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Analysis of the influence of bathymetry on regular representative and realistic irregular waves generated through the WaveMIMO methodology

Análise da influência da batimetria em ondas regulares representativas e irregulares realísticas geradas através da metodologia WaveMIMO

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ABSTRACT

Due to the exponential growth in energy consumption and the possibility of using the energy contained in sea waves, the present study analyzes the influence of wave channel bathymetry on the propagation of representative regular and realistic irregular waves that describe the sea state occurring on the coast of Tramandaí city, state of Rio Grande do Sul, Brazil. The numerical simulations carried out in this study used the Computational Fluid Dynamics software ANSYS Fluent, based on the Finite Volume Method. The treatment of the water-air interface was performed with the Volume of Fluid multiphase model. To generate irregular waves, the WaveMIMO methodology was applied, which enables the numerical simulation of sea states with realistic characteristics. Therefore, in this paper, data from the TOMAWAC spectral model was processed, aiming to obtain orbital velocity profiles of wave propagation and their subsequent imposition as boundary conditions in the wave channel simulated in Fluent. The generation of representative regular waves and realistic irregular waves was analyzed, considering the wave channel with a horizontal bottom and applying bathymetry. Analysis of the results indicates that the use of bathymetry allows a slight improvement in the accuracy of numerical simulations of wave generation.

Keywords: WaveMIMO methodology; Sea state; Representative regular waves; Realistic irregular waves; Bathymetry

RESUMO

Devido ao crescimento exponencial do consumo de energia e à possibilidade de aproveitamento da energia contida nas ondas do mar, o presente estudo analisa a influência da batimetria do canal de ondas na propagação de ondas regulares representativas e irregulares realísticas que descrevem o estado de mar ocorrido em Tramandaí, estado do Rio Grande do Sul. As simulações numéricas realizadas neste estudo utilizaram o software de Dinâmica dos Fluidos Computacional ANSYS Fluent, basedo no Método de Volumes Finitos. O tratamento da interface água-ar, ocorreu através o modelo multifásico Volume of Fluid. Para a geração das ondas irregulares, utilizou-se a metodologia WaveMIMO, que viabiliza a simulação numérica de estados de mar com características realísticas. Para isso, nesse trabalho foram tratados dados provenientes do TOMAWAC, visando a obtenção de perfis de velocidade orbital de propagação das ondas e sua posterior imposição como condição de contorno no canal de ondas simulado no Fluent. Foram analisadas a geração das ondas regulares representativas e irregulares realísticas considerando o canal de ondas com fundo horizontal e com batimetria. A análise dos resultados indica que a utilização da batimetria permite uma leve melhoria na acurácia das simulações numéricas de geração de ondas.

Palavras-chave: Metodologia WaveMIMO; Estado realístico de mar; Ondas regulares representativas; Ondas irregulares realísticas; Batimetria

1 INTRODUCTION

Taken the evolution of technologies and population growth, energy consumption has increased exponentially. Thereby, it is necessary to search for new forms of energy generation that do not cause impacts on the environment. Called renewable energy sources, these forms of energy come from natural sources and are capable of regenerating, that is, they are inexhaustible (REIS *et al.*, 2021). Among renewable energy sources, the present paper deals with wave energy, which, for its extraction, uses converter devices that can be classified according to the physical principle of operation in (Reis et al., 2021): overtopping, oscilating bodies, oscillating water column (OWC) or submerged horizontal plate.

Regarding research on wave energy, studies on the generation of waves with realistic characteristics using the WaveMIMO methodology are cited: Hubner *et al.* (2022), qualitatively evaluated representative regular waves and realistic irregular waves which represent sea states found in three municipalities in the state of Rio Grande do Sul (RS): Rio Grande, Santa Vitoria do Palmar and Tavares. It is worth note that, in this study, the bathymetries found in the evaluated locations were considered for both wave climates;

Machado et al. (2021) evaluated the propagation of representative regular waves and realistic irregular waves of a sea state occurring in Praia dos Ingleses, municipality of Florianopolis, state of Santa Catarina. In this study, bathymetry was considered in the simulations of realistic irregular waves, while in the simulations of representative regular waves, a wave channel with a horizontal bottom (without bathymetry) was considered.

As can be seen, there is no consensus regarding the use or not of bathymetry in numerical simulations that use the WaveMIMO methodology to generate representative regular waves and realistic irregular waves based on sea states. Therefore, the objective of the present paper is to obtain a recommendation regarding the use of bathymetry for simulations that use the WaveMIMO methodology. Thus, it was considered data on the sea state that occurred in the municipality of Tramandaí, state of RS, on May 28, 2018 at 10:14 am, at a point located 2094.33 m from the coast, with geographic coordinates -50°. 06’18” W -29°59’52” S. Also, it should be highlighted that the bathymetry addressed also refers to this location.

2 MATHEMATICAL AND COMPUTATIONAL MODELLING

To carry out the present study, the computational fluid dynamics software ANSYS Fluent was used, which is based on the Finite Volume Method. For the appropriate treatment of the phases (the air and the water), the multiphase model Volume of fluid (VOF) (Hirt and Nichols, 1981) was used, which consists of representing the phases through the concept of volumetric fraction (α), where the sum of the phases in each computational cell is unity. It is also worth note that the multiphase model VOF is used for immiscible fluids, therefore:

$$\alpha_{water} = 1 - \alpha_{air} \quad (1)$$

In the VOF model only one set of equations is used, consisting of the equations of conservation of mass, of volumetric fraction and momentum, which, according to Versteeg and Malalasekera (2007) are represented, respectively, by:

$$\frac{\partial(\rho)}{\partial t} + \nabla.(\rho\vec{v}) = 0 \quad (2)$$

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

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla.p + \nabla.(\mu\bar{\bar{\tau}}) + \rho\vec{g} + S \quad (4)$$

where:

ρ is the fluid specific mass (kg/m^3);

t is time (s);

$\vec{v}$ is the flow velocity vector (m/s);

p is the static pressure (N/m^2);

$\bar{\bar{\tau}}$ is the strain rate tensor (N/m^2);

$\vec{g}$ is the gravity acceleration vector (m/s^2).

Furthermore, S is the sink term, which refers to the numerical beach tool, used to avoid wave reflection, given by (Lisboa et al., 2017):

$$S = -\left[C_1\rho V + \frac{1}{2}C_2\rho|V|V\right]\left(1 - \frac{z - z_{fs}}{z_b - z_{fs}}\right)\left(\frac{x - x_s}{x_e - x_s}\right)^2 \quad (5)$$

where:

C_1 and are, C_2 respectively, the linear (s^{-1}) and quadratic (m^{-1}) damping coefficients;

V fluid velocity module at the analyzed point (m/s);

z_{fs} and z_b are the vertical positions of the free surface and the bottom (m);

x_s and x_e are the horizontal start and end positions of the numeric beach (m).

As recommended by Lisboa et al. (2017), $C_1 = 20$ s^{-1} and $C_2 = 0$ m^{-1} were adopted.

2.1 Wave Generation through the Wave MIMO Methodology

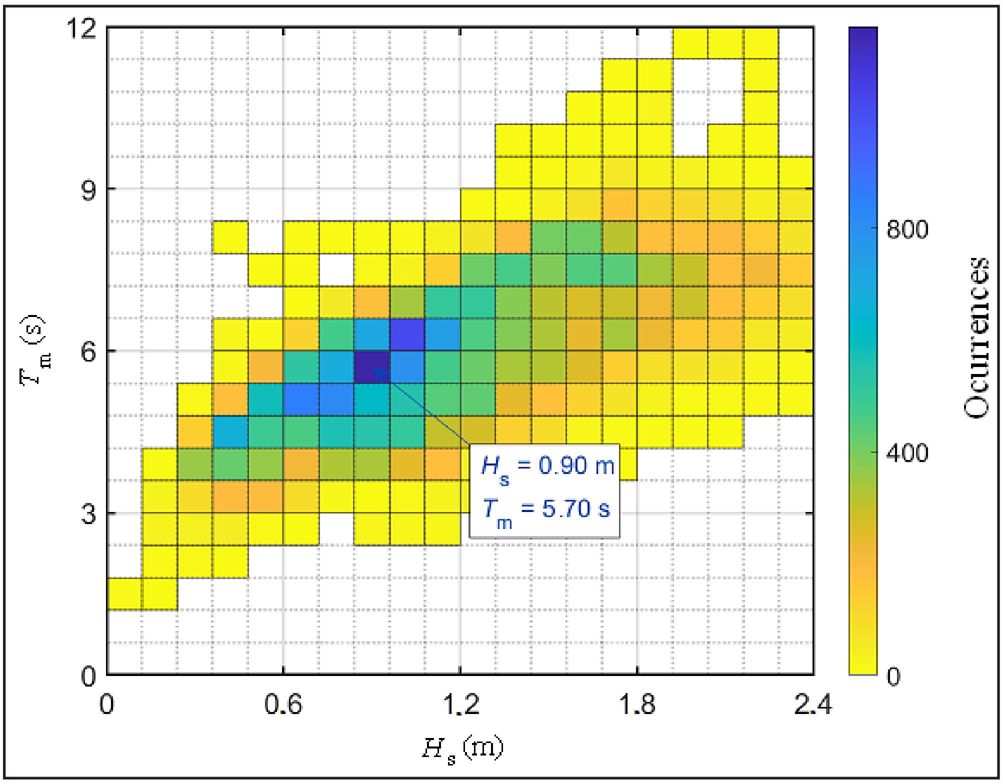
To enable the numerical generation of realistic irregular waves, it was used the WaveMIMO methodology, presented and verified by Machado *et al.* (2021) and validated and verified by Maciel et al. (2021). The WaveMIMO methodology can be based on obtaining a wave spectrum from the TOMAWAC (TELEMAC-based Operational

Model Addressing Wave Action Computation) spectral model and then transform the spectrum into a time series of free surface elevations (Machado et al., 2021).

This time series is treated and transformed into horizontal (u) and vertical (w) components of the orbital velocity of the water particles (Oleinik et al., 2021). Finally, the discrete data velocity of realistic waves propagation is imposed as a boundary condition of prescribed velocity in the wave channel in Fluent, thus allowing waves to be numerically simulated with realistic characteristics.

The realistic data of significant height (H_S) and mean period (T_m) that refer to the selected point were analyzed to determine the most frequent sea state. Thereby, the wave recurrence histogram that relates T_m and H_S is presented in Figure 1.

Figure 1 – Bivariate histogram of H_S and T_m



Source: the authors (2023)

Afterwards, aiming to determine the regular waves representative of the sea state, the wavelength (λ) was calculated through the dispersion relationship. Thus, the characteristics of the representative regular waves are: height, $H_S = 0.90$ m; period, $T_m = 5.70$ s; wavelength, $\lambda = 45.91$ m; and depth, $h = 10.98$ m.

Furthermore, the WaveMIMO methodology was also used to generate representative regular waves. In this case, the waves, which are classified as 2nd order Stokes waves, were discretized into horizontal and vertical propagation velocities, given, respectively, by Chakrabarti (2005) as:

$$u = \frac{H}{2}\frac{gk}{\sigma}\frac{coshk(h+z)}{\cosh kh}\cos(kx-\sigma t) + \frac{3}{16}H^2\sigma k\frac{\cosh 2k(h+z)}{senh^4 kh}cos2(kx-\sigma t) \quad (6)$$

$$w = \frac{H}{2}\frac{gk}{\sigma}\frac{senhk(h+z)}{\cosh kh}\mathrm{sen}(kx-\sigma t) + \frac{3}{16}H^2\sigma k\frac{\mathrm{senh}\, 2k(h+z)}{senh^4 kh}sen2(kx-\sigma t) \quad (7)$$

where:

$H/2$ is the wave amplitude (m);

k is the wavenumber (m^{-1}) given by:

$$k = \frac{2\pi}{\lambda} \quad (8)$$

where:

σ is the angular frequency (Hz) given by:

$$\sigma = \frac{2\pi}{T} \quad (9)$$

where:

T is the wave period (s).

Finally, the discrete wave propagation velocities were inserted as velocity inlet boundary conditions in the wave channel on Fluent, analogous to the procedure performed for realistic irregular waves.

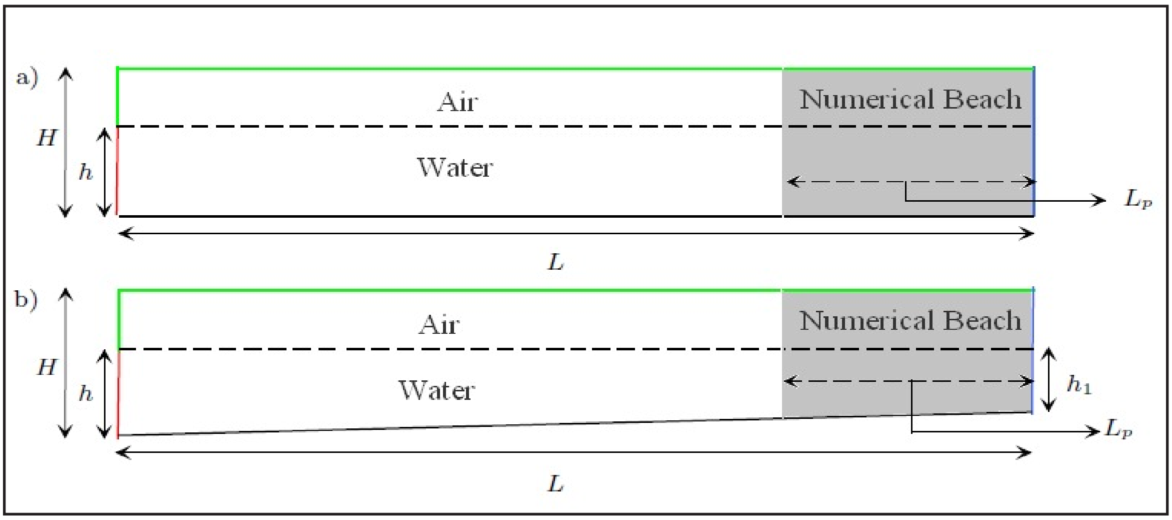
2.2 Description of Cases

As mentioned, the objective of the study is to analyze the influence of bathymetry on the generation and propagation of representative regular waves and realistic irregular waves. To achieve this, the study was subdivided into the following cases: 1 -

generation of regular waves without bathymetry (horizontal bottom); 2 - generation of regular waves with bathymetry; 3 - generation of irregular waves without bathymetry; and 4 - generation of irregular waves with bathymetry.

Regarding the computational domain, two were created, where the first one (Figure 2a) presents a horizontal bottom (without bathymetry) while the second (Figure 2b) presents the bathymetry found in the studied location, which was obtained from the nautical charts of the Directorate of Hydrography and Navigation of the Brazilian Navy. The wave channel has a length of $L = 229.56$ m, which corresponds to 5λ, as recommended by Gomes et al. (2018); height $H = 15.00$ m; and depth $h = 10.98$ m, which is constant for cases 1 and 3 (Figure 2a) and variable for cases 2 and 4 (Figure 2b), where the right side of the channel has $h_1 = 10.52$ m.

Figure 2 – Computational Domain: a) without bathymetry; b) with bathymetry



Source: the authors (2023)

Regarding the boundary conditions, in both cases the following were used: atmospheric pressure (green line); wall (black line), where velocities are considered zero; hydrostatic profile (blue line); and prescribed velocity (red line), which is subdivided into 14 segments of size $h/14$, as recommended by Machado et al. (2021). Finally, it should be noted that the numerical beach (Equation 4) was used to absorb wave energy and reduce the effects of reflection, which is caused by the incidence of waves on the right wall of the channel. Furthermore, according to Lisbon *et al.* (2017), the numerical beach has 2λ, that is, $L_p = 91.82$ m.

As for spatial discretization, a stretched (Gomes et al., 2018) mesh was employed. For this, the computational domain was subdivided into 3 vertical regions with the following discretizations: 60 computational cells in the region that contains only water; 40 cells in the free surface region (air/water interface); 20 cells in the region that contains only air. Horizontally, the computational domain was subdivided into 250 computational cells, i.e., 50 cells per λ.

Regarding temporal discretization, in the representative regular waves' simulations (cases 1 and 2), a time step T/500 was used, equivalent to $\Delta t = 0.0114$ s, as recommended by Gomes *et al.* (2018). While in the realistic irregular waves' simulations (cases 3 and 4), it was employed $\Delta t = 0.05$ s, as recommended by Machado et al. (2021). As for the total simulation time, in both studies it was considered 200 s of wave generation and propagation in the channel.

To compute the results, probes were used to monitor the free surface elevation at positions $x = 41.82$; 50.18; 71.09; 81.55 and 92.00 m, for the simulations of representative regular waves (cases 1 and 2) and at position $x = 0$ m for the simulations of realistic irregular waves (cases 3 and 4), a fact that occurs due to a limitation of the WaveMIMO methodology (more details are found in Machado et al., 2021). For the quantitative analysis of the obtained results, it was considered the metrics MAE (Mean Absolute Error) and RMSE (Root Mean Square Error) given, respectively, by (Chai and Draxler, 2014):

$$\text{MAE} = \frac{\sum_{i=1}^{N} |O_i - P_i|}{N} \quad (10)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (O_i - P_i)^2}{N}} \quad (11)$$

where:

O_i represents the value found numerically;

N represents the total number of data;

P_i represents the value used as a reference.

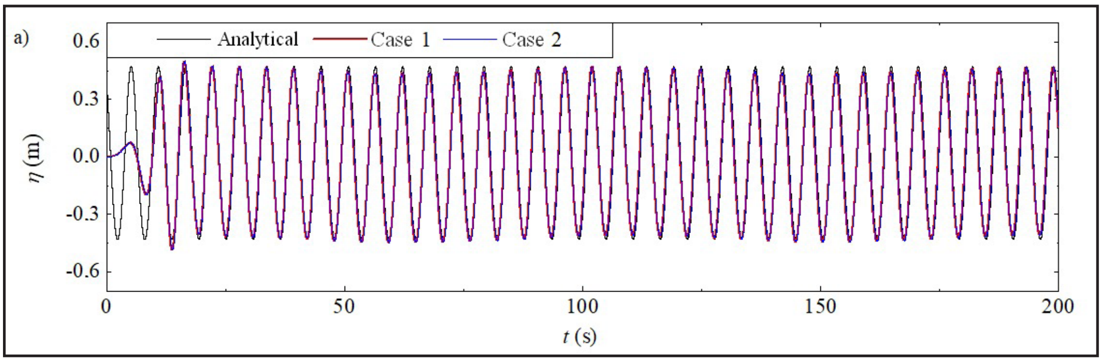
3 RESULTS AND DISCUSSIONS

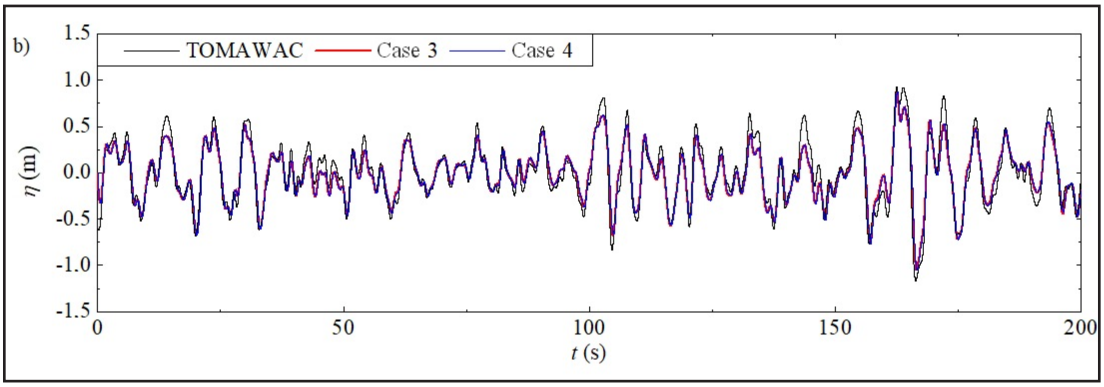
As mentioned, this study was subdivided into evaluating the influence of bathymetry considering representative regular waves (cases 1 and 2) and realistic irregular waves (cases 3 and 4). To analyze the results of cases 1 and 2, the elevation of the free surface obtained numerically was compared with the analytical one given by (Chakrabarti, 2005):

$$\eta = \frac{H}{2}\cos(kx - \sigma t) + \frac{H^2 k}{16}\frac{\cosh kh}{senh^3 kh}(2 + \cosh 2kh) cos2(kx - \sigma t) \quad (12)$$

In order to analyse the results of cases 3 and 4, the elevation of the free surface obtained numerically was compared with the elevation coming from the TOMAWAC spectral model. As seen in Figure 3, the numerical model adequately reproduced both representative regular waves and realistic irregular waves. Regarding Figure 3a, it is highlighted that the series of surface elevations was obtained from the probe located at $x = 41.82$ m.

Figure 3 – Comparison of free surface elevation considering: a) representative regular waves; b) realistic irregular waves





Source: the authors (2023)

It is observed that qualitatively there are no significant differences between the tested cases, therefore, a quantitative analysis of the results obtained was carried out. Therefore, in Table 1 it is presented the MAE and RMSE metrics obtained for cases 1 and 2 considering the five different free surface elevation probes.

Table 1– Results of MAE and RMSE for cases 1 and 2

Probe Location (m)		**41.82**	**50.18**	**71.09**	**81.55**	**92.00**
Case 1	MAE (m)	0.0198	0.0234	0.0208	0.0361	0.0190
	RMSE (m)	0.0240	0.0283	0.0252	0.0422	0.0233
Case 2	MAE (m)	0.0193	0.0223	0.0189	0.0322	0.0168
	RMSE (m)	0.0234	0.0270	0.0230	0.0382	0.0207

Source: the authors (2023)

It is noted that in the analysis of the results of cases 1 and 2, the first 40 s of wave generation were not considered due to the initial condition of flow inertia. As observed in Table 1, no considerable differences were found between the use of bathymetry or the horizontal bottom in the wave channel, which is in line with the qualitative assessment carried out.

Considering the probe located at $x = 41.82$ m, the difference between the MAE and RMSE metrics in each case is, respectively, 2.53% and 2.50%. However, it is possible to notice a gradual increase in this variation as the probes move further away from the wave generation zone. For instance, when considering the location where a converter device would be located, generally at 1.5λ from the beginning of the channel, close to the probe located at $x = 71.09$ m, there is a difference of 9.13 % and 8.73%, respectively, for the MAE and RMSE metrics. However, the differences found for the assessed metrics in cases 1 and 2 remain low, that is, the use of bathymetry does not influence the results considerably. In Table 2, the metrics MAE and RMSE obtained in cases 3 and 4 are presented.

Table 2 – Results of MAE and RMSE for cases 3 and 4

Case	3	4
MAE (m)	0.0925	0.0921
RMSE (m)	0.1195	0.1191

Source: the authors (2023)

It is noted in Table 2 that the use of bathymetry does not have a considerable influence on the generation of realistic irregular waves (cases 3 and 4). The difference found between the MAE and RMSE metrics calculated for each case is, respectively, 0.43% and 0.33%, which explains the proximity of the results presented in Figure 3b.

4 CONCLUSIONS

In both studies, despite the low difference between the obtained results, either for representative regular waves and for realistic irregular waves, the wave channel with bathymetry presented slightly better results, thus being the most efficient approach. For future studies, it is suggested to insert a wave energy converter device into a channel with bathymetry, in order to analyze its performance.

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