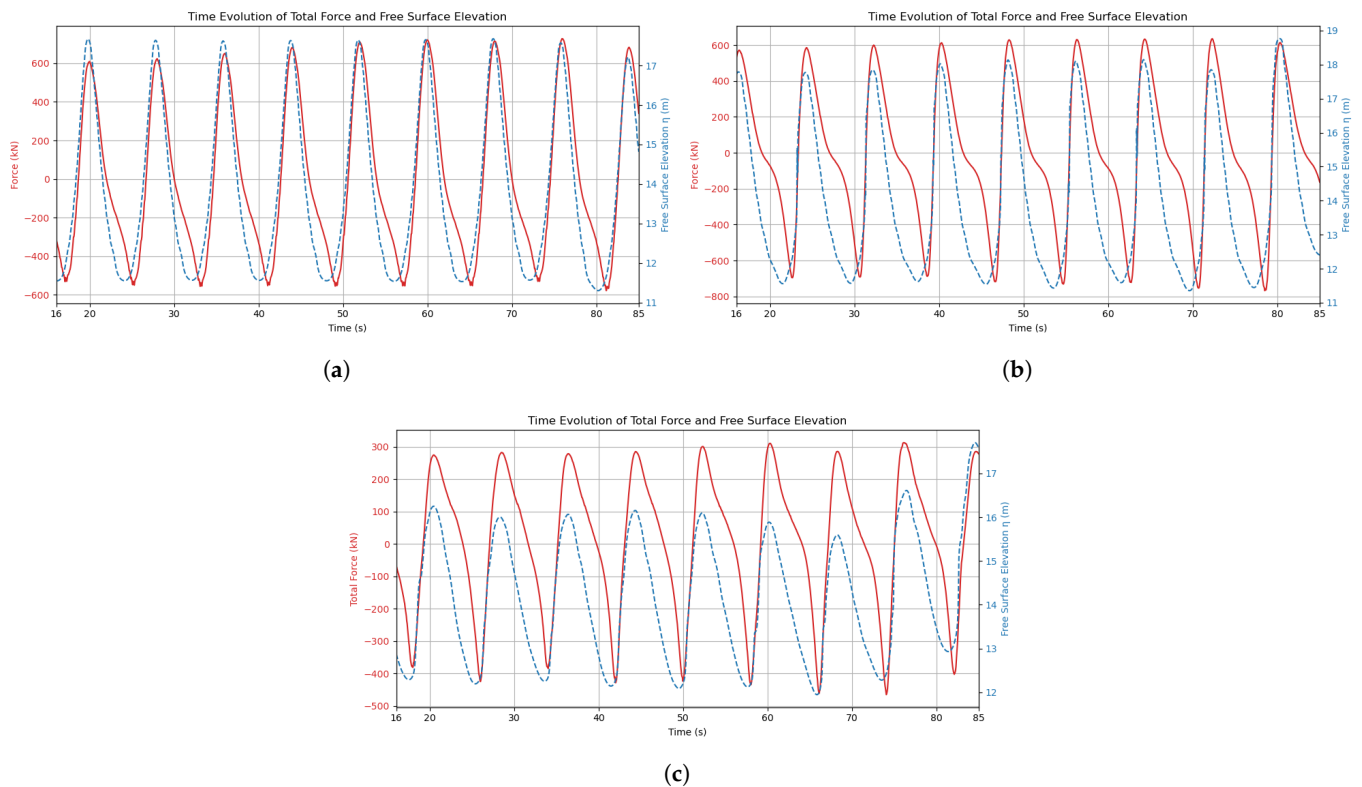


Figure 16. Hydrodynamic loads acting on the floater for wave period $T = 8$ s at three characteristic positions along the wave path: (a) 25 m from the wavemaker under non-breaking conditions, (b) exactly at the breaking point, and (c) 50 m downstream of the breaking point.

To further quantify the effects of wave transformation on the floater response, Table 10 presents the relative changes in maximum wave height and hydrodynamic load: from non-breaking to breaking, and from breaking to post-breaking, for both wave periods.

Finally, Table 11 compares the maximum hydrodynamic loads observed for the two wave periods ($T = 8$ s and $T = 10$ s) under breaking and post-breaking conditions, highlighting the influence of wave period on the intensity of wave–structure interaction.

Table 10. Relative changes in wave height and load between floater positions for $T = 8$ s and $T = 10$ s.

T (s)	Non-Breaking vs. Breaking Case		Breaking vs. Post-Breaking Case	
	Max Wave Height Rise	Max Load Rise	Max Wave Height Diminution	Max Load Diminution
8	18.96%	5.56%	−34.76%	−39.37%
10	−6.13%	29.29%	−13.77%	−41.81%

Table 11. Load increase from $T = 8$ s to $T = 10$ s under breaking and post-breaking conditions.

Case	Comparison	Load Max Increase (%)
Breaking	$T = 8$ vs. $T = 10$	9.46%
Post-Breaking	$T = 8$ vs. $T = 10$	5.04%

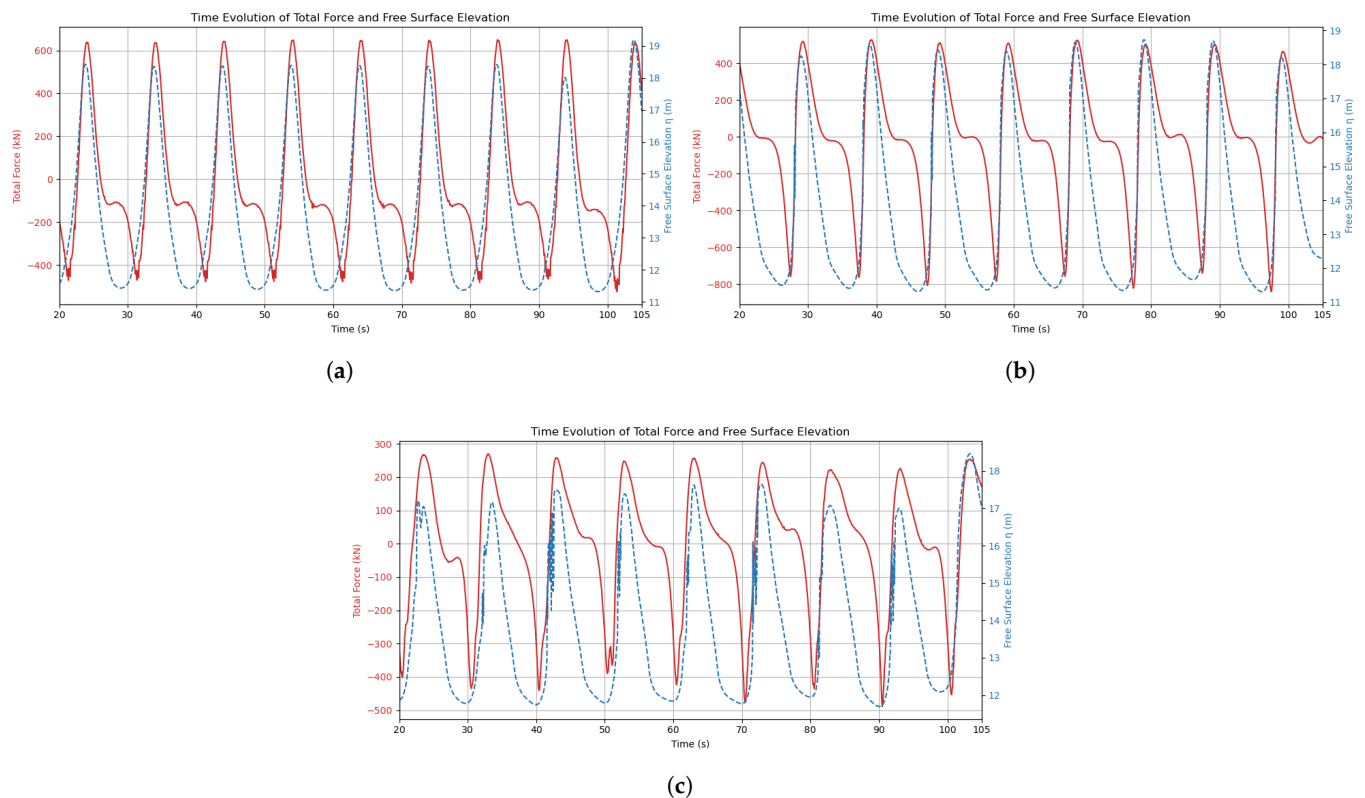


Figure 17. Hydrodynamic loads acting on the floater for wave period $T = 10$ s, at three characteristic positions along the wave path: (a) 25 m from the wavemaker under non-breaking conditions, (b) exactly at the breaking point, and (c) 50 m downstream of the breaking point.

3.2.3. Discussion

The analysis of extreme wave conditions reveals a range of distinct outcomes, depending on wave characteristics and breaking behavior. Although the structural response differs depending on the wave period, in both cases, the breaking event generates the highest loads. For the short, steep wave train ($T = 8$ s), the breaking wave is both the most energetic and the tallest, so the resulting load amplification is due to a combination of increased wave height and crest overturning. In contrast, for the moderate-period wave train

($T = 10$ s), the breaking crest is about 6% lower than the tallest non-breaking wave, yet the peak structural load increases by 30%. In both cases, the agreement between simulated and target wave kinematics at the point of breaking is acceptable: wave-height errors are 2.65% for the short-period case and 14.05% for the moderate-period one with wave-period errors remaining below 1%. In the second case, the 14.05% wave-height error corresponds to an underestimation: the simulated wave is lower than expected. This means that the extra load observed cannot be explained by numerical inaccuracies and must instead be caused by the physical dynamics of crest overturning. When comparing the two breaking wave cases directly, both produce nearly identical peak loads at the point of impact, with only a 9% difference, for almost identical crest heights (7.3 vs. 7.4 m). However, their post-impact evolution differs significantly: the $T = 8$ s wave loses approximately 35% of its amplitude over 50 m, whereas the $T = 10$ s wave loses only 13%. Despite this contrast, both cases exhibit a similar relative decrease in load of around 40% 50 m downstream from the impact point. This consistent reduction in load, regardless of the difference in wave decay, supports the conclusion that the dominant factor driving load amplification is the energy dissipated during the breaking event itself rather than the wave height alone.

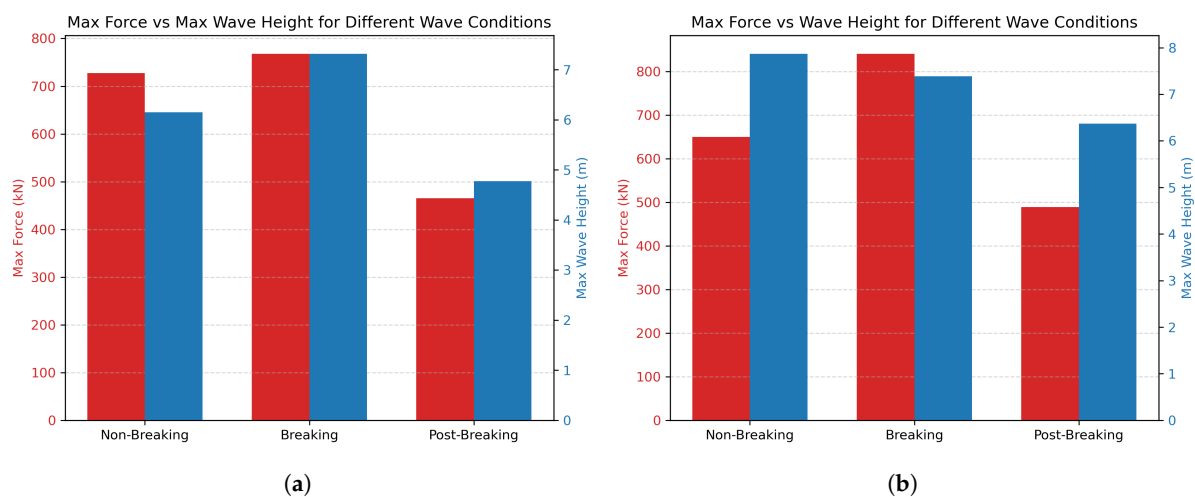


Figure 18. Maximum hydrodynamic loads and wave heights experienced by the floater under three wave conditions: non-breaking, breaking, and post-breaking for (a) $T = 8$ s; (b) $T = 10$ s.

The increase in structural load during a breaking wave impact was caused by four physical mechanisms acting simultaneously. (i) A plunging jet impact: As the wave crest overturns, it forms a high-speed jet that strikes the surface with a short, intense slamming force, transferring momentum rapidly. (ii) An added mass effect: The impact entrains and accelerates surrounding water, causing a sudden increase in effective fluid mass, which amplifies the inertial load on the structure. (iii) An air-pocket compression: Air trapped beneath the jet is rapidly compressed, generating sharp pressure peaks that intensify local loading. (iv) A depth-induced focusing: When the depth-to-wavelength ratio (h/λ) drops to 0.14, wave energy concentrates vertically, increasing the steepness and impact strength of the breaking crest. Together, these mechanisms lead to the large and sudden force spikes observed during wave breaking, making them critical to capture accurately in hydrodynamic load predictions.

3.3. Methodological Limitations and Perspectives

Beyond these results, it is important to point out some limitations of the methodology, which affect the conclusions. Despite the accuracy of the CFD model and the validation performed, four main factors still restrict reliable extrapolation to full scale:

1. The 1:20 scale model follows Froude similarity but not Reynolds similarity. As a result, viscous effects and air–water interactions may be overestimated, potentially leading to artificially different damping compared to real scale;
2. The VOF method used becomes overly diffusive in highly fragmented flows, smoothing out the air–water interface and potentially underestimating peak slamming pressures;
3. All tests were carried out using unidirectional waves, so no off-axis forces. However, in real sea conditions, waves often approach at an angle, which can significantly change the loading patterns;
4. The flap-shaped WEC component is modeled as a fixed rigid body without 6-degree-of-freedom fluid–structure interaction. While this setup is meant to represent a survival-mode configuration, it does not account for potential residual motions due to structural flexibility or imperfect locking, which may still influence inertia forces and wave–structure interactions.

To overcome these issues, several methodological improvements are proposed:

- Carry out a scale-up testing campaign starting with 1:4 scale experiments in a flume followed by sea trials while applying Reynolds-based corrections to account for drag effects in the design of the WEC;
- Switch to higher-fidelity turbulence models such as LES–VOF or hybrid RANS–LES (HRLES), potentially coupled with a compressible air-cushion model, to capture more accurately the dynamics of the plunging jets;
- Use adaptive h–p mesh refinement, triggered by surface elevation gradients and flow velocity gradients, to maintain accuracy while reducing computational cost;
- Include oblique and directional wave conditions to account for transverse loads and yaw moments, which are essential for accurately capturing realistic PTO behavior;
- Introduce full 6-DOF fluid–structure interaction by coupling the CFD solver with a motion solver, using dynamic or overset meshes.

4. Conclusions

This study presents, for the first time, a CFD assessment of a pivotal, single-pin wave energy converter operating in a passive duck diving survival mode, coupling RANS–VOF simulations in OpenFOAM/olaFlow with 1:20 scale basin tests. Across the study, the simulated wave field matches the target kinematics with a mean wave-height error of 5.13% and period errors below 0.75%. The model predicts global loads with RMSE values below 20% of peak values and R^2 values up to 0.80.

The results in this study underscore that accurately representing wave kinematics is essential for predicting hydrodynamic loads: load accuracy closely tracks wave-height fidelity, and a one-percentage-point reduction in height error typically lowers the global-force RMSE by about 40–50%. Accuracy degrades as waves become steeper due to crest smoothing from the mesh and limitations in the turbulence and structural modeling. Within the tested envelope ($H \leq 4$ m, $T = 8$ –12 s, depth = 12 m), the framework delivers reliable load estimates suitable for early-stage design.

Major findings show that plunging breaker impacts govern survivability. Compared to the highest non-breaking crests, breaking waves increase peak loads by 6% to 29%, even when their crest heights are lower. This highlights that the impact mechanism, rather than wave height alone, is the main driver of load amplification. Among the two breaking wave cases, both exhibit similar peak loads and crest heights at impact, yet their post-impact evolution differs considerably with amplitude losses over 50 m of 35% for one and only 13% for the other. Despite this difference in wave decay, both cases show a similar reduction in load of around 40% to 50% at 50 m downstream, reinforcing the idea that the energy

dissipated during breaking, rather than the wave height itself, governs the spatial evolution of impact loads.

Extreme cases were selected using a 100-year return analysis for Matosinhos and a modified Miche criterion, reinforcing relevance to site-specific design. Overall, the validated CFD–experiment framework provides reliable survival-load predictions for the PWEC and supports the effectiveness of its passive duck diving survival mode configuration, demonstrating its structural resilience under extreme wave conditions.

Beyond the hydrodynamic performance demonstrated in this study, the passive duck diving survival mode also carries important implications for the LCOE. The high LCOE of wave energy systems is strongly driven by CAPEX, which is largely inflated by the need to over-dimension structures to withstand extreme loads. By reducing peak forces by up to 65% in survival conditions, the PWEC enables designers to safely lower structural safety margins, limiting material requirements and simplifying support infrastructure. As a result, the design leads to lighter and more modular structures, shorter installation times, reduced transport expenses, and improved maintainability, all of which contribute to lowering the LCOE. Moreover, this highlights the value of survival mode: instead of relying only on structural strength, the device adapts intelligently to the environment, combining resilience with economic competitiveness.

Despite the model's accuracy, several limitations affect its capacity. The 1:20 scale respects Froude but not Reynolds similarity, potentially not well representing viscous and air–water effects for extreme wave tests. The VOF method can overly smooth fragmented flows, underestimating slamming pressures. Tests were limited to unidirectional waves, excluding off-axis loads typical of real seas and, finally, the flap was modeled as a fixed rigid body, neglecting potential motions due to structural flexibility or imperfect locking.

Beyond these modeling constraints, the findings also point to the need for complementary investigations under operational conditions, where the floater is free to move and interact dynamically with incoming waves. In such scenarios, the PTO system becomes a key factor, as its damping behavior directly influences both energy extraction and hydrodynamic loading. Future campaigns should therefore include tests with a mobile floater, coupled with an actively controlled PTO in order to fully capture the load–motion–energy interactions. This would allow for a more complete evaluation of the system's performance and durability under realistic sea states, bridging the gap between survival-mode analysis and continuous operation.

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References

1. International Energy Agency. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach—2023 Update*; International Energy Agency: Paris, France, 2023.
2. European Commission. *The European Green Deal: Communication COM/2019/640 Final*; European Commission: Brussels, Belgium, 2019.
3. Wiatros-Motyka, M.; Jones, D.; Fulghum, N. Global Electricity Review 2024. Available online: <https://policycommons.net/artifacts/12310492/untitled/13206852/> (accessed on 5 August 2025).
4. Mørk, G.; Barstow, S.; Kabuth, A.; Pontes, M.T. Assessing the Global Wave Energy Potential. In Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2010): Volume 3, Shanghai, China, 6–11 June 2010. [CrossRef]
5. Majidi, A.G.; Ramos, V.; Calheiros-Cabral, T.; Santos, P.R.; das Neves, L.; Taveira-Pinto, F. Integrated assessment of offshore wind and wave power resources in mainland Portugal. *Energy* **2024**, *308*, 132944. [CrossRef]
6. Lehmann, M.; Karimpour, F.; Goudey, C.A.; Jacobson, P.T.; Alam, M.R. Ocean wave energy in the United States: Current status and future perspectives. *Renew. Sustain. Energy Rev.* **2017**, *74*, 1300–1313. [CrossRef]
7. von Sydow, T. Investigating the Impact of Wave Energy in the Electric Power System—A Case Study of Southern Sweden. Master’s Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2014.
8. Lian, J.; Wang, X.; Wang, X.; Wu, D. Research on Wave Energy Converters. *Energies* **2024**, *17*, 1577. [CrossRef]
9. Hasan Maheen, M.; Yang, Y. Wave energy converters with rigid hull encapsulation: A review. *Sustain. Energy Technol. Assess.* **2023**, *57*, 103273. [CrossRef]
10. Rezaei, T.; Javadi, A. Environmental impact assessment of ocean energy converters using quantum machine learning. *J. Environ. Manag.* **2024**, *362*, 121275. [CrossRef] [PubMed]
11. Peña, A.; Bidaguren, I.; Izquierdo, U.; Esteban, G.A.; Blanco, J.M.; Albaina, I. The Mutriku Breakwater Wave Plant: Improvements and Their Influence on the Levelized Cost of Electricity (LCOE). *J. Ocean Eng. Technol.* **2025**, *39*, 205–211. [CrossRef]
12. Shipon, M.R.; Ali, M.S.; Kabir, M.A.; Abdullah-Al-Mamun, M.; Farrok, O. Pelamis Wave Energy Converter. In *Oceanic Wave Energy Conversion*; Farrok, O., Islam, M.R., Eds.; Springer Nature Singapore: Singapore, 2024; pp. 45–66. [CrossRef]
13. Dupont, V. *Ocean Energy: Stats & Trends 2023*; Technical Report; Ocean Energy Europe: Brussels, Belgium, 2024.
14. Baca, E.; Philip, R.; Greene, D.; Battey, H. *Expert Elicitation for Wave Energy LCOE Futures*; Technical Report; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2022. [CrossRef]
15. Lyons, M.; Durrant, P.; Kochhar, K. *Reaching Zero with Renewables: Capturing Carbon*; Technical Report; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2021.
16. Coe, R.; Yu, Y.H.; Van Rij, J. A Survey of WEC Reliability, Survival and Design Practices. *Energies* **2017**, *11*, 4. [CrossRef]
17. Pacific Northwest National Laboratory. *Oyster 800 at EMEC*; Pacific Northwest National Laboratory: Richland, WA, USA, 2016.
18. Parkinson, G. CETO Wave Energy Machine Swept Away in Cyclone, Report Says. 2014. Available online: <https://reneweconomy.com.au/ceto-wave-energy-machine-destroyed-cyclone-reports-say/> (accessed on 3 July 2025).
19. Farajvand, M.; García-Violini, D.; Ringwood, J.V. Representative linearised models for a wave energy converter using various levels of force excitation. *Ocean Eng.* **2023**, *270*, 113635. [CrossRef]
20. Spanos, P.D.; Malara, G.; Arena, F. Efficient time domain response computation of massive wave power farms. *Nonlinear Dyn.* **2024**, *112*, 6339–6356. [CrossRef]
21. Raghavan, V.; Lavidas, G.; Metrikine, A.V.; Mantadakis, N.; Loukogeorgaki, E. A Comparative Study on BEM Solvers for Wave Energy Converters. In *Trends in Renewable Energies Offshore*; Guedes Soares, C., Ed.; CRC Press: Boca Raton, FL, USA, 2022; pp. 441–447. [CrossRef]
22. Raghavan, V.; Lavidas, G.; Metrikine, A.V. Comparing Open-Source BEM Solvers for Analysing Wave Energy Converters. *J. Phys. Conf. Ser.* **2024**, *2647*, 072002. [CrossRef]
23. Leary, M.; Rusch, C.; Zhang, Z.; Robertson, B. Comparison and Validation of Hydrodynamic Theories for Wave Energy Converter Modelling. *Energies* **2021**, *14*, 3959. [CrossRef]
24. Karpenko, M. Aircraft hydraulic drive energy losses and operation delay associated with the pipeline and fitting connections. *Aviation* **2024**, *28*, 1–8. [CrossRef]
25. Wiley, W.; Tran, T.T.; Boerner, T.; Weston, C.; Wang, L. An Efficient Three-Dimensional CFD-Based Numerical Wave Tank for a Wave Energy Converter in Extreme Irregular Waves. In Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2023), ASME, Melbourne, Australia, 11–16 June 2023.
26. Katsidoniotaki, E.; Shahroozi, Z.; Eskilsson, C.; Palm, J.; Engström, J.; Göteman, M. Validation of a CFD Model for Wave Energy System Dynamics in Extreme Waves. *Ocean Eng.* **2023**, *268*, 113320. [CrossRef]
27. Sosa, C.; Mariño-Tapia, I.; Silva, R.; Patiño, R. Numerical Performance of a Buoy-Type Wave Energy Converter with Regular Short Waves. *Appl. Sci.* **2023**, *13*, 5182. [CrossRef]

28. Windt, C.; Faedo, N.; García-Violini, D.; Peña-Sanchez, Y.; Davidson, J.; Ferri, F.; Ringwood, J.V. Validation of a CFD-Based Numerical Wave Tank Model of the 1/20th Scale Wavestar Wave Energy Converter. *Fluids* **2020**, *5*, 112. [\[CrossRef\]](#)
29. López, I.; Carballo, R.; Fouz, D.M.; Iglesias, G. Non-linear Turbine Selection for an OWC Wave Energy Converter. *Ocean Eng.* **2024**, *311*, 118877. [\[CrossRef\]](#)
30. Barajas, G.; Lara, J.L.; Davidson, J.; Romano, A. Porous Medium-Based PTO Damping and Overset Mesh Motion: A Combined Approach for Effective OpenFOAM® Simulations of Floating OWCs. *Appl. Ocean Res.* **2025**, *154*, 104309. [\[CrossRef\]](#)
31. Schubert, B.W.; Robertson, W.S.P.; Cazzolato, B.S.; Sergiienko, N.Y.; Ghayesh, M.H. Nonlinear Stiffness Enhancement of Submerged Wave Energy Device in High Fidelity Model. *Ocean Eng.* **2022**, *254*, 111295. [\[CrossRef\]](#)
32. Katsidoniotaki, E.; Nilsson, E.; Rutgersson, A.; Engström, J.; Göteman, M. Response of Point-Absorbing Wave Energy Conversion System in 50-Years Return Period Extreme Focused Waves. *J. Mar. Sci. Eng.* **2021**, *9*, 345. [\[CrossRef\]](#)
33. Rosa-Santos, P.; Taveira-Pinto, F.; Rodríguez, C.A.; Ramos, V.; López, M. The CECO wave energy converter: Recent developments. *Ren. Energy* **2019**, *139*, 368–384. [\[CrossRef\]](#)
34. Giannini, G.; Rosa-Santos, P.; Ramos, V.; Taveira-Pinto, F. On the Development of an Offshore Version of the CECO Wave Energy Converter. *Energies* **2020**, *13*, 1036. [\[CrossRef\]](#)
35. Giannini, G.; Rosa-Santos, P.; Ramos, V.; Taveira-Pinto, F. Wave energy converters design combining hydrodynamic performance and structural assessment. *Energy* **2022**, *249*, 123641. [\[CrossRef\]](#)
36. Giannini, G.; Zavvar, E.; Ramos, V.; Calheiros-Cabral, T.; Iglesias, I.; Taveira-Pinto, F.; Rosa-Santos, P. On the Development of a Near-Shore Pivoting Wave Energy Converter. *Energies* **2024**, *17*, 2695. [\[CrossRef\]](#)
37. Martínez-Iturricastillo, N.; Nic Guidhir, M.; Ulazia, A.; Ringwood, J.V. Extreme Wave Analysis for Marine Renewable Energies in Ireland. *Energy Convers. Manag.* **2025**, *26*, 100972. [\[CrossRef\]](#)
38. Dueholm, B.R.C. Implementation of a VoF Solver with Phase Change for the Simulation of Internal Cavitation and Droplet Break-up in Injectors. In *OpenFOAM® Journal*; OpenFOAM Foundation: Göteborg, Sweden, 2021; Volume 4, pp. 62–78. [\[CrossRef\]](#)
39. CFD Direct. MULES in OpenFOAM in 2025. Available online: <https://cfd.direct/openfoam/free-software/mules/> (accessed on 2 August 2025).
40. Yin, X.; Zarakos, I.; Karadimitriou, N.K.; Raoof, A.; Hassanizadeh, S.M. Direct Simulations of Two-Phase Flow Experiments of Different Geometry Complexities Using the Volume-of-Fluid (VOF) Method. *Chem. Eng. Sci.* **2019**, *195*, 820–827. [\[CrossRef\]](#)
41. Weller, H.G.; Greenshields, C. 5.21 The PIMPLE Algorithm. Notes on Computational Fluid Dynamics: General Principles. 2025. Available online: <https://doc.cfd.direct/notes/cfd-general-principles/the-pimple-algorithm> (accessed on 20 July 2025).
42. Wolf Dynamics. Multiphase flows modeling in OpenFOAM: Guided Tutorials, 2021. In *Online Training—Advanced Session (Slide Deck)*; Wolf Dynamics: Genoa, Italy, 2021.
43. Perić, R.; Abdel-Maksoud, M. Reliable Damping of Free-Surface Waves in Numerical Simulations. *Ship Technol. Res.* **2016**, *63*, 1–13. [\[CrossRef\]](#)
44. Yu, X.; Shao, Y.; Fuhrman, D.R.; Zhang, Y. A viscous numerical wave tank based on immersed-boundary generalized harmonic polynomial cell (IB-GHPC) method: Accuracy, validation and application. *Coast. Eng.* **2023**, *180*, 104273. [\[CrossRef\]](#)
45. You, R.; He, G.; Cheng, Y.; Ju, X. Shoaling and Breaking of Solitary Waves on Slopes. *Int. J. Eng. Technol.* **2018**, *10*, 46–51. [\[CrossRef\]](#)
46. Palmer, H.; Zhao, M.; Wu, H.; Hu, P.; Munir, A.; Zhang, Q.; Dhamelia, V. Wave interference and energy conversion in a 3D land-fixed oscillating water column system. *Renew. Energy* **2025**, *255*, 123707. [\[CrossRef\]](#)
47. Windt, C.; Davidson, J.; Schmitt, P.; Ringwood, J.V. On the Assessment of Numerical Wave Makers in CFD Simulations. *J. Mar. Sci. Eng.* **2019**, *7*, 47. [\[CrossRef\]](#)
48. International Towing Tank Conference. Practical Guidelines for Numerical Modelling of Wave Energy Converters. ITTC Recommended Procedures and Guidelines 7.5-02-07-03.18. In Proceedings of the 30th ITTC—Specialist Committee on Ocean Renewable Energy, Hobart, Tasmania, Australia, 22–27 September 2024; Revision 10. Available online: https://itcc.info/media/11718/0_0.pdf (accessed on 8 July 2025).
49. Miche, R. Contribution à l'étude des mouvements ondulatoires périodiques. *Ann. Des Ponts Chaussées* **1944**, *114*, 25–78. (In French)
50. Battjes, J.A.; Janssen, J.P.F.M. Energy Loss and Set-up due to Breaking of Random Waves. In Proceedings of the 16th International Conference on Coastal Engineering, Hamburg, Germany, 27 August–3 September 1978; pp. 569–587.
51. Giannini, G.; Temiz, I.; Rosa-Santos, P.; Shahrooz, Z.; Ramos, V.; Göteman, M.; Engström, J.; Day, S.; Taveira-Pinto, F. Wave Energy Converter Power Take-Off System Scaling and Physical Modelling. *J. Mar. Sci. Eng.* **2020**, *8*, 632. [\[CrossRef\]](#)

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