

Article

Investigation of Numerical Beach Position Effects on the Hydrodynamics of a Submerged Horizontal Plate Device Under Sea State Conditions

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Abstract

Employing the WaveMIMO methodology, the present numerical study evaluates a submerged horizontal plate (SHP) device under the incidence of representative regular and realistic irregular waves associated with the sea state off the coast of Rio Grande, Brazil. The dual functionality of the SHP device is investigated, considering its operation as a breakwater (BW) and as a wave energy converter (WEC). The main focus of this study is to investigate the effects of numerical beach (NB) positioning on the hydrodynamic response of the SHP. The governing equations for mass, momentum, and volume fraction are solved using the finite volume method (FVM), while the water–air interaction is modeled through the volume of fluid (VOF) approach. The analysis assessed the influence of SHP length (L_p) using five different values. For the tested Rio Grande sea state, SHP geometry, two-dimensional numerical model, and adopted hydrodynamic indicators, the results show that the exclusive use of representative regular waves was not sufficient to reproduce the hydrodynamic trends obtained under realistic irregular waves. The SHP demonstrates its highest BW performance in reducing the significant wave height at $3L_p$ for representative regular waves and realistic irregular waves. As a WEC, it achieves its highest axial velocity at $3L_p$ for representative regular waves and $1.5L_p$ and $2L_p$ for realistic irregular waves. The performance of the SHP as BW-WEC is the highest at $3L_p$ for regular waves and $2.5L_p$ for realistic irregular waves. In contrast to previous work, in which the NB was kept at a fixed position, the present study indicates that the downstream computational-domain configuration, including the relative positioning between the SHP and the NB, is an important factor affecting the monitored hydrodynamic response and should be carefully defined in CFD wave-flume simulations.

Keywords: hybrid BW-WEC device; coastal protection; wave energy; computational fluid dynamics; WaveMIMO methodology



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1. Introduction

Global mean sea level (GMSL) has risen significantly over the last century and is currently increasing at an accelerated rate. Observation-based assessments indicate that GMSL

increased by approximately 0.20 m from 1901 to 2018, while the rate of rise accelerated from $2.3 \text{ mm}\cdot\text{yr}^{-1}$ during 1971–2018 to $3.7 \text{ mm}\cdot\text{yr}^{-1}$ during 2006–2018. This rise is mainly driven by ocean thermal expansion and glacier mass loss, with increasing contributions from the Greenland and Antarctic ice sheets in recent decades [1]. Recent satellite-based analyses confirm that this accelerating trend persists. A NASA-led assessment reported that GMSL rose faster than expected in 2024, reaching approximately $5.9 \text{ mm}\cdot\text{yr}^{-1}$ instead of the projected $4.3 \text{ mm}\cdot\text{yr}^{-1}$, mainly due to enhanced seawater thermal expansion associated with ocean warming [2].

Rising GMSL affects coastal morphodynamics by increasing the baseline water level on which waves and storm surges act, allowing waves to propagate further inland and intensify shoreline erosion. These impacts have been linked to coastal erosion and beach narrowing [1,3], reinforcing the need for effective protection measures, such as submerged and emerged breakwaters (BW), to reduce wave energy reaching vulnerable coastlines [4]. In parallel, global renewable power capacity is projected to double by 2030, with an expected increase of approximately 4600 GW worldwide, mainly driven by solar photovoltaic and wind technologies. However, the concentration of growth in a limited number of technologies and challenges related to grid integration, supply chains, and financing highlight the need to diversify the renewable energy portfolio with complementary sources [5].

Global-scale studies consistently indicate that ocean wave energy represents a substantial renewable resource, although its estimated magnitude strongly depends on the adopted assessment approach. Recent numerical wave-model and long-term hindcast evaluations suggest that global offshore wave energy potential may range from a few hundred to several tens of thousands of terawatt-hours per year, depending on the considered theoretical, technical, or directionally constrained potential. Long-term analyses also highlight pronounced regional and interannual variability, associated with climatic variability and methodological limitations of global-scale numerical assessments [6–15].

Other recent research has explored hybrid systems that integrate wave energy converters (WECs) with coastal protection structures, demonstrating that such configurations can simultaneously attenuate incident waves and generate electrical power. Numerical and physical studies have shown that hybrid BW-WEC concepts can reduce wave energy transmitted toward the shoreline while enabling energy conversion, without compromising the structural performance of the host BW. Therefore, integrating WEC technologies into multi-purpose BW designs represents a promising strategy to combine coastal protection and renewable energy harvesting [16–19]. Recent studies have further reinforced this trend by proposing and assessing different hybrid WEC–breakwater concepts. Wang et al. [20] investigated a hybrid device integrating a WEC with a flexible porous floating breakwater using a RANS-based numerical model validated against experimental data, showing the relevance of simultaneously analyzing wave attenuation and power-generation-related parameters. Song et al. [21] studied a hybrid system combining a hinged WEC and a breakwater with a semi-opened moonpool in a three-dimensional numerical wave tank, evaluating hydrodynamic response, reflection and transmission coefficients, and conversion-efficiency-related quantities. These studies confirm the growing interest in multi-purpose coastal structures that combine wave attenuation and wave-energy harvesting, while also highlighting the need for careful numerical modeling of the hydrodynamic response.

In turn, the importance of carefully defining absorbing regions in numerical wave tanks has also been emphasized in recent CFD studies. Chen et al. [22] discussed the use of relaxation zones for wave absorption in numerical wave tanks and showed that the absorption performance is related to the relaxation-zone configuration and its required length. Perić et al. [23] further demonstrated that wave reflections at computational-domain boundaries can introduce substantial errors in free-surface flow simulations, and

that relaxation-zone parameters should be optimized according to the wave conditions and numerical setup. These studies reinforce the relevance of explicitly defining the numerical beach (NB) length, damping formulation, and relative position with respect to the structure of interest.

In view of the above, the submerged horizontal plate (SHP) device stands out as a multi-purpose concept that can simultaneously operate as a BW and as a WEC. Although previous numerical studies have investigated the hydrodynamic performance of SHP-type devices, the influence of the NB position on the computed results has not yet been specifically addressed, particularly when subjected to irregular waves, a condition for which, to the best of the authors' knowledge, no dedicated studies have been reported, despite its direct impact on wave reflections and, consequently, on the accuracy of the computational predictions [24,25]. In previous work by Thum et al. [24], the SHP length was varied under representative regular and realistic irregular waves, but the beginning of the NB was kept fixed for all plate configurations. As a consequence, the distance between the downstream edge of the SHP and the absorbing region decreased as the plate length increased, which may affect downstream wave-height measurements and the interpretation of the SHP hydrodynamic response.

Therefore, the present study extends and differentiates itself from Thum et al. [24] by focusing specifically on the sensitivity of the numerical results to the relative position between the SHP and the NB. The wave conditions are generated using the WaveMIMO methodology [26], and the analysis is carried out by comparing two formulations employing the same computational model: a first formulation (1stF), in which the NB position remains fixed, as previously presented in Thum et al. [24], and a second formulation (2ndF), proposed in the present study, in which the NB position is adjusted according to the SHP configuration to maintain a constant distance of one wavelength between the downstream edge of the plate and the beginning of the absorbing region. Thus, unlike the previous study [24], which focused mainly on the effect of plate length, the present work investigates whether the domain configuration itself can influence the monitored free-surface elevation and axial velocity beneath the SHP. In addition, the influence of plate length is assessed through five SHP configurations, using not only conventional performance indicators related to wave attenuation and axial velocity, but also the integral-based analysis of the free-surface elevation and axial velocity time series proposed in [25]. This integral approach, which was not applied in Thum et al. [24], is employed here for both the 1stF results obtained from [24] and the 2ndF results generated in the present study, providing a complementary comparative interpretation of the SHP performance as a BW, as a WEC, and as a combined BW-WEC device.

It should be noted that the present study is based on a two-dimensional numerical model, which is suitable for the comparative assessment proposed here but does not resolve three-dimensional effects such as wave diffraction, edge effects, or spanwise flow structures around the SHP. Therefore, the results should be interpreted as comparative hydrodynamic trends within the adopted 2D modeling framework.

To do so, the BW performance was defined based on free surface elevations measured upstream and downstream of the SHP. In this context, the reduction in significant wave height downstream of the device is used as an indicator of wave attenuation, meaning that lower downstream wave heights indicate better coastal protection performance. In turn, the WEC performance was evaluated based on the axial velocity beneath the plate, since the oscillatory horizontal flow generated in this region is the hydrodynamic mechanism that could drive a bidirectional turbine for wave energy conversion. Therefore, higher axial velocity magnitudes beneath the SHP indicate greater potential for energy extraction.

These indicators allow the SHP to be evaluated both as a wave attenuation device and as a wave energy conversion system.

It should be emphasized that the axial velocity beneath the SHP is not used here as a direct measure of converted electrical power or overall WEC efficiency, since no turbine, power take-off system, pressure-drop analysis, or energy-flux calculation is included in the present model. Instead, this variable is adopted as a comparative hydrodynamic indicator of the energy-conversion potential associated with the oscillatory flow induced beneath the plate. This interpretation is physically supported by the fact that the available power in a flow is strongly dependent on the flow velocity. Therefore, higher axial velocity values indicate more favorable hydrodynamic conditions for future energy extraction, but should not be interpreted as final converted power or WEC efficiency.

Based on this scope, the present study is guided by the following research questions: (i) how does the relative position between the SHP and the NB affect the computed hydrodynamic response of the device?; (ii) are the effects of NB positioning different under representative regular waves and realistic irregular waves?; (iii) does the 2ndF, based on a constant distance between the SHP and the NB, reduce possible interference from the absorbing region on downstream measurements?; and (iv) how does the integral-based analysis of free-surface elevation and axial velocity contribute to the comparative assessment of SHP performance as a BW, as a WEC, and as a combined BW-WEC device?

1.1. Operating Principle of the SHP Device

The concept of the SHP as a BW is based on the observation that wave energy is reduced after waves propagate over the device. Early studies on wave attenuation using floating BWs date back to the 1950s [27,28], whereas investigations related to wave energy conversion emerged nearly two decades later, when Dick and Brebner [29] observed a pulsating behavior in the axial velocity beneath the plate. Subsequently, Graw [30] experimentally demonstrated the variation in the flow velocity below the SHP and proposed its application as a WEC by installing a bidirectional hydraulic turbine under the plate.

From the BW perspective, the SHP contributes to coastal erosion mitigation by reducing wave energy and, consequently, the transmitted wave height. The literature highlights additional advantages over conventional BWs, such as lower dependence on local geomorphology and sediment transport conditions, since the incoming wave climate is not fully blocked [31]. The SHP is also recommended for situations where full wave sheltering is neither required nor desirable [31], while its support structure allows mass transport, reducing concerns related to water quality in the sheltered region [29]. Yu [32] further explained that, by properly selecting the plate length, the flow over the plate can become out of phase at the downstream edge, generating a U-shaped motion beneath the plate and significantly reducing the amount of transmitted wave energy.

Regarding the WEC function, experimental and numerical studies have shown that the axial flow under the SHP alternates its direction, producing a pulsating velocity pattern induced by wave propagation over the device. This oscillatory flow can be exploited for power generation through the installation of a turbine beneath the plate, allowing the SHP to operate as a dual-purpose structure combining coastal protection and renewable energy extraction [30,33,34].

1.2. State of the Art of the SHP Device

SHP devices have been investigated in the literature due to their dual functionality in coastal protection and wave energy conversion. As research progressed, several characteristics were analyzed, including submergence depth, plate length, inclination, porosity, plate grouping, among others. Accordingly, this section is subdivided into four

distinct approaches: SHP operating as a BW; SHP operating as a WEC; SHP operating simultaneously as a BW and WEC; and SHP under the incidence of high-order or irregular wave conditions.

1.2.1. SHP Operating as a BW

Dick and Brebner [29] were among the first to report the pulsating behavior of the axial velocity beneath a SHP. However, their main objective was to develop empirical and theoretical relationships for the reflection coefficient (C_r) and transmission coefficient (C_t) based on a wave spectrum number. The investigated structures included a bottom-mounted rectangular submerged BW (step-type) and a permeable submerged horizontal plate. The authors also noted that, at the time, most SHP applications were site-specific due to the limited theoretical background and experimental evidence available.

Wang and Shen [35] advanced analytical approaches by investigating C_r and C_t for a group of SHPs positioned at different depths along the water column. The authors formulated the problem for multiple-plate configurations and discussed the influence of plate spacing on the hydrodynamic response, interpreting the arrangement as a set of horizontal plates (or tubes) supported by piles.

Yu [32] provided a comprehensive discussion on the hydrodynamic mechanisms of SHPs as BWs, emphasizing that the plate length plays a key role in controlling wave transmission. The author explained that wave propagation over the plate can induce a U-shaped flow pattern beneath the structure, contributing to wave energy attenuation. Unlike conventional BWs, the SHP relies primarily on fluid–fluid interaction to block waves, while the structure itself mainly acts by redirecting the flow rather than passively resisting wave action. In addition, Yu [32] reviewed several factors influencing SHP performance, including plate length, installation depth, inclination, porosity, plate vibration, presence of currents, three-dimensional effects, wave irregularity, nonlinear wave effects, fluid viscosity, and wave breaking criteria.

Karmakar and Soares [31] investigated wave interaction with an inclinable floating submerged plate under finite water depth conditions. Their two-dimensional numerical study was formulated within linear wave theory and evaluated the hydrodynamic response through reflection and transmission coefficients, as well as vertical deflections and vertical forces acting on the plate.

1.2.2. SHP Operating as a WEC

The experimental study by Orer and Ozdamar [33] investigated the performance of an SHP WEC under laboratory conditions. The authors analyzed the pulsating flow generated beneath the plate, characterized by velocities opposite to the direction of wave propagation, and evaluated the SHP energy-conversion performance under different wave periods and heights. Additional configurations including a triangular structure and a vertical wall beneath the plate were also tested. The results indicated that conversion efficiencies could reach up to 60%, with the vertical wall configuration showing the best performance.

Seibt et al. [36] numerically investigated the influence of the plate height on the SHP performance as a WEC, addressing a topic that, according to the authors, had not been explored in previous studies. The work focused on the characterization of the flow beneath the plate, highlighting the pulsating behavior of the axial velocity and its consistency with earlier findings reported in the literature [33,37].

1.2.3. SHP Operating Both as a BW and WEC

He et al. [38] analyzed the SHP through a two-dimensional numerical study under regular waves using the weakly compressible smoothed particle hydrodynamics (WCSPH) method. The authors emphasized that, although SHP devices have been studied for wave

attenuation and, separately, for energy conversion, fewer efforts have been dedicated to integrating both functionalities into a single design framework. Their study explored SHP configurations intended to perform as a BW while also operating as a WEC.

More recently, Motta et al. [39] numerically investigated inclined configurations of an SHP operating simultaneously as a BW and WEC under regular wave conditions. Ten inclination angles were analyzed while maintaining constant plate thickness and total material volume, using a horizontal configuration as reference. A full-scale numerical wave channel with a VOF multiphase approach was adopted. The device performance was evaluated based on free surface elevations for the BW function and axial velocity beneath the plate for the WEC function, showing that plate inclination significantly influences the dual hydrodynamic performance.

1.2.4. SHP Under High-Order or Irregular Wave Conditions

In addition to regular-wave investigations, the literature also includes studies addressing the SHP response under high-order and irregular wave conditions. Siew and Hurley [40] investigated the effect of long waves on a submerged plate, motivated by the development of floating or less permanent BW concepts, and proposed solutions for wave reflection and transmission in different regions around the structure. Aghili et al. [41] numerically studied the interaction between solitary waves and an SHP using WCSPH, considering different vertical positions of the plate and focusing on how submergence affects wave transformation and hydrodynamic loading.

Cheng et al. [42] investigated nonlinear wave transformation and dispersion over an SHP in the presence of a uniform current. The authors employed a fully nonlinear numerical wave flume in the time domain, based on a higher-order boundary element method combined with a mixed Eulerian–Lagrangian approach, and performed spectral analyses of the transformed wave field. Hayatdavoodi et al. [43] presented a numerical study on solitary and cnoidal wave transformation over an SHP using the nonlinear Green–Naghdi equations, discussing the role of dispersion mechanisms under different depth regimes and wave conditions.

Fang et al. [44] proposed an analytical model based on potential flow theory to obtain solutions for hydrodynamic pressure and wave forces acting on submerged plates under focused wave groups of the NewWave type. The study discussed the sensitivity of hydrodynamic coefficients and loads to the spectral characteristics of the incident wave group and to geometric parameters of the plate. Xu et al. [45] investigated solitary wave interaction with an SHP using a computational fluid dynamics (CFD) particle-based framework (MLParticle-SJTU) and the moving particle semi-implicit (MPS) method, focusing on the flow and pressure fields around the structure and highlighting the relevance of wave height and submergence in the interaction process.

Zheng et al. [46] presented laboratory experimental results evaluating wave dissipation and velocity-field characteristics beneath both solid and permeable SHP configurations. The study considered combinations of SHP parameters, including permeability, relative plate length, relative submergence, and different wave conditions, and discussed the hydrodynamic behavior under both regular and irregular waves. Their work also contributed to understanding how permeability and wave irregularity affect the relationship between wave transmission and flow velocities beneath the plate.

More recently, Thum et al. [24] numerically investigated an SHP device subjected to both representative regular waves and realistic irregular waves. The study addressed the SHP operating either as a BW or as a WEC, employing the WaveMIMO methodology to generate and propagate irregular sea states representative of the Rio Grande coast in southern Brazil. The authors performed numerical simulations based on the solution of the

conservation equations for mass and momentum and modeled the water–air interaction using the VOF multiphase approach, evaluating the influence of plate length on hydrodynamic indicators relevant to both BW and WEC performance. An NB was implemented at the end of the wave flume to absorb the incident waves. Despite the variations in the length of the SHP, the starting position of the NB was kept fixed.

Building upon investigations under regular wave conditions [39], Motta et al. [25] extended the analysis to include both representative regular waves and realistic irregular sea states, examining the performance of an SHP operating simultaneously as a BW and a WEC. Regular conditions were generated using second-order Stokes theory, whereas irregular conditions were modeled through the WaveMIMO methodology. The BW performance was evaluated based on free surface elevations upstream and downstream of the device, while the WEC performance was assessed through the axial velocity beneath the plate, highlighting the importance of realistic sea-state representation in SHP performance evaluation.

1.3. Research Scope and Main Contributions

The present study extends the analysis conducted by Thum et al. [24], allowing the influence of the initial position of the NB to be evaluated. For this purpose, the results obtained herein are compared with those reported by Thum et al. [24], which are adopted as the 1stF (first formulation) of this study.

A 2ndF (second formulation) of the computational domain is proposed here, in which the position of the NB is adjusted according to the SHP configuration, maintaining a constant distance between the downstream edge of the plate and the beginning of the absorbing region. This approach allows for the assessment of the influence of the downstream computational-domain configuration, including the relative SHP–NB spacing, effective outlet distance, and wave travel path before the damping region, on the monitored hydrodynamic response.

The scope of the present work comprises the numerical investigation of SHP performance under both representative regular waves and realistic irregular sea states from the coast of Rio Grande, Brazil, generated using the WaveMIMO methodology. The analysis considers multiple plate lengths and evaluates the device performance in terms of wave attenuation (BW function) and energy conversion potential (WEC function), including a combined assessment of both functionalities.

The main contributions of this study can be summarized as follows:

1. A systematic assessment of the influence of the downstream computational-domain configuration, including NB positioning on SHP hydrodynamic results, an aspect rarely addressed in the literature, particularly under irregular wave conditions;
2. The proposal of an alternative computational formulation (2ndF) that minimizes the interference of the absorbing boundary on downstream measurements;
3. A comparative analysis between the fixed downstream-domain configuration adopted in the 1stF and the adjusted downstream-domain configuration adopted in the 2ndF under both regular and irregular wave conditions;
4. The identification of SHP configurations that improves performance for BW, WEC, and combined BW-WEC applications based on multiple evaluation criteria.

2. Materials and Methods

This chapter describes the WaveMIMO methodology, used to generate regular or irregular waves based on the sea state observed along the coast of Rio Grande, in southern Brazil, and its application in the numerical simulations. The numerical model and computational domain are presented, as well as the statistical parameters adopted to evaluate the results.

2.1. Realistic Sea State (WaveMIMO Methodology)

The WaveMIMO methodology, presented by Machado et al. [26], enables the propagation of a realistic sea state in a CFD software, through the processing of the wave spectrum for a given region. In the present study, the applied wave spectrum results from a numerical simulation carried out in the TOMAWAC software (version 7.2) for a defined location and time interval, being the corresponding regular and irregular waves generated in the ANSYS Fluent (version 2024 R2).

In the present work, similarly to Maciel et al. [47], the WaveMIMO methodology was applied considering a realistic sea state for the region of Rio Grande (RS), Brazil. The sea state generated in TOMAWAC corresponds to the period from 1 January 2014 to 31 December 2014. The point from which the data were extracted is located at the geographic coordinates $52^{\circ}17'47.25''$ W and $32^{\circ}22'30.95''$ S, approximately 2 km from the coast, at a water depth of 9.52 m.

The wave flume geometry follows the recommendation of Gomes et al. [48] for its length, which is defined as five times the wavelength of the representative regular waves of the sea state. This wavelength has a value of $\lambda = 51.6$ m, obtained from a significant wave height of $H_s = 0.66$ m and a mean wave period of $T_m = 6.30$ s, as in Thum et al. [24]. Hence, the wave flume length is 258 m, while its height is 12 m, and its water depth is 9.52 m, consistent with Maciel et al. [47]. Further information regarding the extraction point location, the time-series histogram, and the temporal frequency density of the sea state can be found in Thum et al. [24] and Maciel et al. [47]. Figures 1 and 2 present the representative regular and realistic irregular waves of the sea state [24], respectively, which will be propagated in the numerical simulations of the two-dimensional wave flume.

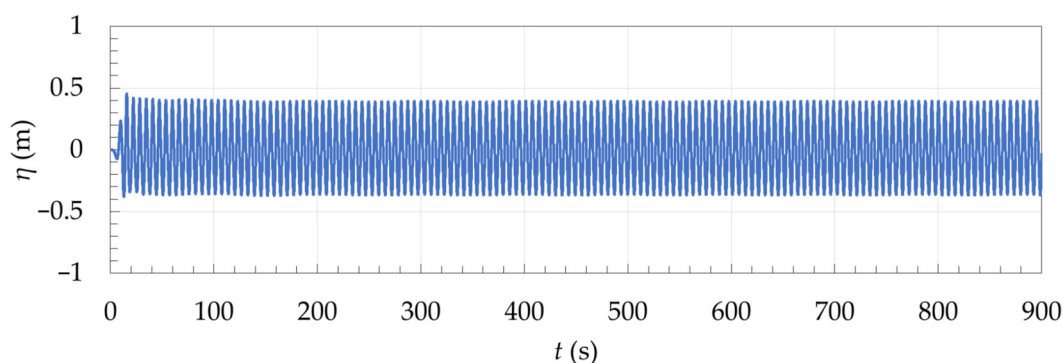


Figure 1. Representative regular waves of the propagated sea state: free-surface elevation (η).

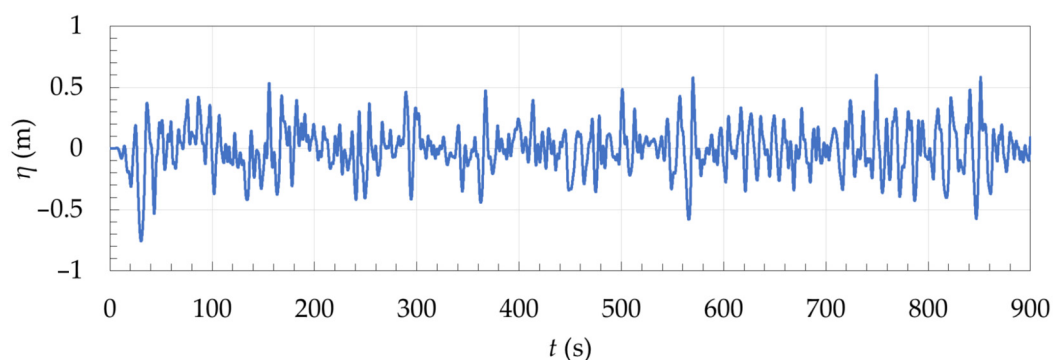


Figure 2. Realistic irregular waves of the propagated sea state: free-surface elevation (η).

To apply the η time series in the numerical wave flume simulations in ANSYS Fluent, it is necessary to transform the free-surface elevation data from Figures 1 and 2 into the velocity components u and w over time. These data are imposed as prescribed velocity

boundary conditions. Further information on this transformation procedure from η to u and w can be found in Machado et al. [26] and Oleinik et al. [49].

In Maciel et al. [50], in addition to validating the WaveMIMO methodology for the generation of regular waves and their incidence on an Oscillating Water Column device, the authors investigated the number of subdivisions of the inlet velocity region. This analysis aimed to obtain the best agreement between the waves generated in the numerical model and the elevation time series from which the velocities were extracted. The results indicate that the inlet velocity region should be subdivided into 10 segments. For each segment, the u and w velocity components are determined over time at a fixed depth at the base of the segment. Thus, each of the 10 segments has its own time-dependent velocity profiles, enabling the generation of both representative regular waves and realistic irregular waves of the sea state. In turn, the WaveMIMO validation for the generation of irregular waves can be found in Paiva et al. [51].

It should be emphasized that the prescribed velocity profiles used in the WaveMIMO methodology are not imposed arbitrarily. They are derived from the target free-surface elevation time series and applied as time-dependent horizontal and vertical velocity components along the inlet subdivisions [26,51]. The consistency between the imposed velocity profiles and the resulting numerical wave fields has been previously assessed for both representative regular waves and realistic irregular waves in the studies cited above. Therefore, the present work applies this previously verified, validated, and calibrated wave-generation methodology, while focusing on the influence of the NB position on the hydrodynamic response of the SHP.

Although the WaveMIMO methodology adopted here was developed for the numerical generation of realistic sea states [26] and later applied to the Rio Grande coastal region with statistical and spectral-density analyses of the generated wave signals [47], a new detailed spectral comparison at each monitoring probe was not performed in the present work. Therefore, aspects such as spectral-shape preservation, phase dispersion, and peak distribution along the flume should be further investigated in future studies to complement the present time-domain hydrodynamic assessment.

2.2. Computational Model

The numerical simulations were performed using ANSYS Fluent, which is a CFD package based on the finite volume method (FVM). The software solves the flow governing equations for mass conservation, momentum conservation, and the transport equation of the water volume fraction.

In this study, simplifying assumptions are adopted for the numerical solution of the flow, namely: isothermal, laminar, incompressible, two-dimensional, and transient flow. The energy equation is not solved, since no heat transfer is considered. Thus, the mass conservation and momentum conservation equations for the water–air mixture are, respectively [52]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \quad (1)$$

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla) \vec{v} = -\nabla p + \nabla \cdot \vec{\tau} + \rho \vec{g} + \vec{S}, \quad (2)$$

where ρ is the fluid density [kg/m³], $\vec{v}$ is the velocity vector [m/s], p is the pressure [Pa], $\vec{\tau}$ is the deformation tensor [N/m²], $\vec{g}$ is the gravitational acceleration [m/s²] and $\vec{S}$ is the sink term that represents energy dissipation when a NB is implemented [N/m³].

To numerically reproduce the interaction between water and air, the volume of fluid (VOF) model proposed by Hirt and Nichols [53] was adopted, which is based on the premise that the volume of one fluid cannot occupy the volume of another fluid. This is

represented in each control volume of the numerical wave flume by the volumetric fraction (α). The volume fraction transport equation is added to the model as [54]:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{v}) = 0. \quad (3)$$

Once the mass conservation and momentum conservation equations are solved for the air–water mixture, averaged values of density and viscosity are calculated as [50]:

$$\rho = \alpha \rho_{water} + (1 - \alpha) \rho_{air}, \quad (4)$$

$$\mu = \alpha \mu_{water} + (1 - \alpha) \mu_{air}. \quad (5)$$

It is important to emphasize that the laminar two-dimensional assumption was adopted because the present study focuses on a comparative sensitivity analysis of the NB position using global hydrodynamic indicators, rather than on the detailed resolution of local turbulent structures around the SHP. This assumption is also supported by previous verification and validation studies using the same VOF-FVM wave-generation methodology [34,48,50,51]. For example, Maciel et al. [50] compared laminar, $k-\epsilon$, and $k-\omega$ SST models for a laboratory-scale OWC device and reported close NRMSE values among the three approaches for the monitored free-surface elevations and pressure. Therefore, although turbulence modeling may be relevant for resolving local flow details, the laminar formulation was considered adequate for the comparative scope of the present study.

Figure 3 presents a schematic of the two-dimensional numerical wave flume geometry with the SHP and the boundary conditions applied to the model. The dimensions defined in Figure 3 are: wave flume height (H_c); wave flume length (L_c); water depth (d); horizontal distance from the inlet to the beginning of the SHP (X_p); SHP length (L_p); SHP submergence depth (h_p); SHP thickness (t_p); and NB length (L_{nb}). The dimensions adopted for the verification and validation procedures and for the case study are presented separately in their respective sections.

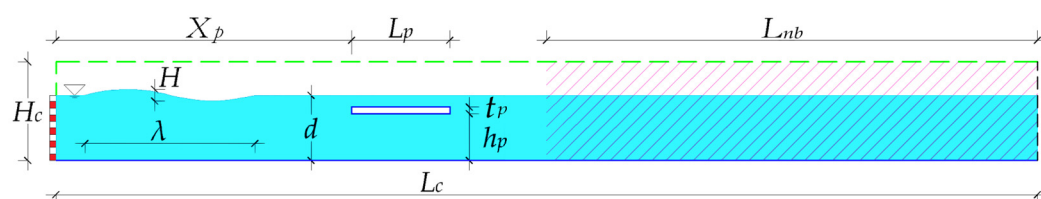


Figure 3. Numerical wave channel geometry with SHP.

Regarding the boundary conditions, in Figure 3, the channel bottom and the SHP contour, represented by the blue line, were assigned an impermeability condition with a fixed-wall boundary, meaning that no mass transport occurs across these edges. The green dashed line represents a pressure outlet. On the right side of the wave flume, a pressure outlet (gray dashed line) was defined with constant depth, referred to as a hydrostatic profile.

The numerical wave maker located on the left side of the flume, composed of 10 segments [50] and highlighted with red and white hatching in Figure 3, was defined as a prescribed velocity inlet. While conventional regular-wave generation prescribes velocity components using analytical wave expressions [34,36,48,55], the WaveMIMO methodology imposes time-dependent discrete profiles of the horizontal and vertical velocity components, u and w , at each inlet subdivision. This procedure was applied in all simulations to generate both representative regular waves and realistic irregular waves corresponding to the adopted sea state.

In addition, an NB is implemented at the end of the wave flume, corresponding to the pink-hatched region in Figure 3. Its primary function is to dampen the incident waves and prevent artificial reflections from contaminating the hydrodynamic response of the SHP. By effectively absorbing the outgoing wave energy, the NB also allows the use of a shorter computational domain, since a significantly longer flume would otherwise be required to avoid reflection effects. Wave damping is performed in a region limited to 2.5λ at the end of the flume opposite to the wave generation region, following the recommendation of Machado et al. [26], and governed by the sink-term equation according to Zwart et al. [56] and Park et al. [57]:

$$\vec{S} = \left(C_1 \rho V + \frac{1}{2} C_2 |V| V \right) \left(1 - \frac{z - z_\eta}{z_b - z_\eta} \right) \left(\frac{x - x_s}{x_e - x_s} \right)^2, \quad (6)$$

where $C_1 = 20 \text{ s}^{-1}$ and $C_2 = 0 \text{ m}^{-1}$ are the linear and quadratic damping coefficients [58], V is the velocity (m/s) in the z direction, z_η and z_b are the vertical positions of η and the bottom, respectively, and x_s and x_e are the horizontal positions of the beginning and end of the NB region, respectively. These damping coefficients were adopted to maintain consistency with previous applications of the same VOF-FVM numerical wave-flume framework, in which this NB formulation was employed for regular and irregular wave propagation [50,51]. This is consistent with recent CFD wave-flume studies emphasizing that the performance of absorbing or relaxation regions depends on the adopted damping strategy, absorption-zone length, wave characteristics, and computational-domain layout [22,23].

It should be highlighted that, in the 1stF [24], the spacing between the downstream edge of the SHP and the beginning of the NB decreased as the SHP length increased. In contrast, in the present study, the 2ndF keeps this spacing fixed at one wavelength (1λ). This value was adopted to allow the transmitted wave to propagate over at least one complete spatial cycle before entering the damping region. Such spacing prevents the direct action of the numerical beach source terms on the near-field region of the plate, where the velocity and pressure fields, phase changes, and free-surface reorganization are still strongly affected by the wave–structure interaction. As a result, the flow around and immediately downstream of the SHP remains governed by the Navier–Stokes equations without artificial damping interference, preserving the physical interpretation of the transmission and reflection phenomena and reducing possible contamination of the downstream probes. It is worth mentioning that this value of 1λ between the downstream edge of the SHP and the beginning of the NB was adopted based on a preliminary sensitivity test, as discussed in Section 4.1.1. This spacing was selected to reduce possible interference from the damping region while avoiding an unnecessary increase in the computational domain and computational cost.

Spatial discretization employed the stretched mesh methodology, as in Gomes et al. [48], and based on Mavriplis [59], in which mesh refinement is increased only in regions of higher variation or greater interest in the results, in order to reduce the computational effort. This mesh-generation strategy is widely used in numerical simulations of wave generation and propagation and, consequently, is broadly adopted in computational modeling applied to WECs.

In the present study, the stretched mesh was applied in the regions upstream and downstream of the SHP location, whereas a finer mesh was employed in the SHP region to capture the hydrodynamic behavior in the vicinity of the device. Vertically, the computational domain was subdivided into three regions: the water-only region, discretized into 60 cells; the air–water interaction region, discretized into 40 cells; and the air-only region, discretized into 20 cells. Along the flume, a horizontal discretization of $\lambda/50$ was adopted consistently with previous studies using VOF-FVM numerical modeling framework for

wave generation and WEC applications [48,59]. This resolution is also consistent with the previous SHP simulations reported by Thum et al. [24], which are adopted in the present study as the 1stF results. Therefore, the 2ndF simulations preserved the same basic horizontal discretization criterion used in the 1stF, including the wave-channel discretization and the local refinement strategy around the SHP. This choice ensured that the comparison between the 1stF and 2ndF was not affected by changes in the basic mesh-resolution criterion, but by the downstream computational-domain configuration, mainly the distance between the downstream edge of the SHP and the beginning of the NB. Therefore, the adopted spatial discretization was selected to maintain consistency with a previously established numerical strategy for SHP wave-flume simulations, rather than as an arbitrary fixed resolution. Figure 4 illustrates the mesh configuration, highlighting the refined region around the SHP and the stretched mesh distribution along the flume. The detailed view shown in Figure 4b corresponds to the mesh adopted in the validation case.

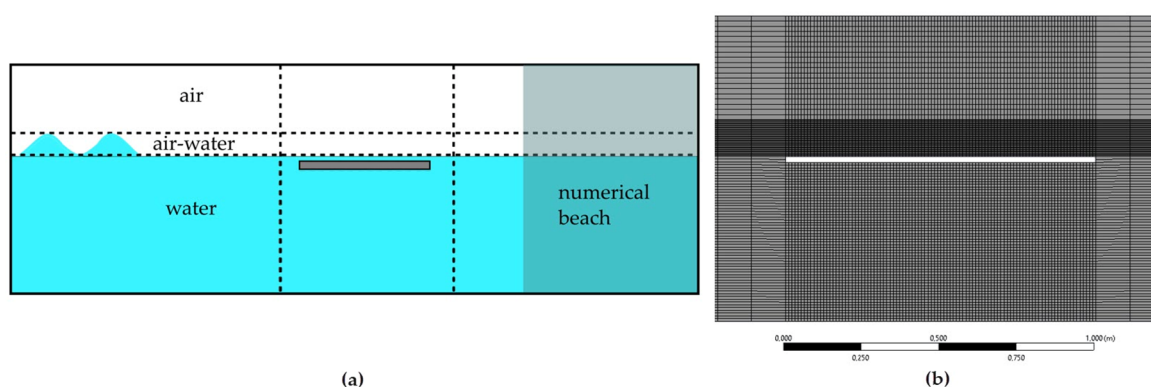


Figure 4. Spatial discretization of the numerical wave flume: (a) overall view of the computational domain with stretched mesh distribution; (b) detailed view of the refined mesh in the vicinity of the SHP used in the validation case.

The first-order upwind scheme was applied for the discretization of the spatial derivatives of the transport equations, and the first-order implicit formulation was used for time discretization [60]. The under-relaxation factors adopted for the solution of the mass and momentum conservation equations were 0.3 and 0.7, respectively. The VOF model with an explicit formulation was employed; therefore, the cell fluxes were interpolated using the geometric reconstruction scheme (geo-reconstruct). With the PRESTO scheme (pressure staggering option), pressure was interpolated at the faces of each cell. For pressure-velocity coupling, the PISO method (pressure-implicit with splitting of operators) was employed [34,47,48]. The convergence of the iterative solution at each time step was monitored through the residuals of the governing equations, adopting a residual criterion of 10^{-3} .

Although first-order spatial and temporal discretization schemes may introduce numerical diffusion in wave-propagation simulations, they were adopted here to maintain consistency with the same VOF-FVM numerical modeling framework and WaveMIMO wave-generation methodology previously verified, validated, and applied to OWC, overtopping, and SHP devices. Moreover, since the objective of this work is comparative, the same numerical schemes, mesh strategy, time step, boundary conditions, and physical assumptions were applied to both the 1stF and 2ndF. Therefore, possible numerical damping effects associated with the adopted schemes are consistently present in all simulated cases, allowing the relative influence of the NB position to be evaluated under controlled numerical conditions.

The time step adopted in the simulations was 0.05 s for the verification procedures, according to Machado et al. [26], 0.001 s for validation, and 0.01 s for the case study. For the case-study simulations, an a posteriori estimate of the Courant–Friedrichs–Lewy (CFL) number was calculated to characterize the adopted temporal resolution [60]. The time step used in the 2ndF simulations was $\Delta t = 0.01$ s, which is the same value adopted in the 1stF simulations reported by Thum et al. [24]. Therefore, the temporal discretization was kept unchanged between the two formulations, ensuring that the comparison between the 1stF and 2ndF was not affected by changes in the time-step definition. This value is also consistent with recent SHP simulations performed with the same VOF-based numerical framework, in which characteristic time steps of the same order of magnitude were adopted in a mesh/time-step convergence assessment for SHP simulations [25]. Considering the representative regular waves used in the present study, with $\lambda = 51.6$ m and $T_m = 6.30$ s, the corresponding characteristic phase velocity was estimated as $c = \lambda/T_m = 8.19$ m/s, following standard wave-kinematics relations adopted in the analytical second-order Stokes formulation [55]. Since the horizontal discretization adopted in the wave-propagation region was $\Delta x = \lambda/50 = 1.032$ m and the time step used in the case study was $\Delta t = 0.01$ s, the resulting characteristic CFL number is approximately 0.079. This value indicates a conservative temporal resolution with respect to the characteristic propagation of the imposed wave field. Nevertheless, this estimate does not replace a formal time-step sensitivity analysis or a complete numerical-uncertainty assessment, which are acknowledged as limitations of the present study.

The average computational time was 44 h, using a computer with an Intel Core i7-8700K 3.70 GHz processor and 32 GB of working memory (Santa Clara, CA, USA).

2.3. Statistical Analyses

The accuracy of the computational model in relation to the reference data, as well as the comparison between the studied cases with and without adjustments in the NB position, were evaluated using the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE) equations, allowing the model verification [61] and the assessment of the influence of the NB position. For the validation procedure, the Relative Percentage Error (RPE) was calculated [62]. The MAE, RMSE, and RPE are defined, respectively, as:

$$\text{MAE} = \frac{\sum_{j=1}^n |PS_j - R_j|}{n}, \quad (7)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{j=1}^n (PS_j - R_j)^2}, \quad (8)$$

$$\text{RPE} = 100 \frac{PS_i - R_i}{R_i}, \quad (9)$$

where PS is the result obtained in the present study, R is the reference value used for comparison, and n is the sample size of the dataset considered.

To determine the significant wave height (H_s) from the numerical results obtained in the simulations with representative regular waves and realistic irregular waves of the sea state, the OCEANLYZ software version 2.0 was used. This software is a toolbox for analyzing wave time-series data collected by buoys or in a laboratory. The software has a graphical interface that allows spectral and wave analysis using the zero-crossing method for the identification and characterization of each wave in the series [63].

Additionally, for the SHP operating as a BW and WEC, an analysis based on the integration of the free surface elevation and axial velocity time series is included for each

case, as performed in Motta et al. [25,39]. This integral-based analysis was applied both to the results of the 1stF reported in Thum et al. [24], for which this procedure had not been previously considered, and to the 2ndF results obtained in the present study. It is known that the integration of a curve results in the value of the area between the curve and the plotting axis [64]. Thus, it is possible to comparatively assess the hydrodynamic performance of the SHP as a BW and WEC from a new perspective in relation to the reference case $1L_p$. To do so, the integral is calculated for each monitored time series in each case: water free surface elevation downstream of the SHP ($I_{\eta i}$) and velocity beneath the SHP (I_{ui}). In addition the integral of the free surface elevation without the presence of the SHP was also monitored ($I_{\eta wSHP}$). These parameters were then correlated to assess how the presence and length of the SHP influence the hydrodynamic behavior under both representative regular and realistic irregular waves of the sea state.

3. Verification and Validation Procedures

The verification and validation of the VOF-FVM computational framework employed in this study were previously carried out and reported in Thum et al. [24], where further details can be found. Since the present work adopts the same governing equations, boundary conditions, wave-generation methodology, numerical schemes, mesh strategy, time-step definition, and post-processing procedures, the previously reported verification and validation procedures remain applicable. The modification introduced in the 2ndF concerns only the computational-domain layout, by maintaining a constant distance of one wavelength between the downstream edge of the SHP and the beginning of the NB. For the sake of brevity, only a brief description of the adopted procedures and the corresponding statistical indicators is provided herein.

The WaveMIMO methodology for generating representative regular waves was verified against the analytical second-order Stokes solution [55], achieving a MAE of 0.090 m and an RMSE of 0.116 m, with these values in good agreement with previous studies [24,47,50]. In turn, for the numerical generation of realistic irregular waves, the WaveMIMO methodology reached a MAE of 0.117 m and an RMSE of 0.152 m, with these quantitative indicators also consistent with previous verification studies [47]. Furthermore, the WaveMIMO methodology was validated for the generation of irregular waves in [51].

After that, considering the SHP, the WaveMIMO methodology was verified, comparing its results with those reported by Seibt et al. [34], who employed the conventional approach for regular wave generation. For the free surface elevation upstream the SHP, a MAE of 0.030 m and RMSE of 0.040 m were observed, while for the axial velocity beneath the SHP values of MAE = 0.061 m/s and RMSE = 0.077 m/s were identified. Furthermore, the WaveMIMO was validated against laboratory experimental data [33], resulting in an RPE of 7.73%.

Regarding the capability of the OCEANLYZ software to compute the significant wave height of the incident waves, a verification was performed, yielding an RPE of 0.002%.

To improve transparency, Table 1 summarizes the main verification and validation evidence supporting the numerical framework adopted in the present study. Table 1 includes the analyzed procedure, the reference dataset or comparison basis, the monitored quantity, and the corresponding statistical indicators.

Table 1. Summary of the verification and validation evidence supporting the numerical framework adopted in the present study.

Procedure	Comparison Basis and Reference	Monitored Quantity	Statistical Indicator
WaveMIMO verification for representative regular waves	Analytical second-order Stokes solution [55]	Free-surface elevation	MAE = 0.090 m; RMSE = 0.116 m
WaveMIMO verification for realistic irregular waves	Reference irregular-wave data from previous WaveMIMO studies [47]	Free-surface elevation	MAE = 0.117 m; RMSE = 0.152 m
SHP model verification	Numerical results of Seibt et al. [34]	Free-surface elevation upstream of the SHP	MAE = 0.030 m; RMSE = 0.040 m
SHP model verification	Numerical results of Seibt et al. [34]	Axial velocity beneath the SHP	MAE = 0.061 m/s; RMSE = 0.077 m/s
SHP/WaveMIMO validation	Laboratory experimental data [33]	Hydrodynamic response of the SHP	RPE = 7.73%
OCEANLYZ verification	Incident-wave significant wave height	H_s calculation	RPE = 0.002%

4. Results and Discussion

Here the 2ndF is presented along with the results and discussion regarding the influence of the NB on the hydrodynamics of the 1stF [24] for both representative regular waves and realistic irregular waves. Considering the range of analyzed cases, recommendations are provided regarding the best-performing SHP cases for the BW function, the WEC function and the combined BW-WEC function for each type of incident wave approach. Additionally for the 2ndF, another analysis methodology is adopted, based on the integration of the time series of free surface elevation and axial velocity [25,39], which is presented here [29]. For both formulations, the numerical wave flume dimensions are based on Gomes et al. [48] and the SHP device dimensions are based on Seibt et al. [34].

4.1. Second Formulation (2ndF) of the Computational Domain

The 2ndF of the computational domain is based on the 1stF [24] and modifies only the distance between the end of the SHP and the beginning of the NB region. As already mentioned, in Thum et al. [24] this distance was fixed regardless of the SHP length, i.e., L_c was constant for any L_p (see Figure 3). Now, in the 2ndF, each case has its own L_c , since a fixed distance of 1λ between the end of the SHP and the beginning of the NB was considered. It should be noted that, in the 2ndF, keeping the SHP–NB distance constant necessarily changes the total flume length for each plate configuration. Therefore, the comparison between the 1stF and 2ndF should be interpreted as an assessment of the downstream computational-domain configuration, including the relative position of the NB, the effective outlet distance, and the wave travel path before the damping region. These aspects may influence reflection, numerical dissipation, and phase behavior at the monitoring probes. Thus, the present analysis does not isolate the NB source-term location from the associated downstream-domain length, but evaluates their combined effect on the monitored hydrodynamic indicators. This difference in the geometry of each formulation can be visualized in Figure 5.

The numerical solution was maintained with the new geometry, where the representative regular waves and realistic irregular waves generated through the WaveMIMO methodology were propagated, using the same time step and solution parameters described in Section 3.

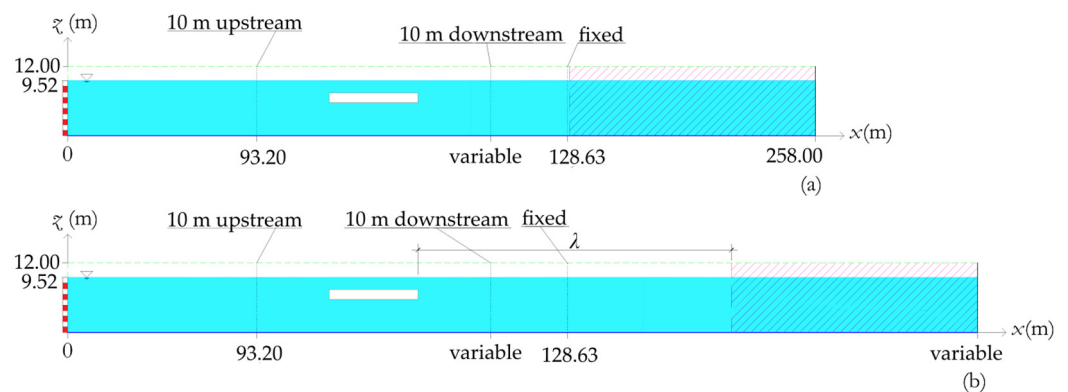


Figure 5. Difference between the computational domains of the (a) 1stF and (b) 2ndF.

To evaluate the SHP in the BW function, the free-surface elevation is monitored at horizontal coordinates 10 m upstream and 10 m downstream of the SHP for each case, as already analyzed in the 1stF [24]. The fixed probe at $x = 128.63$ m is also present in the 2ndF, and the H_s at this point will be interpreted as the wave height reaching the coast after propagating over the device. In the 2ndF, there is also interest in analyzing the free-surface elevation monitoring at the channel inlet at $x = 0$ m. Previously, this monitoring was used as an internal simulation verification procedure. It now receives a new objective: in addition to verifying the incident waves in the numerical channel, it also enables comparison between the 1stF and 2ndF and the possible effects of the NB in this region. Furthermore, in the 2ndF, monitoring of the free-surface elevation is added at the horizontal coordinate x corresponding to the beginning of the NB region, which varies for each case. Table 2 presents the monitoring coordinates for the free-surface elevation at the beginning of the NB in the 2ndF and the values of L_p (same for 1stF and 2ndF) and L_c for each case.

Table 2. Position of the NB start probe, L_p and L_c for each case in the 2ndF.

Case	Free Surface NB Start Probe Horizontal Position (m)	L_p (m)	L_c (m)
$1L_p$	158.25	3.4570	287.25
$1.5L_p$	159.99	5.1858	288.99
$2L_p$	161.71	6.1940	290.71
$2.5L_p$	163.44	8.6420	292.44
$3L_p$	165.17	10.3710	294.17

Therefore, the determination of the free-surface elevation probes was performed strategically to ensure comparison between the results of the 2ndF with those of the 1stF [24]. The addition of the probe at the channel inlet aims to observe the incident H_s in the numerical simulation and compare it with the representative H_s of the realistic sea state presented in Thum et al. [24]. The probe added at the beginning of the NB for each case aims to evaluate the effects of this region on H_s .

To evaluate the SHP in the WEC function, the axial velocity beneath the SHP is monitored at all points shown in Figure 6, i.e., the same points already considered in the 1stF [24]. In this 2ndF, the maximum axial velocity (u_{max}) was determined for two reference points in depth: $z = 4.284$ m (1stF and 2ndF) and $z = 5.236$ m (2ndF).

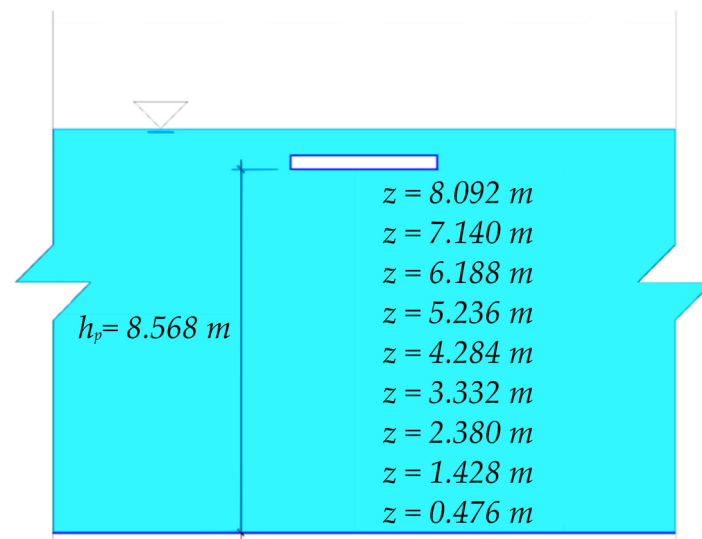


Figure 6. Numerical probe locations for the SHP operating as a WEC.

In the 1stF, the decision regarding the analysis point was based on the experimental study by Orer and Ozdamar [33], which evaluates the velocity only at the central point between the SHP and the channel bottom. Considering the results obtained from the u_{max} profiles along the depth in Thum et al. [24], one can note that the velocity increases at depths above this central point used as reference for determining the maximum values of each case. For this reason, here in the 2ndF, the depth $z = 5.236$ m is added as a reference for profile construction, representing 60% of the depth, as in the study by Seibt et al. [34]. This means that the determination of the u_{max} now occurs at a depth closer to the SHP device.

The methodology for constructing the velocity profiles is the same, whether using the reference point $z = 4.284$ m or $z = 5.236$ m. For the reference point, the time instant t at which the maximum axial velocities occur for each case is identified. Using this instant t , the axial velocities at each monitored point along the depth are obtained as defined in Figure 6, thus ensuring the construction of the maximum axial velocity profile along the depth for each case. It should be emphasized that when the axial velocity has a negative sign, it indicates that the flow beneath the SHP occurs in the direction opposite to wave propagation [33,34,38,65].

The case study methodology for the 2ndF computational domain begins with a test of the influence of the NB on the hydrodynamics of the SHP device to evaluate possible distortions in the 1stF observed in the results of Thum et al. [24]. Subsequently, the results of the 2ndF are analyzed for the SHP in the BW and WEC functions, as well as a combined analysis of the BW and WEC functions.

4.1.1.1. Test of the Influence of the NB Location on the Hydrodynamics of the SHP Device

The results obtained using the 1stF of the computational domain show oscillations in H_s after wave propagation over the SHP in specific cases. The increase in H_s for cases $1L_p$ and $2.5L_p$ between the probes located 10 m downstream ($x = 121.84$ m and $x = 123.57$ m, respectively) and the fixed downstream probe ($x = 128.63$ m) motivated an assessment of possible distortions in these 1stF results [24].

These results raise the question of how H_s can increase downstream of the plate in the absence of any energy source during wave propagation. One possible explanation is the influence of the NB. In the 1stF, the fixed probe at $x = 128.63$ m is positioned very close to the NB region, which begins at $x = 129$ m.

The purpose of this study is to investigate whether there is any effect from the computational model itself distorting the numerical results. For this purpose, the five cases were simulated for both representative regular waves and realistic irregular waves of the realistic sea state, considering the 2ndF of the computational domain. The effects on H_s due to the NB position will be discussed in this subsection, and comparative results between the formulations will be presented.

To do so, before comparing the 1stF and 2ndF, a preliminary sensitivity test was performed to support the adoption of the distance between the downstream edge of the SHP and the beginning of the NB in the 2ndF. Considering the case $3L_p$ under the incidence of realistic irregular waves, four spacings were evaluated: 0.3λ , 0.7λ , 1λ , and 1.5λ . The comparison was carried out using the relative differences in the integral of the downstream free-surface elevation and in the integral of the axial velocity beneath the SHP, since these quantities are related to the BW and WEC-related hydrodynamic indicators adopted in the present study. The obtained results are reported in Table 3.

Table 3. Sensitivity test for the spacing between the downstream edge of the SHP and the beginning of the NB.

SHP-NB Spacing	$I_{\eta 3L_p}$ [m·s]	RPE [%]— $I_{\eta 3L_p}$	$I_{u 3L_p}$ [m]	RPE [%]— $I_{u 3L_p}$
0.3λ	95.31	4.06	121.41	4.57
0.7λ	91.44	4.08	115.86	3.97
1λ	87.01	1.15	111.26	2.49
1.5λ	86.01	-	114.03	-

In Table 3 the $I_{\eta 3L_p}$ and $I_{u 3L_p}$ represent the free-surface elevation integral evaluated at 10 m downstream and the axial velocities beneath the SHP at the point $z = 4.284$ m, respectively, for the case 3; while |RPE| is the absolute value of the relative percentual error between the results of two consecutive SHP-NB spacing. One can note in Table 3 that the smallest differences were observed between the 1.0λ and 1.5λ cases, with absolute values lower than 2.5%. Therefore, the 1.0λ spacing was adopted in the 2ndF because it provided results close to those obtained with the larger 1.5λ spacing, while avoiding an unnecessary increase in computational-domain length and computational cost.

After that, considering the representative regular waves, Table 4 compares the H_s values obtained in the 2ndF with those from the 1stF, presented in Thum et al. [24]. The H_s values are similar, with cases $1L_p$ and $3L_p$ showing no significant difference. The largest H_s differences, on the order of centimeters, occur at different monitoring points for the regular waves. In some cases, the main difference occurs at the channel inlet, while in others it occurs at the probe located 10 m upstream of the SHP. The $2.5L_p$ case in the 2ndF stands out as the one with the greatest change in results compared to the 1stF.

Regarding H_s at the beginning of the NB in the 2ndF, when compared with the fixed probe for each case, there is no uniform trend among the 2ndF cases. In cases $1L_p$, $1.5L_p$, and $2.5L_p$, H_s varied by less than one centimeter, which is negligible for the present analysis. Cases $2L_p$ and $3L_p$ showed a reduction in H_s at the beginning of the NB for the incidence of regular waves.

Table 5 presents the SHP performance in the BW function through the percentage reduction in H_s . As previously observed, there is low variation between the 1stF and 2ndF results. For regular waves, the greatest influence of the NB on the percentage reduction in H_s is only 1.2%, occurring between the 1stF and 2ndF of cases $2L_p$ and $2.5L_p$. Therefore, for the BW function, the proximity between the fixed probe and the NB in the 1stF is negligible for representative regular wave propagation.

Table 4. H_s values [m] monitored at the same points for the 1stF and 2ndF for the representative regular waves.

Case	Channel Inlet	10 m Upstream	10 m Downstream	Fixed Probe	NB Start
1 L_p 2ndF	0.4782	0.5488	0.4688	0.4628	0.4667
1 L_p 1ndF	0.4659	0.5402	0.4612	0.4559	-
Difference	0.0123	0.0086	0.0076	0.0069	-
1.5 L_p 2ndF	0.3535	0.6238	0.3431	0.3242	0.3301
1.5 L_p 1ndF	0.3512	0.5994	0.3294	0.3087	-
Difference	0.0023	0.0244	0.0137	0.0155	-
2 L_p 2ndF	0.3968	0.7435	0.2453	0.2456	0.2127
2 L_p 1ndF	0.3384	0.7130	0.2270	0.2290	-
Difference	0.0584	0.0305	0.0183	0.0166	-
2.5 L_p 2ndF	0.4167	0.7375	0.2190	0.1866	0.1856
2.5 L_p 1ndF	0.5524	0.8120	0.2466	0.2150	-
Difference	-0.1357	-0.0745	-0.0276	-0.0284	-
3 L_p 2ndF	0.7676	0.8351	0.2462	0.2359	0.2102
3 L_p 1ndF	0.7617	0.8400	0.2461	0.2385	-
Difference	0.0059	-0.0049	0.0001	-0.0016	-

Table 5. Comparison of the SHP-BW performance for the 1stF and 2ndF through the percentage reduction in H_s [m] between the downstream probes relative to the probe located 10 m upstream of the SHP for the representative regular waves.

Case	10 m Downstream	Fixed Probe	NB Start
1 L_p 2ndF	-14.6%	-15.7%	-15.0%
1 L_p 1ndF	-14.6%	-15.6%	-
Difference	0%	0.1%	-
1.5 L_p 2ndF	-45.0%	-48.0%	-47.1%
1.5 L_p 1ndF	-45.0%	-48.5%	-
Difference	0%	-0.5%	-
2 L_p 2ndF	-67.0%	-67.0%	-71.4%
2 L_p 1ndF	-68.2%	-67.0%	-
Difference	-1.2%	-0.9%	-
2.5 L_p 2ndF	-70.3%	-74.7%	-74.8%
2.5 L_p 1ndF	-69.6%	-73.5%	-
Difference	0.7%	1.2%	-
3 L_p 2ndF	-70.5%	-71.6%	-74.8%
3 L_p 1ndF	-70.7%	-71.6%	-
Difference	0.2%	0%	-

Considering realistic irregular waves, Table 6 compares the H_s values obtained in the 2ndF with those from the 1stF [24]. The 2ndF shows differences relative to the 1stF with significant values (>0.30 m), especially for cases 2 L_p and 2.5 L_p at the channel inlet. In the 1stF, the cases with the largest oscillations in H_s at the downstream probes are 1 L_p and 3 L_p [24]. In the 2ndF, this behavior occurs for cases 1.5 L_p and 3 L_p , as shown in Table 6. In the 1stF, the variation in H_s at the downstream probes has maximum values of 0.02 m, while the 2ndF shows smaller variations. In other words, the 2ndF presents lower H_s variability in the monitoring points downstream the SHP.

The fixed probe downstream of the SHP showed reduced H_s values for all cases in the 2ndF compared to the values obtained at the probe located 10 m downstream, except for case 2 L_p (negligible variation). This is consistent with the physical behavior of wave propagation after the device and toward the coast. This demonstrates that, for irregular waves, increasing the distance between the SHP and the NB removed the influence observed in the 1stF results.

Table 6. Comparison of the H_s values [m] monitored at the same points for the 1stF and 2ndF considering the realistic irregular waves.

Case	Channel Inlet	10 m Upstream	10 m Downstream	Fixed Probe	NB Start
1 L_p 2ndF	0.7150	0.6687	0.6210	0.6163	0.6287
1 L_p 1ndF	0.7460	0.6620	0.6321	0.6489	-
Difference	−0.0310	0.0067	−0.0111	−0.0326	-
1.5 L_p 2ndF	0.7331	0.6977	0.6147	0.6011	0.6160
1.5 L_p 1ndF	0.7739	0.6828	0.6192	0.6153	-
Difference	−0.0408	0.0149	−0.0045	−0.0142	-
2 L_p 2ndF	0.8055	0.7379	0.5390	0.5412	0.6014
2 L_p 1ndF	1.1200	0.7376	0.5940	0.5829	-
Difference	−0.3145	0.0003	−0.0250	−0.0417	-
2.5 L_p 2ndF	0.8454	0.7828	0.5367	0.5257	0.5685
2.5 L_p 1ndF	1.2881	0.7826	0.5597	0.5620	-
Difference	−0.4427	0.0002	−0.0230	−0.0363	-
3 L_p 2ndF	0.8937	0.7959	0.4823	0.4625	0.5128
3 L_p 1ndF	0.9814	0.8289	0.5339	0.5116	-
Difference	−0.0877	−0.0330	−0.0516	−0.0491	-

Table 7 presents a comparison of the SHP performance in the BW function for the 1stF and 2ndF under realistic irregular waves. Cases 1 L_p and 2 L_p stand out as those with the greatest difference when comparing the 1stF and 2ndF in the reduction in H_s at the fixed probe. The percentage reductions in H_s indicate that the NB influence was greater on the fixed probe results than on the probe located 10 m downstream in the 1stF. For example, case 1 L_p showed a 5.9% difference at the fixed probe between the formulations. These results indicate the importance of distinguishing between local hydrodynamic effects near the SHP and domain-induced effects at downstream monitoring locations. In the present study, the local response is mainly associated with the wave–SHP interaction region, including the free-surface behavior immediately upstream and downstream of the plate and the axial velocity field beneath the SHP. In contrast, domain-induced effects are mainly related to the downstream computational-domain layout, including the distance between the SHP and the beginning of the NB, the effective wave travel path before the damping region, and the position of the fixed downstream probe. Therefore, the larger differences observed at the fixed probe under realistic irregular waves are interpreted as possible interference from the downstream domain configuration, rather than as changes in the intrinsic local hydrodynamic behavior of the SHP. This supports the use of the 2ndF as a more controlled numerical setup for comparing different plate lengths.

Table 7. SHP-BW performance: Percentage reduction in H_s [m] between the downstream probes relative to the probe located 10 m upstream of the SHP for the 1stF and 2ndF under realistic irregular waves.

Case	10 m Downstream	Fixed Probe	NB Start
1 L_p 2ndF	−7.1%	−7.8%	−6.0%
1 L_p 1ndF	−4.5%	−2.0%	-
Difference	2.6%	5.9%	-
1.5 L_p 2ndF	−11.9%	−13.8%	−11.7%
1.5 L_p 1ndF	−9.3%	−9.9%	-
Difference	2.6%	4.0%	-
2 L_p 2ndF	−22.9%	−26.7%	−18.5%
2 L_p 1ndF	−19.5%	−21.0%	-

Table 7. Cont.

Case	10 m Downstream	Fixed Probe	NB Start
Difference	3.4%	5.7%	-
$2.5L_p$ 2ndF	−31.4%	−32.8%	−27.4%
$2.5L_p$ 1ndF	−28.5%	−28.2%	-
Difference	3.0%	4.7%	-
$3L_p$ 2ndF	−39.4%	−41.9%	−35.6%
$3L_p$ 1ndF	−35.6%	−38.3%	-
Difference	3.8%	3.6%	-

Table 7 also helps clarify that there is an increase in H_s at the beginning of the NB region, as observed in the last column.

The analysis of the influence of the NB region on H_s monitoring for regular and irregular waves allowed improvement of the obtained results. Given the better performance of the 2ndF, it is adopted for the final discussion of results presented in the following Sections 4.1.2 and 4.1.3. The results in those sections correspond to the same numerical simulations presented here, but without the comparison with the 1stF.

4.1.2. Second Formulation (2ndF)—Representative Regular Waves of the Sea State

In this subsection, the results of the 2ndF are discussed for the SHP operating as a BW, as a WEC, and under the combined BW and WEC analysis, subjected to representative regular waves of the sea state.

The objective of a BW is the reduction in the H_s after wave propagation over the device; therefore, a good BW is the one that provides the highest reduction. In this study, as shown in Figure 5, the comparison between the probes located 10 m upstream and 10 m downstream of the device is considered as the SHP performance in the BW function. The fixed probe located at 128.63 m is assumed to represent the waves that reach the coast.

Figure 7a–e presents the free-surface elevations 10 m upstream and 10 m downstream of the SHP for each case throughout the entire simulated time. Figure 8 highlights the interval $400\text{ s} < t < 450\text{ s}$ for each case (represented by the red dashed boxes in Figure 7), explicitly showing the BW performance.

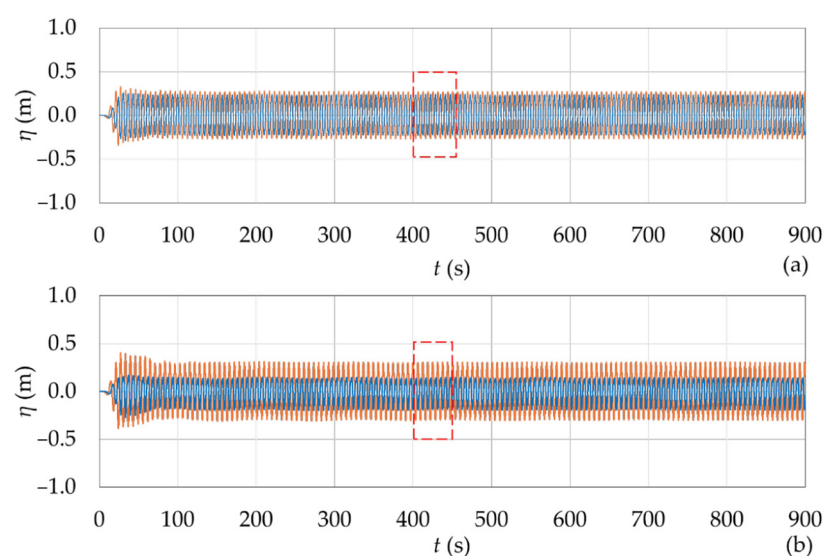


Figure 7. Cont.

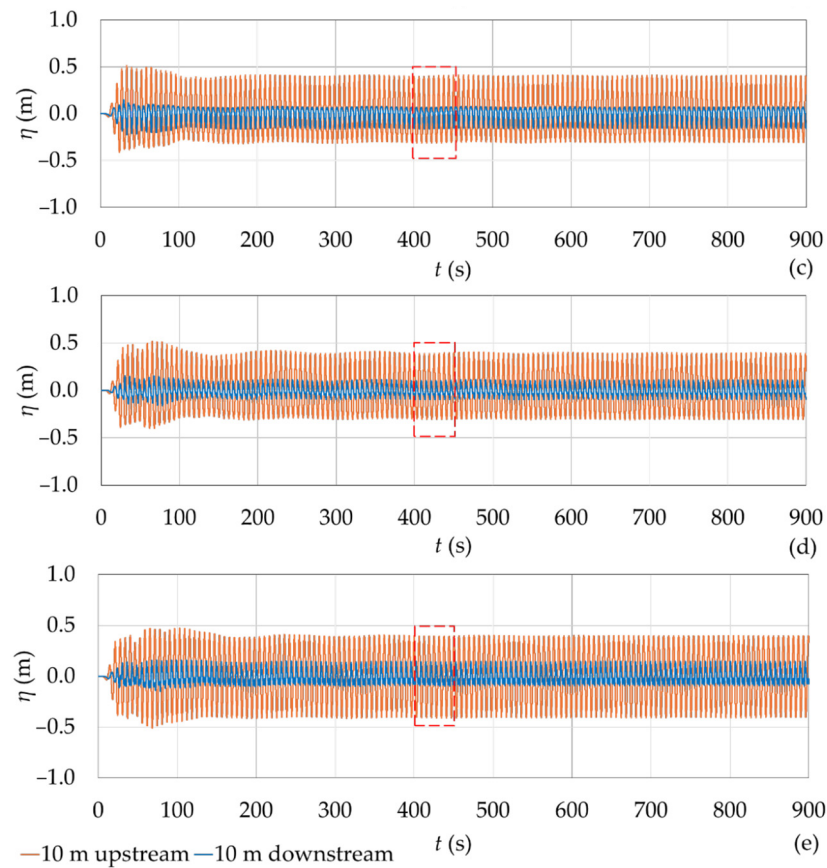


Figure 7. Evaluation of the SHP under the incidence of representative regular waves as a BW in the 2ndF: (a) $1L_p$; (b) $1.5L_p$; (c) $2L_p$; (d) $2.5L_p$; (e) $3L_p$.

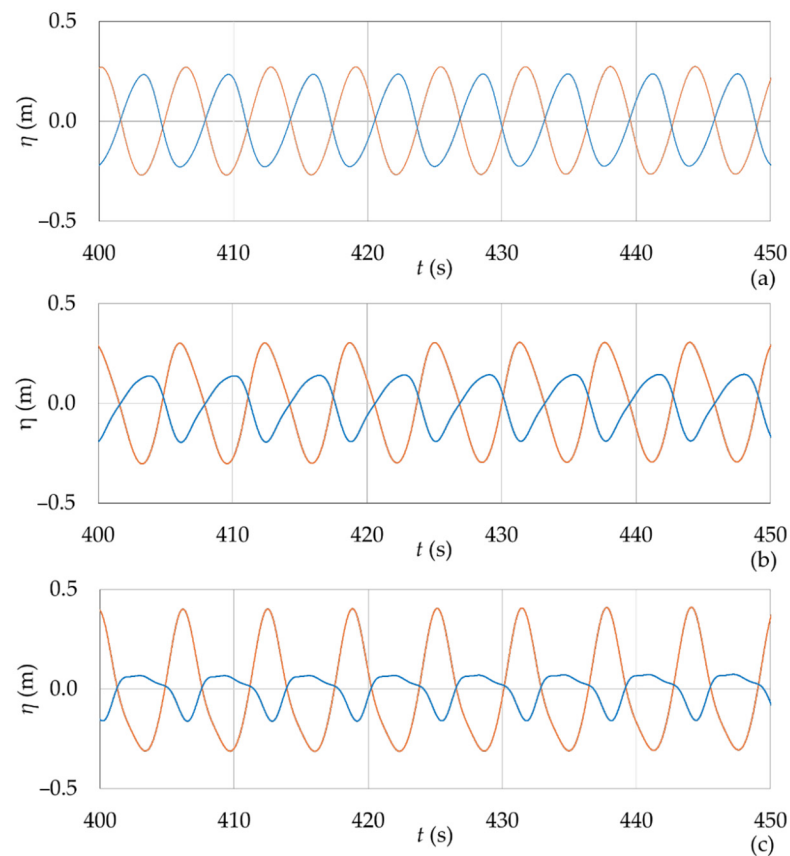


Figure 8. Cont.

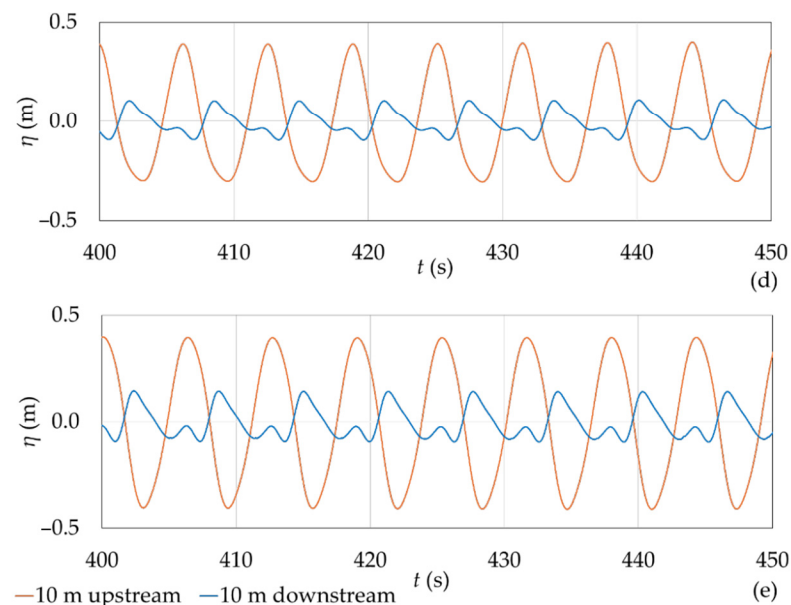


Figure 8. Highlight of the monitoring interval $400 \text{ s} < t < 450 \text{ s}$ for each case under representative regular waves in the 2ndF: (a) $1L_p$; (b) $1.5L_p$; (c) $2L_p$; (d) $2.5L_p$; (e) $3L_p$.

Qualitatively, Figures 7 and 8 indicate that the presence of the SHP modifies the hydrodynamic behavior of the representative regular waves, leading not only to a reduction in H_s but also to a phase shift between the signals monitored upstream and downstream of the device. Moreover, one can note that longer SHP configurations are more effective when operating as a BW, as they promote greater reductions in the wave height reaching the downstream region.

Table 8 presents the quantitative values of H_s monitored at different positions in the numerical wave flume for each simulated case.

Table 8. H_s values [m] for each case subjected to representative regular waves of the sea state in the 2ndF.

Case	10 m Upstream	10 m Downstream	Fixed Probe
$1L_p$	0.5488	0.4688	0.4628
$1.5L_p$	0.6238	0.3431	0.3242
$2L_p$	0.7435	0.2453	0.2456
$2.5L_p$	0.7375	0.2190	0.1866
$3L_p$	0.8351	0.2462	0.2359

By observing Figure 7 together with Table 9, which presents the H_s reduction downstream of the SHP, the $1L_p$ case had the lowest performance and the $3L_p$ case had the highest performance for the SHP when operating as a BW, with the best-performing case being 4.8 times higher than the worst one. Except for the $1L_p$ case, all others show performances above 40% for the SHP acting as a BW under representative regular waves of the sea state. Still in Table 9, it can be observed that the performance of the cases with the three largest L_p values are approximately similar (H_s reduction around 70%).

At the fixed probe, the $2.5L_p$ case presented the highest H_s reduction after the SHP. By comparing the H_s values at the fixed probe with the values 10 m downstream of the SHP for the $2.5L_p$ and $3L_p$ cases in Table 7; it is notable that both cases present a satisfactory reduction for the BW function. This means that, even though BW performance is evaluated through the comparison between the probes located 10 m upstream and 10 m downstream

of the SHP, the $2.5L_p$ case also presented interesting results regarding the reduction in waves reaching the coast.

Table 9. SHP-BW performance: Percentage reduction in H_s [m] for the downstream probes relative to the probe located 10 m upstream of the SHP, subjected to representative regular waves of the realistic sea state.

Case	10 m Downstream	Fixed Probe
$1L_p$	−14.6%	−15.7%
$1.5L_p$	−45.0%	−48.0%
$2L_p$	−67.0%	−67.0%
$2.5L_p$	−70.3%	−74.7%
$3L_p$	−70.5%	−71.6%

In turn, a good SHP device in the WEC function, in the present study, is the one with the highest axial velocity at the depths $z = 4.284$ m and $z = 5.236$ m (see Figure 6). The axial velocity results are compared using the maximum values of each case, which may occur at different instants of time.

Thus, for the SHP operating as a WEC, Figures 9 and 10 present the maximum axial velocity profiles along the depth monitored at $z = 4.284$ m and $z = 5.236$ m, respectively. Both velocity profiles show similar behavior, with low variation in velocities along the depth.

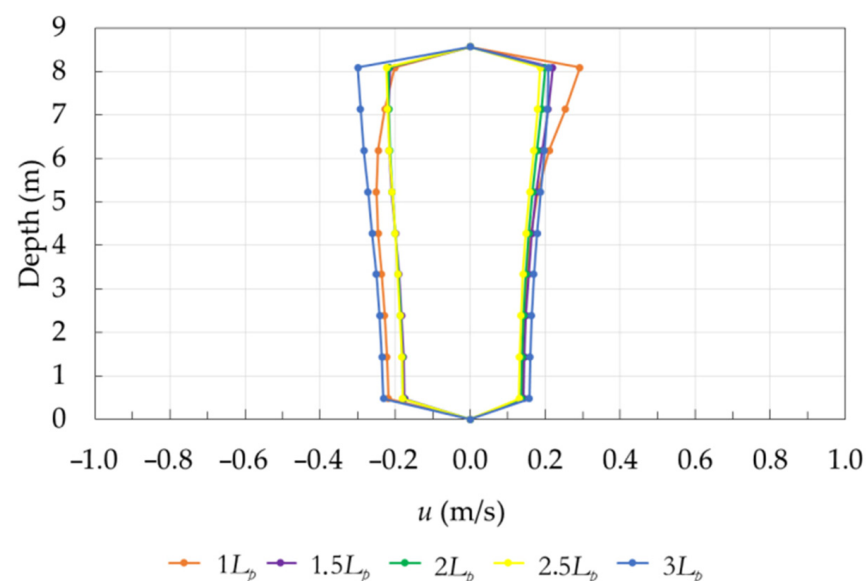


Figure 9. Profile of maximum axial velocities beneath the SHP for representative regular waves at different instants of time for monitoring at $z = 4.284$ m.

Tables 10 and 11 present the quantitative values considered to build the velocity profile shown in Figure 9, i.e., considering the maximum value determined at the point $z = 4.284$ m. From the discrete results, it can be observed that the $3L_p$ case presents the best performance as a WEC, i.e., the highest axial velocity. In any case, the $1L_p$ case shows values close to the best case, which is strongly supported by the numerical optimization study of the SHP as a WEC under regular waves performed by Seibt et al. [34]. The other three intermediate cases show a difference of almost 0.05 m/s in their maximum axial velocities at this point compared to the best-performing WEC case.

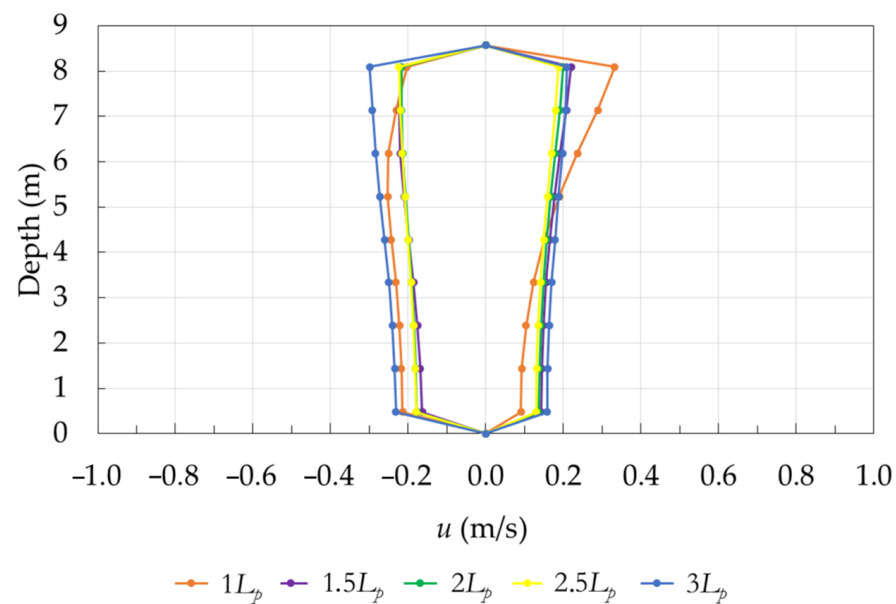


Figure 10. Profile of maximum axial velocities beneath the SHP for representative regular waves at different instants of time for monitoring at $z = 5.236$ m.

Table 10. Maximum negative axial velocity along the depth for each case subjected to representative regular waves (reference depth $z = 4.284$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	309.97	423.68	202.29	202.23	227.86
Depth (m)	Axial Velocity (m/s)				
0.000	0.000	0.000	0.000	0.000	0.000
0.476	−0.218	−0.175	−0.179	−0.180	−0.231
1.428	−0.222	−0.178	−0.181	−0.182	−0.235
2.380	−0.228	−0.183	−0.185	−0.186	−0.241
3.332	−0.236	−0.190	−0.192	−0.193	−0.250
4.284	−0.245	−0.199	−0.200	−0.200	−0.261
5.236	−0.250	−0.209	−0.208	−0.208	−0.273
6.188	−0.245	−0.216	−0.214	−0.216	−0.284
7.140	−0.227	−0.218	−0.217	−0.221	−0.292
8.092	−0.201	−0.214	−0.217	−0.223	−0.299
8.568	0.000	0.000	0.000	0.000	0.000

Table 11. Maximum positive axial velocity along the depth for each case subjected to representative regular waves (reference depth $z = 4.284$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	249.93	249.98	256.26	401.41	281.56
Depth (m)	Axial Velocity (m/s)				
0.000	0.000	0.000	0.000	0.000	0.000
0.476	0.140	0.142	0.137	0.131	0.158
1.428	0.141	0.144	0.138	0.132	0.160
2.380	0.146	0.149	0.142	0.135	0.164
3.332	0.152	0.155	0.148	0.141	0.170
4.284	0.163	0.165	0.157	0.149	0.178
5.236	0.181	0.177	0.167	0.159	0.188

Table 11. Cont.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	249.93	249.98	256.26	401.41	281.56
Depth (m)	Axial Velocity (m/s)				
6.188	0.211	0.192	0.179	0.170	0.198
7.140	0.254	0.208	0.191	0.180	0.206
8.092	0.293	0.220	0.200	0.187	0.209
8.568	0.000	0.000	0.000	0.000	0.000

Tables 12 and 13 provide the quantitative results used to plot the velocity profiles presented in Figure 10, i.e., taking into account the maximum value occurred at the point $z = 5.236$ m. It is possible to observe that the $3L_p$ case presents the best performance as a WEC. The behavior of similar values between the $1L_p$ and $3L_p$ cases is also repeated at this monitored point. As observed in the previous monitoring point, the other three intermediate cases show a significant reduction in their maximum axial velocities at this depth. Now, the $3L_p$ case stands out with a difference of 0.06 m/s, while the $1L_p$ case varies only 0.04 m/s compared to the worst cases, $2L_p$ and $2.5L_p$.

Table 12. Maximum negative axial velocity along the depth for each case subjected to representative regular waves (reference depth $z = 5.236$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	202.54	897.68	202.26	202.21	227.86
Depth (m)	Axial Velocity (m/s)				
0	0.000	0.000	0.000	0.000	0.000
0.476	−0.214	−0.164	−0.178	−0.180	−0.231
1.428	−0.217	−0.169	−0.181	−0.182	−0.235
2.380	−0.223	−0.176	−0.185	−0.186	−0.241
3.332	−0.232	−0.186	−0.192	−0.193	−0.250
4.284	−0.243	−0.198	−0.199	−0.200	−0.261
5.236	−0.253	−0.210	−0.208	−0.208	−0.273
6.188	−0.251	−0.220	−0.214	−0.216	−0.284
7.140	−0.231	−0.223	−0.218	−0.221	−0.292
8.092	−0.203	−0.218	−0.217	−0.223	−0.299
8.568	0.000	0.000	0.000	0.000	0.000

Table 13. Maximum positive axial velocity along the depth for each case subjected to representative regular waves (reference depth $z = 5.236$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	850.29	249.98	256.27	401.42	281.56
Depth (m)	Axial Velocity (m/s)				
0	0.000	0.000	0.000	0.000	0.000
0.476	0.090	0.142	0.137	0.131	0.158
1.428	0.093	0.144	0.138	0.132	0.160
2.380	0.104	0.149	0.142	0.135	0.164
3.332	0.123	0.155	0.148	0.141	0.170
4.284	0.152	0.165	0.157	0.149	0.178
5.236	0.189	0.177	0.167	0.159	0.188

Table 13. Cont.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	850.29	249.98	256.27	401.42	281.56
Depth (m)	Axial Velocity (m/s)				
6.188	0.237	0.192	0.179	0.170	0.198
7.140	0.288	0.208	0.191	0.180	0.206
8.092	0.333	0.220	0.200	0.187	0.209
8.568	0.000	0.000	0.000	0.000	0.000

By comparing the maximum axial velocities at the different analysis points for the best-performing WEC cases, i.e., $1L_p$ and $3L_p$, the second case consistently appears as the best WEC. In addition, the $3L_p$ case also presents the highest velocities in the wave propagation direction (positive). The decision to analyze a new depth point resulted in an increase of 0.01 m/s in the maximum axial velocity of the $3L_p$ case, and there was no difference in this parameter for the $1L_p$ case.

In agreement with the physical behavior of the SHP-WEC device observed in the experimental study by Orer and Ozdamar [33] and the numerical study by Seibt et al. [34], for simulations with regular waves, no positive velocity had a higher magnitude than the negative ones. This demonstrates that the dominant flow beneath the device occurs in the direction opposite to wave propagation.

Finally, seeking a version of the SHP under the combined BW and WEC function for representative regular wave incidence, the $3L_p$ case achieved the best results.

4.1.3. Second Formulation (2ndF)—Realistic Irregular Waves from the Sea State

In this subsection, the results of the 2ndF are discussed for the SHP operating as a BW, as a WEC, and under the combined BW and WEC assessment, subjected to realistic irregular waves from the sea state. These are the results of the present case study to be considered as a recommendation of the SHP for its different functions.

In Figure 11a–e, the free-surface elevations monitored 10 m upstream and 10 m downstream of the SHP subjected to irregular waves are presented for the entire simulation time. Figure 12 highlights the interval $400\text{ s} < t < 450\text{ s}$ for each case of Figure 11 (see the red dashed boxes), explicitly indicating the BW performance.

Based on the results from Figures 11 and 12, one can observe that, from a qualitative point of view, the presence of the SHP promotes a reduction in H_s , which increases as its length increases.

Table 14 presents the quantitative values H_s monitored at different positions along the numerical wave flume for each simulated case.

By observing Figure 11 together with the data in Table 15, which presents the percentage reduction in H_s downstream of the SHP, case $1L_p$ exhibited the lowest performance and case $3L_p$ the highest performance for the BW function. This is similar to the results obtained for the SHP operating as a BW under the incidence of representative regular waves. However, for the present results under realistic irregular wave incidence, no other case shows performance similar to case $3L_p$. The lowest performance is 5.5 times smaller than the best BW. All cases presented a reduction in H_s after the device, i.e., H_s at the fixed probe was lower than at the probe located 10 m downstream.

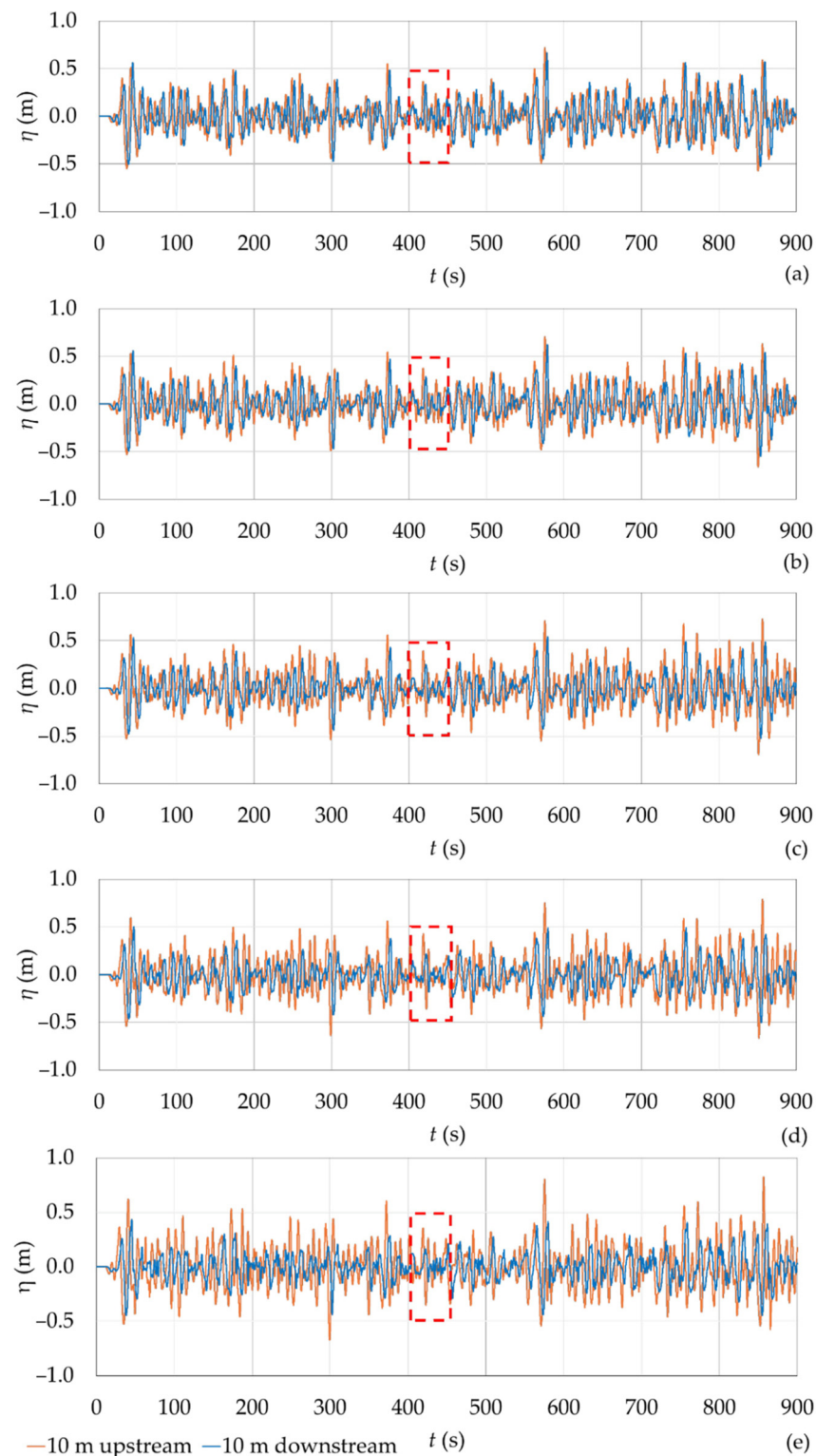


Figure 11. Evaluation of the SHP as a BW under the incidence of realistic irregular waves as a BW in the 2ndF: (a) $1L_p$; (b) $1.5L_p$; (c) $2L_p$; (d) $2.5L_p$; (e) $3L_p$.

By comparing the BW performances for regular and irregular waves (Tables 9 and 15, respectively), a significant reduction in the BW performance is observed for all cases under irregular waves. While the four largest cases under regular waves presented reductions in H_s higher than 45%, under irregular waves not even the best-performing case reached this value. For instance, case $3L_p$ exhibited a performance 1.7 times lower under irregular waves than under regular waves. The other cases under irregular waves showed reduc-

tions between 2 and 3.7 times compared to their own BW performances under regular wave incidence.

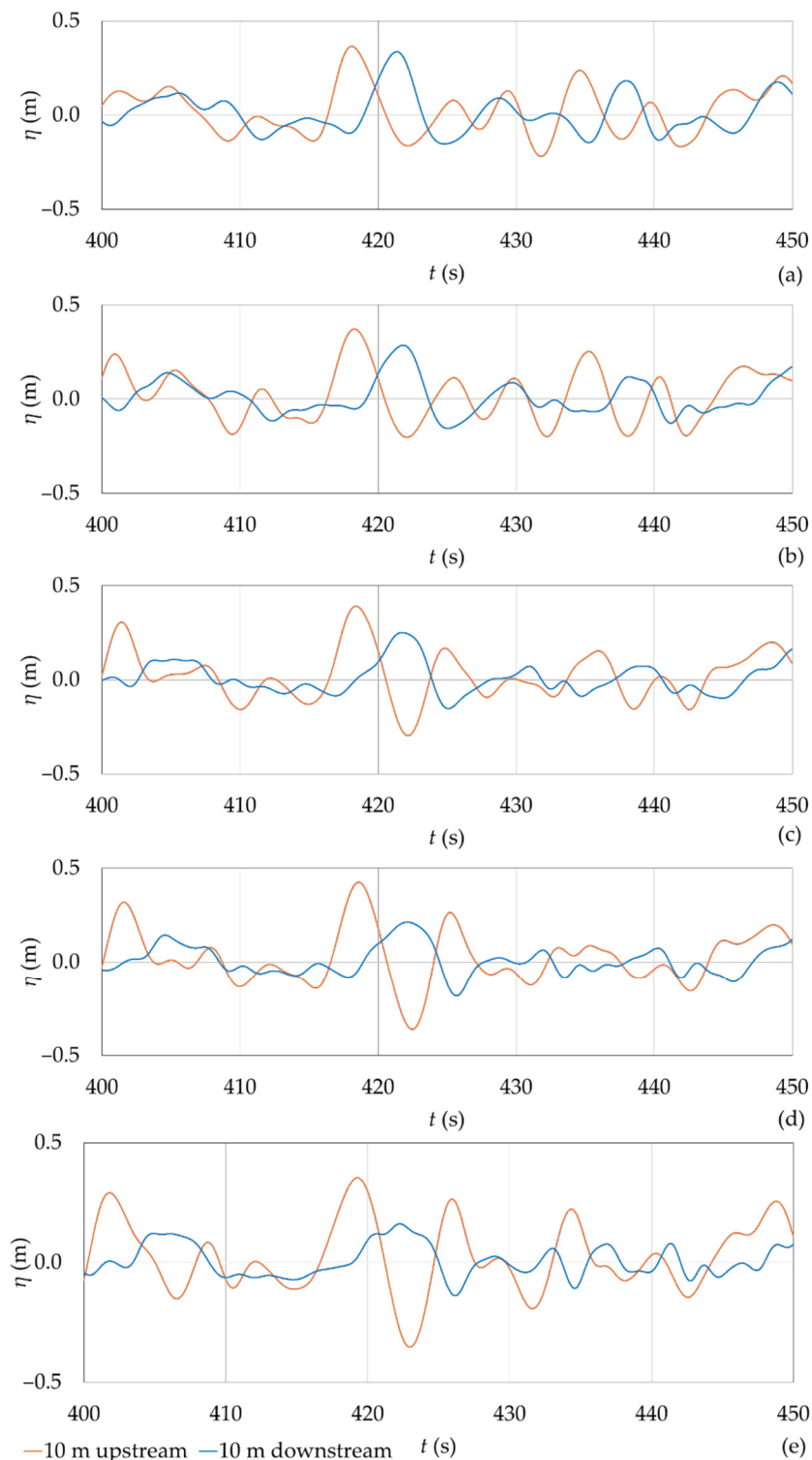


Figure 12. Highlight of the monitoring interval for $400 \text{ s} < t < 450 \text{ s}$ for each case: (a) $1L_p$; (b) $1.5L_p$; (c) $2L_p$; (d) $2.5L_p$; (e) $3L_p$.

This fact reinforces the need to address coastal protection devices through numerical studies considering realistic irregular waves. After all, this approach provides results that better reflect real sea state conditions than those obtained with representative regular waves.

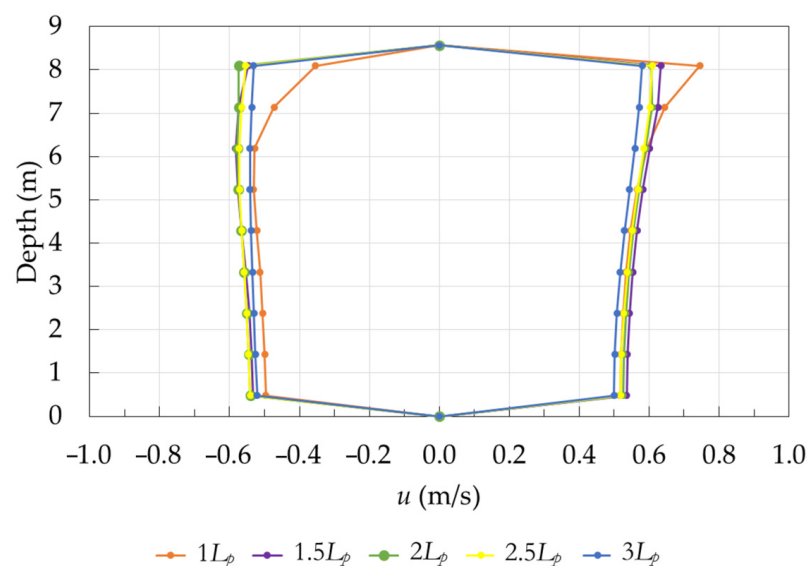
Table 14. H_s values [m] for each case subjected to realistic irregular waves of the sea state.

Case	10 m Upstream	10 m Downstream	Fixed Probe	NB Start
$1L_p$	0.6687	0.6210	0.6163	0.6287
$1.5L_p$	0.6977	0.6147	0.6011	0.6160
$2L_p$	0.7379	0.5390	0.5412	0.6014
$2.5L_p$	0.7828	0.5367	0.5257	0.5685
$3L_p$	0.7959	0.4823	0.4625	0.5128

Table 15. SHP-BW performance: Percentage reduction in H_s [m] between the downstream probes relative to the probe located 10 m upstream of the SHP subjected to realistic irregular waves from the sea state.

Case	10 m Downstream	Fixed Probe
$1L_p$	−7.1%	−7.8%
$1.5L_p$	−11.9%	−13.8%
$2L_p$	−22.9%	−26.7%
$2.5L_p$	−31.4%	−32.8%
$3L_p$	−39.4%	−41.9%

For the SHP operating as a WEC, Figures 13 and 14 present, respectively, the maximum axial velocity profiles along the water depth monitored at $z = 4.284$ m and $z = 5.236$ m, as in the analysis of representative regular waves. It is possible to note that both profiles show a similar behavior, with low variation in velocities along the water depth for each case. By comparing these SHP profiles under irregular wave incidence with the results for regular waves (Figures 9 and 10), it is evident that irregular waves yield significantly higher velocities throughout the entire depth. This reinforces the importance of considering a numerical generation wave approach closer to real sea conditions for SHP studies, since both the representative regular waves and the realistic irregular waves used in the analysis are derived from the same sea state.

**Figure 13.** Profile of maximum axial velocities beneath the SHP for realistic irregular waves at different time instants for monitoring at $z = 4.284$ m.

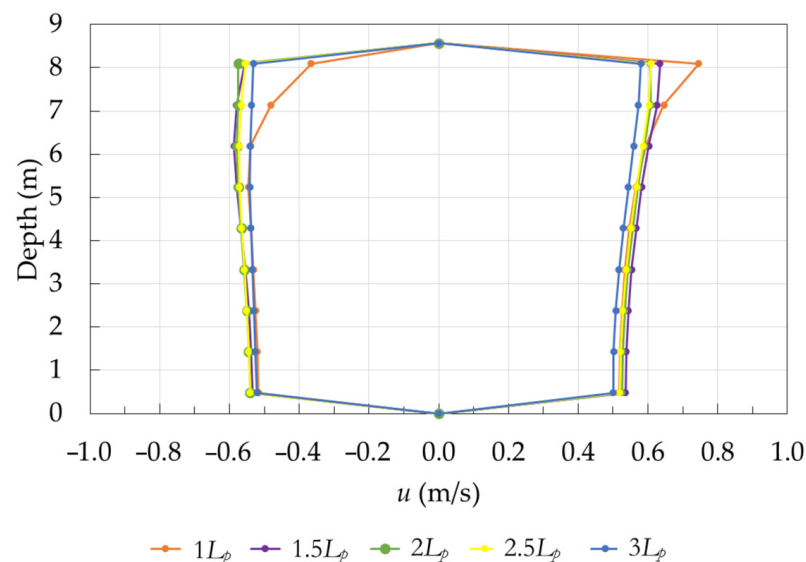


Figure 14. Profile of maximum axial velocities beneath the SHP for realistic irregular waves at different time instants for monitoring at $z = 5.236$ m.

Tables 16 and 17 present the quantitative values considered to build the velocity profile of Figure 13, i.e., considering the maximum value determined at $z = 4.284$ m. Case $2L_p$ presents the highest performance as a WEC for irregular waves, and case $2.5L_p$ reaches similar values. The lowest performance at this depth is observed for case $1L_p$. The performance pattern among the cases is also observed for the positive velocities at this depth, as shown in Table 17. All positive velocities are smaller than the maximum negative velocities, although with a small difference between their magnitudes. This behavior had already been identified for SHP-type devices subjected to regular wave incidence [33,34] and was also observed under irregular waves.

Table 16. Maximum negative axial velocity along the depth for each case subjected to realistic irregular waves (reference depth $z = 4.284$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	852.38	852.85	852.98	853.24	853.61
Depth (m)	Axial Velocity (m/s)				
0	0.000	0.000	0.000	0.000	0.000
0.476	−0.496	−0.518	−0.541	−0.541	−0.522
1.428	−0.499	−0.521	−0.545	−0.546	−0.526
2.380	−0.505	−0.526	−0.551	−0.551	−0.530
3.332	−0.513	−0.532	−0.558	−0.558	−0.535
4.284	−0.522	−0.539	−0.567	−0.565	−0.539
5.236	−0.531	−0.545	−0.575	−0.571	−0.542
6.188	−0.529	−0.539	−0.578	−0.572	−0.541
7.140	−0.472	−0.480	−0.573	−0.566	−0.536
8.092	−0.354	−0.366	−0.574	−0.554	−0.532
8.568	0.000	0.000	0.000	0.000	0.000

Tables 18 and 19 present the quantitative values considered to build the velocity profiles of Figure 14, i.e., considering the maximum value determined at $z = 5.236$ m. Case $1.5L_p$ presents the highest performance at this depth, and cases $2L_p$ and $2.5L_p$ show similar results. Case $3L_p$ presents the lowest performance as a WEC under realistic irregular wave incidence.

Table 17. Maximum positive axial velocity along the depth for each case subjected to realistic irregular waves (reference depth $z = 4.284$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	576.66	577.05	576.92	577.00	577.18
Depth (m)	Axial Velocity (m/s)				
0	0.000	0.000	0.000	0.000	0.000
0.476	0.491	0.518	0.525	0.519	0.500
1.428	0.493	0.520	0.528	0.521	0.502
2.380	0.499	0.525	0.534	0.527	0.508
3.332	0.508	0.534	0.543	0.537	0.517
4.284	0.521	0.547	0.556	0.551	0.530
5.236	0.541	0.565	0.571	0.567	0.544
6.188	0.572	0.593	0.590	0.585	0.559
7.140	0.628	0.645	0.609	0.602	0.572
8.092	0.718	0.745	0.605	0.609	0.580
8.568	0.000	0.000	0.000	0.000	0.000

Table 18. Maximum negative axial velocity along the depth for each case subjected to realistic irregular waves (reference depth $z = 5.236$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	852.8	852.68	852.94	853.2	853.6
Depth (m)	Axial Velocity (m/s)				
0	0.000	0.000	0.000	0.000	0.000
0.476	−0.517	−0.534	−0.540	−0.541	−0.522
1.428	−0.520	−0.538	−0.545	−0.545	−0.526
2.380	−0.525	−0.545	−0.550	−0.551	−0.530
3.332	−0.532	−0.555	−0.558	−0.558	−0.535
4.284	−0.539	−0.567	−0.567	−0.565	−0.539
5.236	−0.546	−0.579	−0.575	−0.571	−0.542
6.188	−0.539	−0.587	−0.579	−0.573	−0.541
7.140	−0.481	−0.580	−0.575	−0.567	−0.536
8.092	−0.366	−0.557	−0.575	−0.556	−0.532
8.568	0.000	0.000	0.000	0.000	0.000

Table 19. Maximum positive axial velocity along the depth for each case subjected to realistic irregular waves (reference depth $z = 5.236$ m).

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
Time Instant (s)	577.03	576.81	576.9	576.98	577.18
Depth (m)	Axial Velocity (m/s)				
0	0.000	0.000	0.000	0.000	0.000
0.476	0.517	0.535	0.525	0.519	0.500
1.428	0.520	0.538	0.527	0.521	0.502
2.380	0.525	0.544	0.533	0.527	0.508
3.332	0.534	0.553	0.543	0.537	0.517
4.284	0.547	0.566	0.556	0.551	0.530
5.236	0.565	0.582	0.572	0.567	0.544
6.188	0.593	0.602	0.590	0.586	0.559
7.140	0.645	0.626	0.609	0.603	0.572
8.092	0.745	0.634	0.606	0.609	0.580
8.568	0.000	0.000	0.000	0.000	0.000

In Table 19, the case with the highest axial velocity in the direction of wave propagation is $2.5L_p$, followed by $2L_p$ with similar values. A discussion point regarding the results obtained in this monitoring is that, in the negative direction, the best-performing case was $1.5L_p$. However, for the positive velocity values, this case is not even among the best cases. In addition, the positive velocities are not smaller than the negative ones for the present cases under realistic irregular wave incidence. This result raises concerns regarding the physical principle that, until this point, has been reported in the literature as the maximum values occurring in the negative direction for $z = h_p/2$ [33,34].

It is important to note, however, that this analysis was not conducted at the central depth ($z = h_p/2$), but rather at $z = 5.236$ m. Therefore, the difference in the observed behavior may be associated with the change in the monitoring position, since the axial velocity profile varies along the vertical direction. In this sense, the lack of a clear predominance of negative velocities at this depth does not necessarily contradict the literature, but instead reflects the influence of evaluating a different vertical location under irregular wave conditions.

Therefore, the differences between the positive and negative values were calculated for each case at the depth $z = 5.236$ m. The highest difference between these velocities for a given case was found to be 0.01 m/s. This value is considered insignificant and does not compromise the quality and physical coherence of the results obtained and analyzed for the SHP under irregular wave incidence.

This interpretation is supported by the premise that the studies mentioning the hydrodynamic characteristic of the axial velocity being higher in the negative direction are studies of the SHP under regular wave incidence. To the present authors' knowledge, there is no other study assessing this SHP parameter under realistic irregular waves. Therefore, the possibility that this premise changes for the SHP under irregular waves cannot be ruled out.

For the incidence of realistic irregular waves, the SHP operating as a WEC achieved its highest performance for case $2L_p$ at the depth $z = 4.284$ m, and for case $2.5L_p$ at the depth $z = 5.236$ m.

Finally, seeking a SHP configuration that performs well under the combined BW and WEC assessment for realistic irregular wave incidence, case $2.5L_p$ is the most recommended, since it is the second best-performing case both as a BW and as a WEC. It is also a case that presents maximum axial velocities with very similar values at both depths $z = 4.284$ m and $z = 5.236$ m.

4.2. Integral Analysis of the 2ndF Results

Another way to analyze the 2ndF results for the SHP operating as a BW and as a WEC is by integrating the time series over the entire simulation time interval, as proposed in Motta et al. [25,39]. This approach provides an alternative and more comprehensive perspective for evaluating the SHP hydrodynamics, as it considers the full temporal evolution of the monitored signal. When analyzing the SHP as a BW, the significant wave height (H_s) approach earlier adopted is based only on the upper third of the wave heights, which may limit its ability to capture the overall flow behavior, particularly under irregular wave conditions. In turn, for the SHP as a WEC only the maximum instantaneous velocity magnitude was considered in the previous evaluation. In the integral analysis, for the BW function, the free-surface elevation curves (without the plate) presented in Figures 1 and 2 were integrated over time ($I_{\eta wSHP}$) and compared with the free-surface elevation integral evaluated at 10 m downstream for each case ($I_{\eta i}$); while for the WEC function, the axial velocities beneath the SHP, at the point $z = 4.284$ m, are integrated over time (I_{ui}) and their resulting areas are compared relative to the reference case $1L_p$ (I_{u1Lp}).

4.2.1. Representative Regular Waves

For representative regular waves, the free-surface elevation curves integrated correspond to those shown in Figure 1 ($I_{\eta wSHP}$) and Figure 7 ($I_{\eta i}$). The results are summarized in Table 20, where the first row presents the integrated values for each case (in area units). For Figure 1, a value of $I_{\eta wSHP} = 211.43 \text{ m}\cdot\text{s}$ was obtained, representing the area under the free-surface elevation curve without the presence of the plate. This value is used in the second row of Table 20, where the expression $(1 - I_{\eta i} / I_{\eta wSHP}) \cdot 100$ indicates the percentage reduction in area due to the insertion of the SHP, thus directly quantifying the device performance as a BW.

Table 20. Integrated free-surface elevation values and area reduction for SHP performance assessment under representative regular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
$I_{\eta i} [\text{m}\cdot\text{s}]$	130.54	89.79	58.20	46.89	66.63
$(1 - I_{\eta i} / I_{\eta wSHP}) \cdot 100 [\%]$	38.26	57.53	72.47	77.82	68.48

According to the results in Table 20, all other cases present a higher wave height reduction than case $1L_p$. The $2L_p$, $2.5L_p$, and $3L_p$ exhibit the best performance, with the $2.5L_p$ configuration achieving the highest reduction among all cases.

It is possible to visualize in Figure 15 the higher retention in case $3L_p$ compared to case $1L_p$. Thus, it is identified that the increase in BW performance (reduction in H_s) is related to wave reflection due to the presence of the SHP.

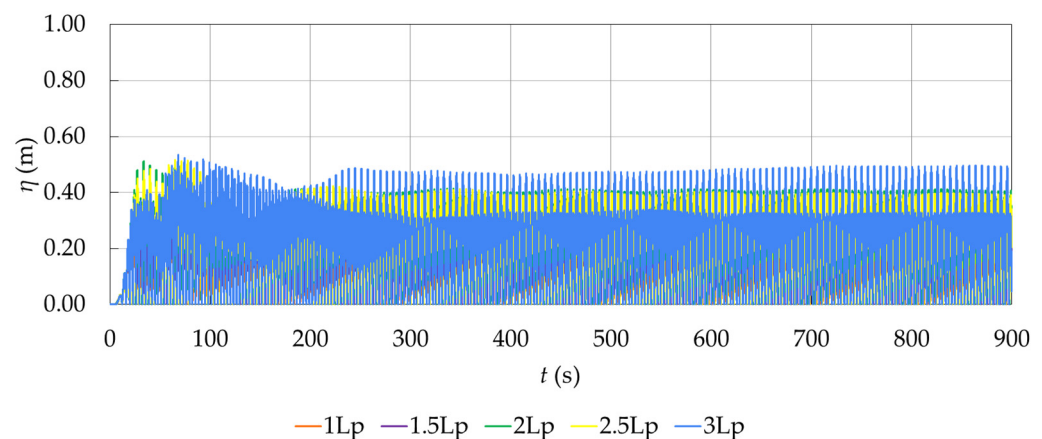


Figure 15. Absolute free-surface elevation curves for the probe located 10 m upstream of the SHP under representative regular waves.

The integral analysis of the SHP operating as a WEC under the incidence of representative regular waves from the sea state expanded the understanding of the pulsating effect beneath the device and the comparison of mean axial velocity values over time.

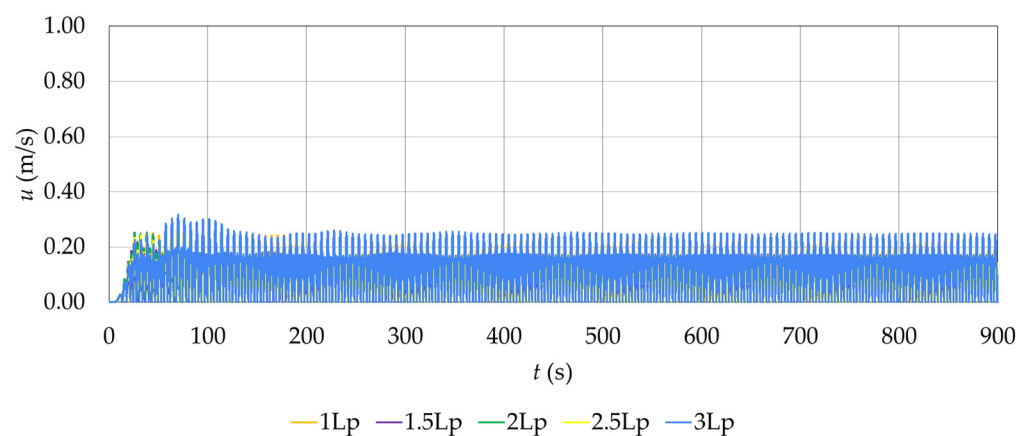
A best-performing WEC is one that presents high axial velocity beneath the device, with the capability to rotate a turbine and generate electrical energy. The best-performing case, according to Table 21, is case $3L_p$. The integrated area of the velocity curve for the best case is very similar to case $1L_p$. In general, although there is variation among the cases, it does not exceed 20% for representative regular waves. This demonstrates the impact on the SHP performance as a WEC due to the L_p length. However, this dependence is less significant than the impacts of varying the five L_p cases for the BW function.

Table 21. Area and proportion of the area of each case in comparison to the reference case $1L_p$, for monitoring the axial velocity beneath the SHP at $z = 4.284$ m under representative regular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
I_{ui} [m]	116.13	102.54	99.29	96.72	117.85
I_{ui}/I_{u1Lp}	1.00	0.88	0.85	0.83	1.01

The pulsating effect of axial velocity over time, observed in experimental studies [33] and numerical studies with wave generation without the WaveMIMO methodology [34], is also visible in this integral analysis method. Therefore, this is another indication that the computational model is aligned with the real physical principles of the device.

Figure 16 presents the absolute curves of axial velocities over time for all cases. It is highlighted that the areas of cases $1.5L_p$, $2L_p$, and $2.5L_p$ are similar and stabilize after 200 s.

**Figure 16.** Absolute axial velocity curves over time for representative regular waves.

4.2.2. Realistic Irregular Waves

For realistic irregular waves from the sea state, the free-surface elevations that were integrated are those presented in Figures 2 and 11. The results of this methodology are presented in Table 22. For Figure 2, a value of $I_{\eta wSHP} = 127.8992$ m·s was obtained.

Table 22. Integrated free-surface elevation values and area reduction for SHP performance assessment under realistic irregular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
$I_{\eta i}$ [m·s]	113.30	107.11	100.95	96.68	87.01
$(1 - I_{\eta i}/I_{\eta wSHP}) \cdot 100$ [%]	11.41	16.25	21.07	24.41	31.97

According to the results in Table 22 and Figure 17, all cases present a higher wave height reduction than case $1L_p$. Similarly to the results obtained with representative regular waves, cases $2L_p$, $2.5L_p$, and $3L_p$ showed the highest area reduction. However, here the best one is the $3L_p$. One can observe that the differences among the cases occur mainly in the velocity peaks, while the intermediate values are closer (see Figure 17).

Regarding the SHP operating as a WEC, there is little variation in the axial velocity integral area among the cases, with the highest difference being only 3%. Based on the data in Table 23, it can be interpreted that, for realistic irregular waves, the mean axial velocity, or the velocity behavior over time, was not influenced by the SHP length.

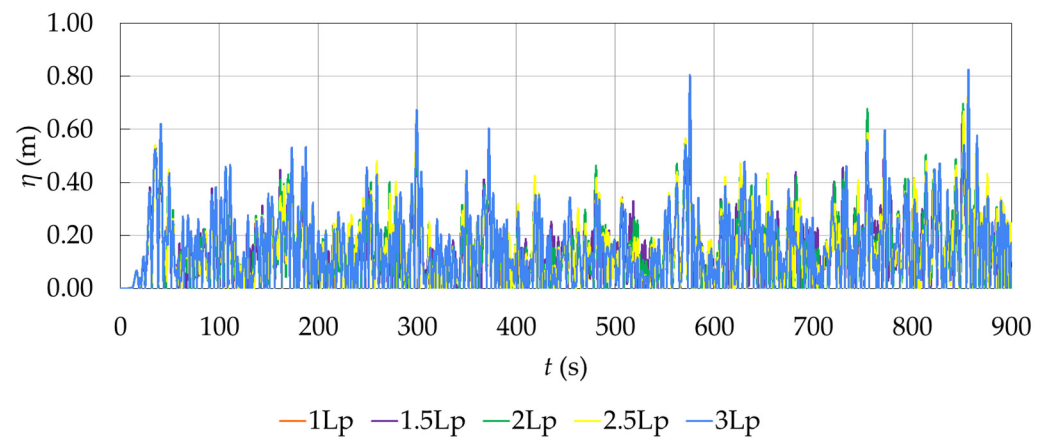


Figure 17. Absolute free-surface elevation curves for the probe located 10 m upstream of the SHP under realistic irregular waves.

Table 23. Area and proportion of the area of each case in comparison to the reference case $1L_p$, for monitoring the axial velocity beneath the SHP at $z = 4.284$ m under realistic irregular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
I_{ui} [m]	109.95	109.95	111.07	112.89	111.26
I_{ui}/I_{u1Lp}	1.00	1.00	1.01	1.03	1.01

Figure 18 presents the absolute axial velocity curves beneath the SHP. It is possible to observe that the curves show a high degree of similarity, which is consistent with the nearly identical values obtained.

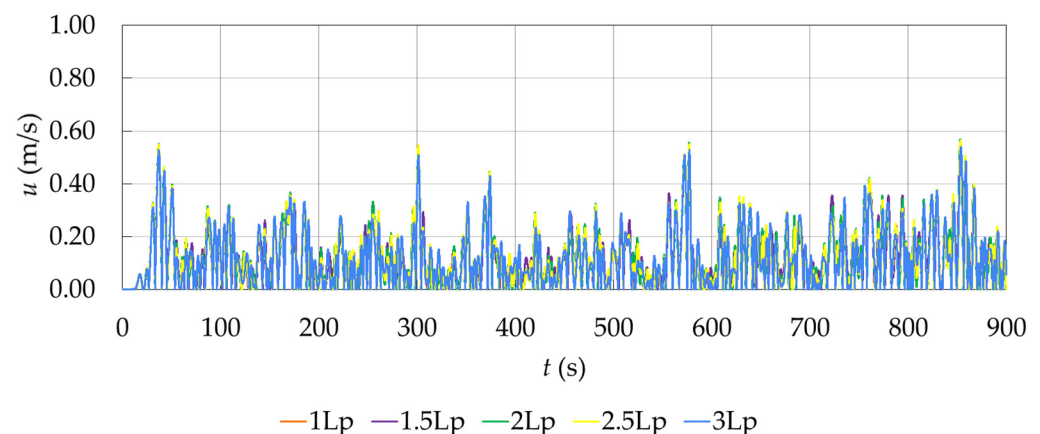


Figure 18. Absolute axial velocity curves over time for realistic irregular waves.

4.3. Integral Comparison Between the 1stF and 2ndF Results

In this section, the results obtained from the 1stF and 2ndF approaches are compared through the integrals presented in Section 4.2 (corresponding to the 2ndF), alongside their respective counterparts computed using the 1stF [24]. The RPE was used to quantitatively assess the discrepancies between both methodologies, adopting the results of the 1stF as reference.

It is important to highlight that in Thum et al. [24] the analysis by the integral approach was not carried out, being a complementation for the 1stF developed in the present work.

Table 24 presents the values of $I_{\eta i}$ obtained from the 1stF and 2ndF for the representative regular waves, as well as the corresponding RPE for each case. In general, good agreement is observed for the $1L_p$, $1.5L_p$, and $2L_p$ cases, with RPE below 1.3%. However,

larger differences are observed for the $2.5L_p$ and $3L_p$ cases, with RPE of approximately 12% in magnitude. This indicates that the influence of the NB position on η is not negligible and may become more pronounced for larger plate lengths.

Table 24. $I_{\eta i}$ values obtained from the 1stF and 2ndF approaches and corresponding RPE for representative regular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
1stF $I_{\eta i}$ [m·s]	129.94	88.71	57.99	53.80	59.25
2ndF $I_{\eta i}$ [m·s]	130.54	89.79	58.20	46.89	66.63
RPE [%]	0.46	1.2	0.36	−12.84	12.46

Table 25 presents the values of u_i for the same set of representative regular waves. In addition to the $2.5L_p$ case (RPE = −9.94%), the $3L_p$ case also exhibited a relatively higher absolute difference (RPE = −3.56%).

Table 25. I_{ui} values obtained from the 1stF and 2ndF approaches and corresponding RPE for representative regular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
1stF I_{ui} [m]	115.78	101.53	100.18	107.39	122.20
2ndF I_{ui} [m]	116.13	102.54	99.29	96.72	117.85
RPE [%]	0.30	0.99	−0.89	−9.94	−3.56

Table 26 presents the $I_{\eta i}$ values for the realistic irregular waves. In this case, a more significant influence of the NB position is observed across all configurations, with the largest discrepancy occurring for the $3L_p$ case (RPE = −8.71%).

Table 26. $I_{\eta i}$ values obtained from the 1stF and 2ndF approaches and corresponding RPE for realistic irregular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
1stF $I_{\eta i}$ [m·s]	114.83	108.66	103.96	99.63	95.31
2ndF $I_{\eta i}$ [m·s]	113.30	107.11	100.95	96.68	87.01
RPE [%]	−1.33	−1.43	−2.90	−2.96	−8.71

Finally, Table 27 shows the I_{ui} values for the realistic irregular waves. Similarly to the behavior observed for I_{η} , in a general way, higher RPE values are found for all cases when compared to the regular wave conditions. Moreover, the average RPE for I_{ui} is higher than that observed for I_{η} , indicating that NB positioning has a stronger effect on the axial velocity beneath the plate than on the η .

Table 27. I_{ui} values obtained from the 1stF and 2ndF approaches and corresponding RPE for realistic irregular waves.

Case	$1L_p$	$1.5L_p$	$2L_p$	$2.5L_p$	$3L_p$
1stF I_{ui} [m]	115.97	115.33	116.68	119.17	121.41
2ndF I_{ui} [m]	109.95	109.95	111.07	112.89	111.26
RPE [%]	−5.19	−4.66	−4.81	−5.27	−8.36

4.4. Influence of Incident-Wave Representation on SHP Hydrodynamic Assessment

The differences observed between representative regular waves and realistic irregular waves should be interpreted within the limits of the present Rio Grande sea state,

SHP geometry, two-dimensional numerical model, and adopted hydrodynamic indicators. Nevertheless, this behavior is consistent with previous studies showing that regular-wave representations may lead to hydrodynamic responses different from those obtained under irregular-wave conditions. In the specific context of SHP devices, Motta et al. [25] showed that the recommended configuration of a submerged plate operating as a BW-WEC system may depend on whether representative regular waves or realistic irregular sea-state waves are considered. Similar differences have also been reported in other WEC and wave–structure interaction problems. Zang et al. [66] experimentally investigated a heaving-buoy WEC with PTO damping and showed that its hydrodynamic response and capture-width ratio depend on whether regular or irregular waves are considered. Wu et al. [67] performed flume experiments on a two-body WEC with hydraulic PTO damping under both regular and irregular waves, reporting different relative heave responses and capture-width ratios depending on wave condition and external load. Zhang et al. [68] investigated a triple-cylinder bundle structure and observed that regular and irregular waves can lead to different mechanical responses. In addition, Wang et al. [69] demonstrated that wave attenuation trends under irregular waves may differ from those inferred from regular-wave conditions in floating sea–ice interaction problems. Therefore, the present findings should not be interpreted as a universal statement that regular waves are always insufficient, but rather as further evidence that, for sea-state-dependent wave–structure interaction problems, realistic irregular-wave simulations can provide complementary and sometimes substantially different hydrodynamic information.

4.5. Summary of the Best-Performing SHP Configurations

Due to the different assessment criteria adopted in this study, the identification of the best-performing SHP configuration depends on the considered function, incident-wave approach, monitoring position, and post-processing methodology. Therefore, Table 28 summarizes the recommended SHP configurations according to the conventional H_s -based and u_{max} -based indicators and to the integral-based indicators. This synthesis improves the readability of the results and clarifies that the optimal configuration may change depending on whether the SHP is assessed as a BW, as a WEC-related hydrodynamic device, or as a combined BW-WEC system.

Table 28. Summary of the best-performing SHP configurations according to each assessment criterion.

Assessment Approach	Criterion	Representative Regular Waves	Realistic Irregular Waves
Conventional BW assessment	Highest reduction in H_s downstream of the SHP	$3L_p$ at 10 m downstream; $2.5L_p$ at the fixed probe	$3L_p$
Conventional WEC-related assessment	Highest maximum axial velocity beneath the SHP, u_{max}	$3L_p$, with $1L_p$ showing similar values	$2L_p$, with $2.5L_p$ showing similar values, at $z = 4.284$ m; $1.5L_p$ at $z = 5.236$ m
Conventional combined BW-WEC assessment	Best compromise between H_s reduction and maximum axial velocity	$3L_p$	$2.5L_p$
Integral BW assessment	Highest reduction in integrated downstream free-surface elevation, $I_{\eta i}$	$2.5L_p$	$3L_p$
Integral WEC-related assessment	Highest integrated axial velocity, I_{ui}	$3L_p$, very close to $1L_p$	$2.5L_p$, with weak dependence on L_p
Integral combined BW-WEC assessment	Best compromise between $I_{\eta i}$ reduction and I_{ui}	$2.5L_p$ for BW-dominant assessment; $3L_p$ for WEC-dominant assessment	$3L_p$ for BW-dominant assessment; $2.5L_p$ for WEC-dominant assessment

5. Conclusions

This numerical study investigated the hydrodynamic response of a submerged horizontal plate (SHP) with different lengths under representative regular waves and realistic irregular waves associated with the sea state observed in 2014 off the coast of Rio Grande, southern Brazil. The SHP was assessed according to its performance as a breakwater (BW), as a wave energy converter (WEC), and as a combined BW-WEC device, using the WaveMIMO methodology to generate the incident wave conditions.

Based on the research questions proposed in the Introduction, the main findings of this study can be summarized as follows: (i) the comparison between the 1stF and 2ndF showed that the downstream computational-domain configuration, including the relative SHP–NB spacing, the effective outlet distance, and the wave travel path before the damping region, affects the computed hydrodynamic response, particularly in downstream measurements, where the absorbing region may influence the monitored wave field; (ii) this effect was more pronounced under realistic irregular waves, whereas representative regular waves showed smaller differences between the two formulations; (iii) the 2ndF, which maintains a constant 1λ distance between the downstream edge of the SHP and the beginning of the NB, provided a more controlled computational-domain configuration and reduced possible interference from the damping region on the monitored results; and (iv) the integral-based analysis of free-surface elevation and axial velocity provided a complementary interpretation of the SHP performance, supporting the comparative assessment of the device as a BW, as a WEC, and as a combined BW-WEC system.

The comparison showed that the downstream computational-domain configuration had a limited influence under representative regular waves, with a maximum difference of 1.2% in the H_s reduction. However, under realistic irregular waves, this influence reached 5.9%, especially affecting the fixed downstream probe. These results indicate that the relative SHP–NB spacing, effective outlet distance, and wave travel path before the damping region should be carefully defined to avoid artificial interference in the monitoring of wave attenuation and flow behavior.

For the BW function, the $3L_p$ case presented the best performance under both incident-wave approaches, producing the greatest reduction in significant wave height downstream of the device. However, for the tested Rio Grande sea state, SHP geometry, two-dimensional numerical model, and adopted hydrodynamic indicators, the performance obtained under realistic irregular waves was lower than that obtained under representative regular waves. This reinforces that representative regular waves alone were not sufficient to reproduce the hydrodynamic trends observed under realistic irregular waves within the scope of the present study.

For the WEC function, the best-performing configuration depended on the incident-wave approach and on the monitored depth. Under representative regular waves, the $3L_p$ case presented the highest axial velocity beneath the plate, while the $1L_p$ case showed similar results. Under realistic irregular waves, the highest axial velocities were obtained for the $2L_p$ and $2.5L_p$ cases at $z = 4.284$ m and for the $1.5L_p$ case at $z = 5.236$ m. Therefore, within the tested conditions and adopted WEC-related hydrodynamic indicators, the optimal SHP length for energy-conversion potential cannot be defined from regular-wave simulations alone. However, the axial-velocity results should be interpreted as hydrodynamic indicators of energy-conversion potential, not as direct estimates of extracted power, electrical energy yield, or overall WEC efficiency.

In the combined BW-WEC assessment, the $3L_p$ case provided the best performance under representative regular waves, whereas the $2.5L_p$ case achieved the best result under realistic irregular waves. The integral-based analysis of free-surface elevation and axial velocity confirmed the sensitivity of the SHP response to both wave irregularity and the

downstream computational-domain configuration, particularly for larger plate lengths and for axial velocity under irregular waves.

Overall, within the tested Rio Grande sea state, SHP geometry, two-dimensional numerical model, and adopted hydrodynamic indicators, the results indicate that realistic irregular waves should be considered when evaluating SHP devices, especially when the objective is to identify configurations suitable for simultaneous coastal protection and wave-energy conversion. The proposed 2ndF computational domain provides a more controlled configuration for this type of comparative hydrodynamic analysis.

Based on these findings, it can be stated that the influence of the downstream computational-domain configuration, including NB positioning, was limited under representative regular waves, for which only small variations were observed between the 1stF and 2ndF. However, more noticeable differences were obtained under realistic irregular waves, especially in the downstream significant wave height and in the integral-based hydrodynamic indicators. Therefore, this combined domain-configuration effect of NB positioning should be interpreted as more relevant for irregular-wave simulations than for representative regular-wave cases.

From a methodological perspective, the results indicate that the downstream computational-domain configuration should be explicitly defined, justified, and reported in CFD wave-flume simulations, including the relative distance between the downstream edge of the SHP and the beginning of the NB, the effective outlet distance, and the wave travel path before the damping region, since these numerical-domain parameters may affect downstream hydrodynamic indicators.

Finally, future studies are recommended to further deepen the analysis of SHP hydrodynamics, especially under realistic irregular wave conditions. These future works can be grouped into the following thematic directions:

- Geometric parameters and SHP configuration:

Future studies should expand the range of L_p and L_p/λ values, including larger relative plate lengths, to verify the robustness of the velocity patterns observed in the present study. The influence of the plate thickness t_p should also be evaluated under irregular waves, especially regarding wave reflection and BW performance.

- Incident wave conditions and sea-state variability:

Further investigations should assess different realistic sea states to verify whether the hydrodynamic behavior observed here remains consistent under a broader range of wave conditions. Additional spectral and statistical analyses of the irregular-wave signals along the flume should also be performed, including spectral-shape preservation, phase dispersion, peak distribution, and comparisons between incident, upstream, downstream, and NB-start probes.

- Numerical beach modeling and computational-domain effects:

Future studies should investigate different NB lengths, damping coefficients, damping configurations, and alternative absorbing-boundary techniques. The NB performance should be quantified through reflection and transmission coefficients, absorption-efficiency indicators, formal decomposition of the wave field into incident, reflected, and transmitted components, and wave-energy balance analyses. These evaluations would support more robust computational-domain recommendations for SHP simulations. In addition, future analyses should be designed to decouple the individual effects of NB starting position, total flume length, effective outlet distance, and wave travel path before the damping region.

- Turbine, PTO, and energy-conversion modeling:

The axial-velocity-based indicator adopted here should be extended toward a direct assessment of extracted power, electrical energy yield, and overall WEC efficiency. For this purpose, future studies should include turbine or PTO modeling beneath the SHP, considering turbine type, installation height, effective flow-passage area, pressure field, pressure drop, flow reversal, energy-flux calculation, PTO characteristics, and electromechanical efficiency.

- Advanced numerical, structural, and experimental modeling:

Future works should assess the influence of turbulence models, higher-order discretization schemes, mesh and time-step sensitivity, CFL constraints, solver convergence criteria, boundary-condition sensitivity, and numerical uncertainty bounds. Three-dimensional numerical and experimental models should also be developed to investigate wave diffraction, edge effects, spanwise flow structures, fastening elements, structural loads, installation aspects, and multiple SHP units under uni- and bi-directional waves.

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Abbreviations

The following abbreviations are used in this manuscript:

GMSL	Global mean sea level
BW	Breakwater
WEC	Wave energy converters
SHP	Submerged horizontal plate
NB	Numerical Beach
C_r	Reflection coefficient
C_t	Transmission coefficient
WCSPH	Weakly Compressible Smoothed Particle Hydrodynamics
CFD	Computational Fluid Dynamics
MPS	Moving Particle Semi-implicit
λ	Wavelength [m]

H_s	Significant wave height [m]
T_m	Mean wave period [s]
η	Free-surface elevation [m]
u	Wave horizontal velocity component [m/s]
w	Wave vertical velocity component [m/s]
FVM	Finite Volume Method
ρ	Fluid density [kg/m ³]
v	Velocity vector [m/s]
p	Pressure [Pa]
$\bar{\bar{\epsilon}}$	Deformation tensor [N/m ²]
$\vec{S}$	Damping sink term [N/m ³]
VOF	Volume of Fluid
α	Volume fraction
H_c	Wave flume height [m]
L_c	Wave flume length [m]
d	Water depth [m]
X_p	Horizontal distance from the inlet to the beginning of the SHP [m]
L_p	SHP length [m]
h_p	SHP submergence depth [m]
t_p	SHP thickness [m]
L_{nb}	Numerical beach length [m]
C1	Linear damping coefficient [s ⁻¹]
C2	Quadratic damping coefficient [m ⁻¹]
V	Velocity [m/s]
z_η	Vertical position of the free-surface [m]
z_b	Vertical position of the bottom [m]
x_s	Horizontal position of the beginning of the numerical beach region [m]
x_e	Horizontal position of the end of the numerical beach region [m]
PRESTO	Pressure staggering option
PISO	Pressure-Implicit Splitting of Operators
MAE	Mean Absolute Error
RMSE	Root Mean Square Error
RPE	Relative Percentage Error
PS	Result of the present study used for comparison
R	Reference value used for comparison
n	Sample size of the dataset considered
I_η	Integral of free surface elevation [m·s]
I_u	Integral of axial velocity [m]
t	Time [s]
1stF	First formulation of the computational domain
2ndF	Second formulation of the computational domain

References

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed.; Cambridge University Press: Cambridge, UK, 2023.
2. NASA. NASA Analysis Shows Unexpected Amount of Sea Level Rise in 2024. 2025. Available online: <https://www.nasa.gov/missions/jason-cs-sentinel-6/sentinel-6-michael-freilich/nasa-analysis-shows-unexpected-amount-of-sea-level-rise-in-2024/> (accessed on 8 June 2026).
3. NASA. As Sea Level Rises, Beaches Shrink 2003. Available online: <https://www.jpl.nasa.gov/news/as-sea-level-rises-beaches-shrink/> (accessed on 8 June 2026).
4. Saengsupavanich, C.; Ariffin, E.H.; Yun, L.S.; Pereira, D.A. Environmental Impact of Submerged and Emerged Breakwaters. *Heliyon* **2022**, *8*, e12626. [CrossRef]
5. International Energy Agency. *International Energy Agency Renewables 2025*; International Energy Agency: Paris, France, 2025.

6. Reguero, B.G.; Losada, I.J.; Méndez, F.J. A Global Wave Power Resource and Its Seasonal, Interannual and Long-Term Variability. *Appl. Energy* **2015**, *148*, 366–380. [\[CrossRef\]](#)
7. Gunn, K.; Stock-Williams, C. Quantifying the Global Wave Power Resource. *Renew. Energy* **2012**, *44*, 296–304. [\[CrossRef\]](#)
8. 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: Volume 3*; ASMEDC: Shanghai, China, 2010; pp. 447–454.
9. Anglivié de La Beaumelle, N.; Blok, K.; de Chalendar, J.A.; Clarke, L.; Hahmann, A.N.; Huster, J.; Nemet, G.F.; Suri, D.; Wild, T.B.; Azevedo, I.M.L. The Global Technical, Economic, and Feasible Potential of Renewable Electricity. *Annu. Rev. Environ. Resour.* **2023**, *48*, 419–449. [\[CrossRef\]](#)
10. Ulazia, A.; Saenz-Aguirre, A.; Ibarra-Berastegui, G.; Sáenz, J.; Carreno-Madinabeitia, S.; Esnaola, G. Performance Variations of Wave Energy Converters Due to Global Long-Term Wave Period Change (1900–2010). *Energy* **2023**, *268*, 126632. [\[CrossRef\]](#)
11. Rusu, L.; Rusu, E. Evaluation of the Worldwide Wave Energy Distribution Based on ERA5 Data and Altimeter Measurements. *Energies* **2021**, *14*, 394. [\[CrossRef\]](#)
12. Lavidas, G.; Kamranzad, B. Assessment of Wave Power Stability and Classification with Two Global Datasets. *Int. J. Sustain. Energy* **2021**, *40*, 514–529. [\[CrossRef\]](#)
13. Martinez, A.; Iglesias, G. Wave Exploitability Index and Wave Resource Classification. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110393. [\[CrossRef\]](#)
14. Perez, J.; Menendez, M.; Losada, I.J. GOW2: A Global Wave Hindcast for Coastal Applications. *Coast. Eng.* **2017**, *124*, 1–11. [\[CrossRef\]](#)
15. Satymov, R.; Bogdanov, D.; Dadashi, M.; Lavidas, G.; Breyer, C. Techno-Economic Assessment of Global and Regional Wave Energy Resource Potentials and Profiles in Hourly Resolution. *Appl. Energy* **2024**, *364*, 123119. [\[CrossRef\]](#)
16. Calheiros-Cabral, T.; Majidi, A.G.; Ramos, V.; Giannini, G.; Rosa-Santos, P.; Taveira-Pinto, F. Development and Assessment of a Hybrid Breakwater-Integrated Wave Energy Converter. *Int. Mar. Energy J.* **2022**, *5*, 281–291. [\[CrossRef\]](#)
17. Koutrouveli, T.I.; Di Lauro, E.; das Neves, L.; Calheiros-Cabral, T.; Rosa-Santos, P.; Taveira-Pinto, F. Proof of Concept of a Breakwater-Integrated Hybrid Wave Energy Converter Using a Composite Modelling Approach. *J. Mar. Sci. Eng.* **2021**, *9*, 226. [\[CrossRef\]](#)
18. Cabral, T.; Clemente, D.; Rosa-Santos, P.; Taveira-Pinto, F.; Morais, T.; Belga, F.; Cestaro, H. Performance Assessment of a Hybrid Wave Energy Converter Integrated into a Harbor Breakwater. *Energies* **2020**, *13*, 236. [\[CrossRef\]](#)
19. Cao, D.; He, J.; Chen, H. Empirical Predictions on Wave Overtopping for Overtopping Wave Energy Converters: A Systematic Review. *Processes* **2024**, *12*, 1940. [\[CrossRef\]](#)
20. Wang, S.; Xu, H.; Gao, Z.; Li, Y. Performance Analysis of a Novel Hybrid Device with Floating Breakwater and Wave Energy Converter Integrated. *Renew. Energy* **2024**, *237*, 121392. [\[CrossRef\]](#)
21. Song, F.; Cheng, Y.; Dai, S.; Yuan, Z.; Incecik, A. Hydrodynamic Characteristics and Parametric Optimizations of a Hybrid System Combining a Hinged Wave Energy Converter and a Breakwater with a Semi-Opened Moonpool. *Energy Convers. Manag.* **2024**, *313*, 118614. [\[CrossRef\]](#)
22. Chen, Q.; Kelly, D.M.; Zang, J. On the Relaxation Approach for Wave Absorption in Numerical Wave Tanks. *Ocean Eng.* **2019**, *187*, 106210. [\[CrossRef\]](#)
23. Perić, R.; Vukčević, V.; Abdel-Maksoud, M.; Jasak, H. Optimizing Wave Generation and Wave Damping in 3D-Flow Simulations with Implicit Relaxation Zones. *Coast. Eng.* **2022**, *171*, 104035. [\[CrossRef\]](#)
24. Thum, G.Ü.; Maciel, R.P.; Oleinik, P.H.; Rocha, L.A.O.; Dos Santos, E.D.; Seibt, F.M.; Machado, B.N.; Isoldi, L.A. Numerical Analysis of the Submerged Horizontal Plate Device Subjected to Representative Regular and Realistic Irregular Waves of a Sea State. *Fluids* **2024**, *9*, 188. [\[CrossRef\]](#)
25. Motta, V.E.; Thum, G.Ü.; Paiva, M.D.S.; Gonçalves, R.A.A.C.; Rocha, L.A.O.; Dos Santos, E.D.; Machado, B.N.; Isoldi, L.A. Numerical Investigation of Inclination Effects on a Submerged Plate as Breakwater and Wave Energy Converter Under Realistic Sea State Waves. *J. Mar. Sci. Eng.* **2025**, *13*, 1438. [\[CrossRef\]](#)
26. Machado, B.; Oleinik, P.; Kirinus, E.; Domingues dos Santos, E.; Rocha, L.; Gomes, M.; Conde, J.M.P.; Isoldi, L.A. WaveMIMO Methodology: Numerical Wave Generation of a Realistic Sea State. *J. Appl. Comput. Mech.* **2021**, *7*, 2129–2148. [\[CrossRef\]](#)
27. Heins, A.E. Water Waves Over a Channel of Finite Depth with a Submerged Plane Barrier. *Can. J. Math.* **1950**, *2*, 210–222. [\[CrossRef\]](#)
28. Greene, T.R.; Heins, A.E. Water Waves Over a Channel of Infinite Depth. *Q. Appl. Math.* **1953**, *11*, 201–214. [\[CrossRef\]](#)
29. Dick, T.M.; Brebner, A. Solid and Permeable Submerged Breakwaters. In *Coastal Engineering Proceedings*; Coastal Engineering Research Council (CERC): Reston, Virginia, 1968; p. 72. [\[CrossRef\]](#)
30. Graw, K. Is the Submerged Plate Wave Energy Converter Ready to Act as a New Coastal Protection System? In *Proceedings of the XXIV Convegno di Idraulica e Costruzioni Idrauliche*, Napoli, Italy, 20–22 September 1994.
31. Karmakar, D.; Guedes Soares, C. Wave Motion Control Over Submerged Horizontal Plates. *J. Offshore Mech. Arct. Eng.* **2018**, *140*, 031101. [\[CrossRef\]](#)

32. Yu, X. Functional Performance of a Submerged and Essentially Horizontal Plate for Offshore Wave Control: A Review. *Coast. Eng. J.* **2002**, *44*, 127–147. [\[CrossRef\]](#)
33. Orer, G.; Ozdamar, A. An Experimental Study on the Efficiency of the Submerged Plate Wave Energy Converter. *Renew. Energy* **2007**, *32*, 1317–1327. [\[CrossRef\]](#)
34. Seibt, F.M.; Dos Santos, E.D.; Isoldi, L.A.; Rocha, L.A.O. Constructal Design on Full-Scale Numerical Model of a Submerged Horizontal Plate-Type Wave Energy Converter. *Mar. Syst. Ocean Technol.* **2023**, *18*, 1–13. [\[CrossRef\]](#)
35. Wang, K.-H.; Shen, Q. Wave Motion over a Group of Submerged Horizontal Plates. *Int. J. Eng. Sci.* **1999**, *37*, 703–715. [\[CrossRef\]](#)
36. Seibt, F.M.; Couto, E.C.; Dos Santos, E.D.; Isoldi, L.A.; Rocha, L.A.O.; Teixeira, P.R.D.F. Numerical Study on the Effect of Submerged Depth on the Horizontal Plate Wave Energy Converter. *China Ocean Eng.* **2014**, *28*, 687–700. [\[CrossRef\]](#)
37. Carter, R.W. Wave Energy Converters and a Submerged Horizontal Plate. Master's Thesis, University of Hawaii, Manoa, HI, USA, 2005.
38. He, M.; Gao, X.; Xu, W.; Ren, B.; Wang, H. Potential Application of Submerged Horizontal Plate as a Wave Energy Breakwater: A 2D Study Using the WCSPPH Method. *Ocean Eng.* **2019**, *185*, 27–46. [\[CrossRef\]](#)
39. Motta, V.E.; Thum, G.Ü.; Gonçalves, R.A.A.C.; Rocha, L.A.O.; Dos Santos, E.D.; Machado, B.N.; Isoldi, L.A. Numerical Study of Inclined Geometric Configurations of a Submerged Plate-Type Device as Breakwater and Wave Energy Converter in a Full-Scale Wave Channel. *J. Exp. Theor. Anal.* **2025**, *3*, 3. [\[CrossRef\]](#)
40. Siew, P.F.; Hurley, D.G. Long Surface Waves Incident on a Submerged Horizontal Plate. *J. Fluid Mech.* **1977**, *83*, 141–151. [\[CrossRef\]](#)
41. Aghili, M.; Ghadimi, P.; Faghfoor Maghrebi, Y.; Nowruzi, H. Simulating the Interaction of Solitary Wave and Submerged Horizontal Plate Using SPH Method. *Int. J. Phys. Res.* **2014**, *2*, 16–26. [\[CrossRef\]](#)
42. Cheng, Y.; Ji, C.; Ma, Z.; Zhai, G.; Oleg, G. Numerical and Experimental Investigation of Nonlinear Focused Waves-Current Interaction with a Submerged Plate. *Ocean Eng.* **2017**, *135*, 11–27. [\[CrossRef\]](#)
43. Hayatdavoodi, M.; Ertekin, R.C.; Valentine, B.D. Solitary and Cnoidal Wave Scattering by a Submerged Horizontal Plate in Shallow Water. *AIP Adv.* **2017**, *7*, 065212. [\[CrossRef\]](#)
44. Fang, Q.; Yang, C.; Guo, A. Hydrodynamic Performance of Submerged Plates During Focused Waves. *J. Mar. Sci. Eng.* **2019**, *7*, 389. [\[CrossRef\]](#)
45. Xu, Y.; Zhao, W.; Wan, D. MPS Method for Interaction Between Solitary Waves and Submerged Horizontal Plate. *China Ocean Eng.* **2020**, *34*, 314–327. [\[CrossRef\]](#)
46. Zheng, Y.; Zhou, Y.; Jin, R.; Mu, Y.; He, M.; Zhao, L. Experimental Study on Submerged Horizontal Perforated Plates under Irregular Wave Conditions. *Water* **2023**, *15*, 3015. [\[CrossRef\]](#)
47. Maciel, R.P.; Machado, B.N.; Oleinik, P.H.; Dos Santos, E.D.; Gomes, M.D.N.; Isoldi, L.A. Investigation of Numerical Irregular Wave Generation Using Transient Discrete Data as Boundary Conditions of Prescribed Velocity. *Defect Diffus. Forum* **2023**, *427*, 227–235. [\[CrossRef\]](#)
48. das N. Gomes, M.; Lorenzini, G.; Rocha, L.A.O.; Dos Santos, E.D.; Isoldi, L.A. Constructal Design Applied to the Geometric Evaluation of an Oscillating Water Column Wave Energy Converter Considering Different Real Scale Wave Periods. *J. Eng. Thermophys.* **2018**, *27*, 173–190. [\[CrossRef\]](#)
49. Oleinik, P.H.; Tavares, G.P.; Machado, B.N.; Isoldi, L.A. Transformation of Water Wave Spectra into Time Series of Surface Elevation. *Earth* **2021**, *2*, 997–1005. [\[CrossRef\]](#)
50. Maciel, R.P.; Fragassa, C.; Machado, B.N.; Rocha, L.A.O.; Dos Santos, E.D.; Gomes, M.N.; Isoldi, L.A. Verification and Validation of a Methodology to Numerically Generate Waves Using Transient Discrete Data as Prescribed Velocity Boundary Condition. *J. Mar. Sci. Eng.* **2021**, *9*, 896. [\[CrossRef\]](#)
51. Paiva, M.D.S.; Mocellin, A.P.G.; Oleinik, P.H.; Dos Santos, E.D.; Rocha, L.A.O.; Isoldi, L.A.; Machado, B.N. Theoretical Recommendations and Validation for the Generation of Realistic Irregular Waves Through the WaveMIMO Methodology. *Processes* **2025**, *13*, 1395. [\[CrossRef\]](#)
52. Versteeg, H.K.; Malalasekera, W. *An Introduction to Computational Fluid Dynamics: The Finite Volume Method*, 2nd ed.; Pearson/Prentice Hall: Harlow, UK, 2007.
53. Hirt, C.W.; Nichols, B.D. Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries. *J. Comput. Phys.* **1981**, *39*, 201–225. [\[CrossRef\]](#)
54. Srinivasan, V.; Salazar, A.J.; Saito, K. Modeling the Disintegration of Modulated Liquid Jets Using Volume-of-Fluid (VOF) Methodology. *Appl. Math. Model.* **2011**, *35*, 3710–3730. [\[CrossRef\]](#)
55. Dean, R.G.; Dalrymple, R.A. *Water Wave Mechanics for Engineers and Scientists*; World Scientific Publishing Company: Singapore, 1991; Volume 2.
56. Zwart, P.; Godin, P.; Penrose, J.; Rhee, S. Ship Hull Simulations with a Coupled Solution Algorithm. In *10th International Symposium on Practical Design of Ships and other Floating Structures, PRADS 2007*; American Bureau of Shipping: Spring, TX, USA, 2007; Volume 2, pp. 989–996.

57. Park, J.-C.; Kim, M.-H.; Miyata, H. Fully Non-Linear Free-Surface Simulations by a 3D Viscous Numerical Wave Tank. *Int. J. Numer. Methods Fluids* **1999**, *29*, 685–703. [\[CrossRef\]](#)
58. Lisboa, R.C.; Teixeira, P.R.F.; Didier, E. Regular and Irregular Wave Propagation Analysis in a Flume with Numerical Beach Using a Navier–Stokes Based Model. *Defect Diffus. Forum* **2017**, *372*, 81–90. [\[CrossRef\]](#)
59. Mavriplis, D.J. Unstructured Grid Techniques. *Annu. Rev. Fluid Mech.* **1997**, *29*, 473–514. [\[CrossRef\]](#)
60. Maliska, C.R. *Fundamentals of Computational Fluid Dynamics: The Finite Volume Method*; Springer: Cham, Switzerland, 2023.
61. Chai, T.; Draxler, R.R. Root Mean Square Error (RMSE) or Mean Absolute Error (MAE)?—Arguments against Avoiding RMSE in the Literature. *Geosci. Model Dev.* **2014**, *7*, 1247–1250. [\[CrossRef\]](#)
62. Kat, C.-J.; Els, P.S. Validation Metric Based on Relative Error. *Math. Comput. Model. Dyn. Syst.* **2012**, *18*, 487–520. [\[CrossRef\]](#)
63. Karimpour, A. *OCEANLYZ 2024*; GitHub: San Francisco, CA, USA, 2024.
64. Chapra, S.C.; Canale, R.P. *Numerical Methods for Engineers*; McGraw-Hill: New York, NY, USA, 2011; Volume 1221.
65. Seibt, F.M. Estudo Numérico de um Dispositivo de Placa Horizontal Submersa para Conversão de Energia das Ondas do Mar em Energia Elétrica Aplicando Design Construtal. Ph.D. Thesis, Federal University of Rio Grande do Sul, Porto Alegre, Brazil, 2019. (In Portuguese)
66. Zang, Z.; Zhang, Q.; Qi, Y.; Fu, X. Hydrodynamic Responses and Efficiency Analyses of a Heaving-Buoy Wave Energy Converter with PTO Damping in Regular and Irregular Waves. *Renew. Energy* **2018**, *116*, 527–542. [\[CrossRef\]](#)
67. Wu, S.; Wu, P.; Cao, G.; Liu, Z.; Deng, Z. Experimental Analyses of Two-Body Wave Energy Converters with Hydraulic Power Take-Off Damping in Regular and Irregular Waves. *IET Renew. Power Gener.* **2021**, *15*, 2976–2987. [\[CrossRef\]](#)
68. Zhang, Z.; Tu, J.; He, Y.; Han, Z.; Yang, H.; Zhou, D.; Fu, S. The Influence of Regular Wave and Irregular Wave on the Mechanical Characteristics of a Triple-Cylinder Bundle Structure. *Ocean Eng.* **2021**, *220*, 108379. [\[CrossRef\]](#)
69. Wang, X.; Zhang, C.; Ye, L.; Wang, C.; Yu, F. Wave Attenuation by Three-Dimensional Circular Floating Sea Ice: Regular and Irregular Waves. *Ocean Eng.* **2024**, *305*, 117918. [\[CrossRef\]](#)

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