NUMERICAL GENERATION OF REGULAR WAVES USING DISCRETE ANALYTICAL DATA AS BOUNDARY CONDITION OF PRESCRIBED VELOCITY

Bianca Neves Machado

Elissandro Vaz Kisner

Maycon da Silveira Paiva

biancamachado@furg.br

elissandrokisner@furg.br

zmayconp@furg.br

Escola de Engenharia

Universidade Federal do Rio Grande

Av. Itália, km 8, 96201-900, Cx. P. 474, Rio Grande, RS, Brasil.

Mateus das Neves Gomes

mateus.gomes@ifpr.edu.br

Instituto Federal do Paraná

Rua Antônio Carlos Rodrigues, Nº 453, Porto Seguro, Paranaguá, PR, Brasil.

Luiz Alberto Oliveira Rocha

laorocha@gmail.com

Universidade do Vale do Rio dos Sinos

Av. Unisinos, 950, 93022-750, São Leopoldo, RS, Brasil.

Wiliam Correa Marques

wilian_marques@yahoo.com.br

Instituto de Matemática, Estatística e Física

Universidade Federal do Rio Grande

Av. Itália, km 8, 96201-900, Cx. P. 474, Rio Grande, RS, Brasil.

Elizaldo Domingues dos Santos

Liércio André Isoldi

elizaldosantos@furg.br

liercioisoldi@furg.br

Escola de Engenharia

Universidade Federal do Rio Grande

Av. Itália, km 8, 96201-900, Cx. P. 474, Rio Grande, RS, Brasil.

Abstract. *This paper aims to computationally analyze the wave tank in two situations: laboratory scale and real scale. To do so, the FLUENT software was employed, which is the Computational Fluid Dynamic (CFD) package based on the Finite Volume Method (FVM). The intention is to evaluate a new system to impose the velocity boundary condition for the regular numerical waves generation, using transient discrete values. For this, we compared the magnitude of the numerical waves generated by this procedure with the waves generated through the imposition of prescribed velocities by means the time-dependent function -with the User Defined Function (UDF) tool in FLUENT- aiming to verify this computational modeling. The two-dimensional computational domain (2D) generated with the GAMBIT software was used. The volume of fluid (VOF) multiphase model was applied in the treatment of the water-air interaction, so the computational model solves the conservation equations of mass and momentum associated with the transport equation of the volumetric fraction. The results indicated that the proposed computational model, using discrete data as velocity boundary conditions for the regular waves generation, can be satisfactorily applied. In this way, the present paper contributes for future geometric optimization studies of Wave Energy Converters (WEC) employing the Constructal Design method.*

Keywords: *Boundary condition, Prescribed velocities, Table data, User defined function (UDF), Computational modeling.*

1 INTRODUCTION

Currently there is a need to supply an immense worldwide energy demand. The increase energy demand and the Kyoto Protocol, which aims to reduce emissions of greenhouse gases, have increased the interest for the renewable energies study (Beels et al., 2010). Other benefits from the use of renewable energies can be mentioned, for example, minimizing the exploitation of fossil fuel deposits and their associated environmental impacts (Tolmasquim, 2003).

The main cause of environmental impacts is related to the indiscriminate fossil fuels use. Regardless the country development degree, the use of these fuels, either for the generation of electricity, heat or mechanical force, was still dominant in the energy matrix of most nations over the past decade (Garcia, 2004). Thus, a greater use of renewable energy sources provides enormous environmental gains, opening up space for technological development and the production of new knowledge on the energy field (Santos et al., 2006).

Therefore, a definition for renewable energy is necessary. According to Assis (2010) renewable energy is obtained from natural sources and is available on a cyclical basis.

Brazil presents an expressive participation of renewable energy sources on the energy matrix, obtaining a large advantage in relation to the developed countries. While in industrialized countries the participation of renewable energy reaches 6.00%, in Brazil the percentage reaches 46.90%. This fact is, among other factors, due to the small use of nuclear energy and the meaningful participation of biomass and hydropower on the total energetic supply in the country (Assis, 2010).

In the last 25 years, wave energy has passed through a cyclic process with stages of excitement, disappointment and reconsideration. However, the persistent effort in research, development and the accumulated experience have constantly increased the performance of techniques for wave energy obtaining. This has induced the wave energy resource to a greater proximity of commercial exploitation which, until now, had not been seen. From 2009 to the present day, several distinct devices were developed for extraction of wave energy (Falcão, 2010).

According to Cruz and Sarmento (2004), the existing devices can be classified by their location in: Coastal devices (onshore), devices near the coast (nearshore) and devices away from the coast (offshore). Also, according to its principle of sea wave energy conversion in electric energy: Oscillating Water Column (OWC) devices; Floating Bodies devices, which may be Surging devices or Point Absorbers devices; and Overtopping devices.

In this context, the present paper computationally analyzes a wave tank in two situations: laboratory scale and real scale. A two-dimensional (2D) computational domain was used for this. The purpose is to verify a new imposition system of boundary conditions for the numerical wave generation, the Table Data. With this new way to impose the numerical wave, it is aim to carry out numerical studies about sea wave energy converters. For the Table Data verification, a comparison between the amplitude of the numerical wave generated by this procedure and the wave generated by the imposition of a user-defined function (UDF) is performed.

As mentioned earlier, the present study is developed through computational modeling, which employs numerical simulation solutions to scientific problems, analyzing the phenomena, developing mathematical models for its description and developing computational codes to obtain these solutions. Numerical simulation is defined as a process to design a real system computational model and conduct analyzes with this model aiming to understand their behavior and/or evaluate strategies for its operation (Pegden, 1990)

2 WAVE ENERGY CONVERTER TECHNOLOGIES

After decades of research and development, there are different solutions that respond to the wave energy extraction technological challenge nowadays. It is noteworthy that these technologies are at different development stages and often present distinct conceptions and principles. Therefore, it is essential to establish standards to classify them pointing out their differences and similarities (Cruz and Sarmento, 2004).

For that reason, the wave energy converter devices are classified in accordance with the depth, also according to the device type, in other words, the way it converts wave energy into electrical energy (WavEC, 2004). Concerning to the location, the devices can be set on the coast, in shallow waters, or further away from the coast, in deep waters. See below and in Fig. (1) the proper classification, in accordance with WavEC (2004):

- Onshore: accessible by land, also known as coastal devices or first-generation devices.

The coastal devices are those that are attached or built at the coastline. This proximity provides them immediate advantages, such as easier installation and maintenance, absence of large submarine cables extension and of complex fastening systems (Cruz and Sarmento, 2004).

- Nearshore: devices installed near the coast, with depth ranging between 8.00 and 20.00 m.

The nearshore systems are set on the ocean in a position between onshore and the offshore systems. These systems are characterized by being used to extract the potency directly from the wave breaking zone (Rhinefrank et al., 2006).

- Offshore: devices installed away from the coast, with depth greater than 25.00 m.

This class of wave energy converter is the most recent and therefore, these devices are commonly mentioned as devices of third generation. They are located in high depth areas and thus benefit from the most energetic waves compared with the previous cases and present a lower visual impact (ETSU, 2001).

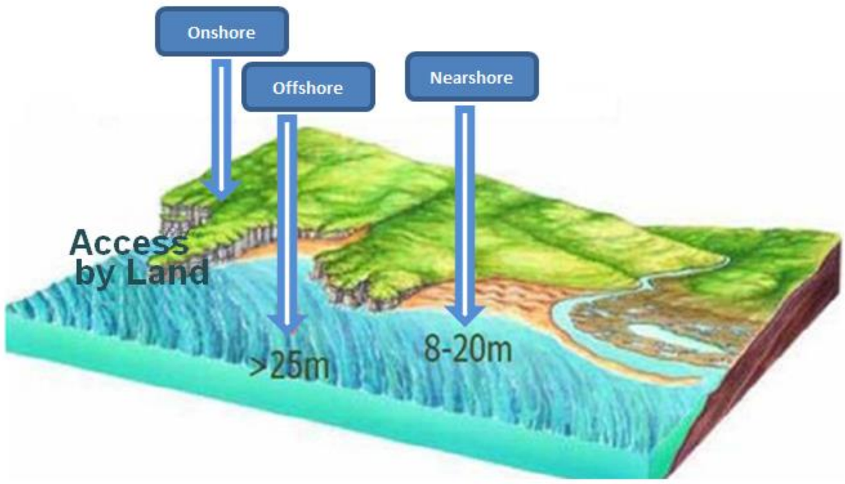

Figure 1. Classification regarding to the wave energy converter location

Differently to other renewable energy sources, there is a large variety of wave energy conversion systems. Although there are several conversion techniques patented, the apparently large concepts number for wave energy converters, can be divided into some distinct types, established on its operation principle (Lima, 2010). According to this classification, there are three classes of wave energy conversion devices (see Fig. (2)):

- **Oscillating Water Column** – OWC;
- **Oscillating Bodies**, which may be Point Absorbers or Surging Devices;
- **Overtopping Devices**.

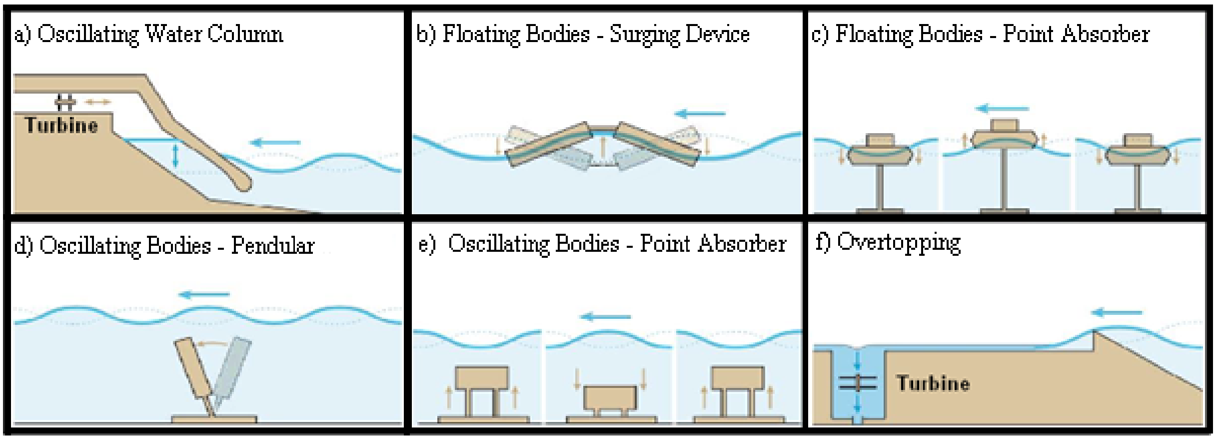

Figure 2. Operation principles in the wave energy converters illustration (adapted from Callaway, 2007)

Regarding the operation principle, from the devices shown in Fig. (2), stands out:

Overtopping Devices: It is based on the water accumulation in a reservoir raised over the average free surface level from the sea. The accumulated water when returned to the sea drives hydraulic low fall turbines that are coupled to related fabrication electric generators. (WavEC, 2004).

Oscillating Water Column (OWC): the OWC devices, in physical part terms, are partially submerged hollow structures. The generating electricity process is divided into two stages: in the first one the wave enters the structure and forces the existing air through a turbine (a pressure increase consequence in the chamber) and in the second one, when the sea recedes, the air flows again through the turbine in the opposite direction. These waves alternating movement pressurizes and depressurizes the air present inside the structure. This internal pressure variation moves the turbine and create electrical power production. Aiming the energy production in both directions of air flow that passes through the turbine a Wells turbine is used.

Oscillating Bodies: these devices have a primary energy principle based on the movement of a body in relation to a stable reference point or another body.

2.1 State of Art

Nowadays, several solutions for the wave energy use have been studied and developed, but none of them by the commercial point of view. Due to the very singular characteristics for the installation place, it is expected that different prototypes of wave energy conversion are used in the converters development (Chozas & Soerensen, 2009; Son et al., 2016). Due to the financial demand to perform prototypes tests, it is also used the numerical simulation as a way to execute the tests. Consequently, there are some numerical studies that stand out on converters of sea waves energy into electrical energy:

- Horko (2007) presents an OWC device study, where different geometries and lip dimensions are evaluated. The wave generation is given through UDF, which considers transient functions for the wave velocity components;
- Conde e Gato (2008) studies the air flow within a two chimneys OWC device. The numerical wave was simulated through a sine function imposition;
- Gomes (2014) optimizes a two-dimensional OWC numerical model, through Constructal Design. The numerical wave generator in the boundary conditions variation of velocity inlet, through a user-defined function, UDF;
- Seibt (2014) studies a numerical model for a two-dimensional horizontal submerged plate using the VOF multiphase model, and the wave generation happens through a UDF based on the 2nd order Stokes equation;
- Seibt et al. (2017) simulates, numerically, a horizontal submerged plate converter in real scale and analyzes similarity with the previous results of a laboratory scale model. The numerical wave generation came through an UDF;
- Machado et al. (2017) presents a study of a three-dimensional numerical model regarding an overtopping sea wave energy converter. The Constructal Design method was applied, along with an exhaustive search, to define the best geometric shape to the device ramp. The wave movement was generated through the imposition velocity inlet field in the wave tank through an UDF use;
- Liu (2008) presents a two-dimensional overtopping device computational modeling, the wave was generated through an UDF and the VOF method was used;
- Machado (2016) presents two studies of a three-dimensional numerical model regarding an overtopping sea wave energy converter. On the first one a laboratory scale device was optimized and, in the second, a geometrical optimization of a three-dimensional numerical model of an onshore real scale overtopping device was realized. The wave generation was performed through an UDF based on Stokes 2nd order equation;
- Dos Santos et al. (2014) performed a geometry numerical evaluation of OWC and overtopping devices through Constructal Design. The numerical wave generation came through a user-defined function (UDF). The numerical results presented in this study illustrated the Constructal Design applicability in wave energy converters optimization.

As described earlier, the present paper consists in the two-dimensional computational analysis of a real scale wave tank. The purpose is to verify a new boundary conditions imposition system for the numerical wave generation, the Table Data. With this new numerical wave imposition method, it will be possible to perform numerical studies on sea wave energy converters.

3 PROBLEMS DESCRIPTION

For both presented studies in this paper the verifying methodology for the numerical model consists in defining, first, computational domain, which, in this case, represents a wave generation tank on a two-dimensional plane (see Fig. (3)). The main difference between the studies is the scale used: the first study approaches a laboratory scale numerical model (represented by a wave tank with total area equal to A = 8 m^2), while in the second, it presents a real scale numerical model (A = 6540 m^2).

The analysis consists on finding a solution to the flow of an air and water mixture, for that, the flow was considered transient and laminar. As for the boundary conditions, there is the velocity inlet (red line) generated by a field imposition in the wave tank left wall. Regarding to the other boundary conditions, the upper region of the left surface in the wave tank, as well as its upper surface, have prescribed atmospheric pressure (blue dashed line). In other tank areas (bottom and right surface - continuous black line) velocities are prescribed as null, which means, a boundary condition of no-slip or impermeability was adopted. In terms of initial conditions, the fluid is considered at rest.

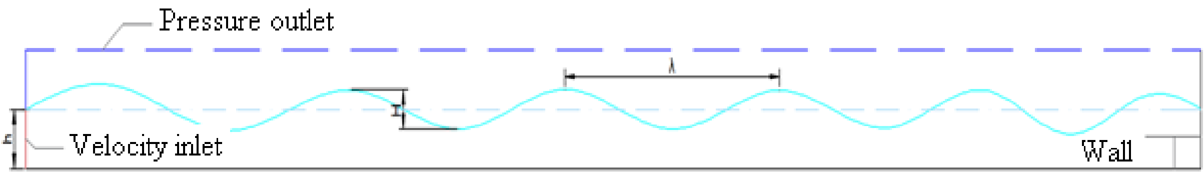

Figure 3. Wave tank computational domain illustration

The Table Data system, which enables a new method to impose the boundary conditions for the wave generation proposed in this study, presents a geometric particularity, which is, for discrete transient data imposition as boundary conditions of velocity inlet it is necessary that this region of geometry (continuous red line of Fig. (3)) is divided into sub-regions (blended line in red and green colors), as shown in Fig. (4).

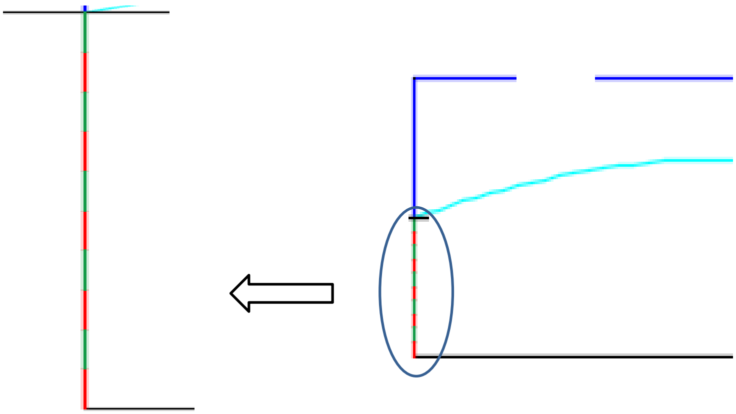

Figure 4. Fractioning region of boundary condition for the wave generation with Table Data methodology illustration

In both cases, the computational domain construction and discretization was through GAMBIT® software. The numerical simulations were performed using the FLUENT® software, which is based on the Finite Volumes method. The multiphase Volume of Fluid

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(VOF) model was applied, which allows to properly deal with the interaction between tank, water and air (Fluent, 2009).

The discretization of the computational domain and the temporal discretization, were carried out in a particular manner to each studied case. For the laboratory scale wave tank case, a regular mesh composed of quadrilaterals with dimension Δx = 0.01 m, a time step of Δt = 0.01 s and the total simulation time was of t = 8.00 s. As for the real scale case, a regular mesh composed of quadrilaterals with dimension Δx = 0.30 m, a time step of Δt = 0.07 s and the total simulation time was of t = 50.00 s.

The characteristics of simulated waves in each study can be seen in Table (1). Thereunto, it should be emphasized that the wave characteristics shown in the third column represent a laboratory scale wave, while the characteristics shown in the fourth column describes a real scale wave.

Table 1. Wave Characteristics.

Characteristic	Nomenclature	Laboratory Scale	Real Scale
Wave Period	T (s)	0.88	7.50
Wave Height	H (m)	0.18	1.00
Wave Length	λ (m)	1.20	65.40
Tank Depth	h (m)	0.60	10.00

4 MATHEMATICAL AND NUMERICAL MODEL

4.1 Wave Generator

As mentioned before, the wave generation is given by a prescribed velocities imposition at the bottom on the left surface (red line in Fig. (3)). So, the velocity inlet boundary condition is imposed in this surface.

To verify the new wave generation methodology proposed in this paper, at first, the described computational domain was simulated through a user-defined function (UDF). This methodology was developed by Horko (2007) and employed in the studies of Gomes (2014); Machado et al. (2017); Machado, (2016), among others. It is important to highlight that the wave adopted in this study is a 2nd order Stokes wave. Thus, according to McCormick (1976) and Dean & Dalrymple (1991), the imposed velocity boundary conditions in the wave tank entrance surface are given by Eqs. (1) and (2).

$$u = Agk \frac{cosh(kz + kh)}{\omega\, cosh(kh)} cos\left(kx\text{-}\omega t\right) + A^2 \omega K \frac{cosh\, 2k(\mathrm{h} + \mathrm{z})}{sen^4(kh)} cos\; 2\left(kx - \omega t\right) \tag{1}$$

$$w = Agk \frac{senh(kz + kh)}{\omega\, senh(kh)}\, sen\left(kx - \omega t\right) + A^2 \omega K \frac{senh\, 2k(h + z)}{cos^4(kh)}\, sen\, 2\left(kx - \omega t\right) \quad (2)$$

where: u is the horizontal component of the velocity, w is the vertical component of the velocity, A is the wave amplitude (m); g the gravitational acceleration (m/s²); k is the wave number given by $k = 2\pi / \lambda$ (m^{-1}); h is the depth (m); T is the wave period (s); ω is the frequency given by $\omega = 2\pi / T$ (Hz); x is the streamwise coordinate (m); t is the time (s) and z is the normal coordinate (m).

According to McCormick (1976) and Dean & Dalrymple (1991), it is possible to define an equation that describes the free surface elevation analytically:

$$\eta = \frac{H}{2} cos\left(\mathrm{kx} - \sigma \mathrm{t}\right) + \frac{H^2 kconsh(kh)}{16\, senh^3(kh)} \left(2 + cosh\, 2kh\right)\, cos\, 2\, (kx - \sigma t) \quad (3)$$

The Equation (3) plays an important role in the numerical simulation of a wave tank, since through this equation it is possible to verify the computational model. For the new wave generation procedure proposed, the horizontal and vertical components of the wave velocity from an analytical database were employed. To do so, the velocity components of wave propagation in the direction x and z, respectively represented by u and w, for both studied cases, were extracted. For the laboratory scale case, a variation 0.001 s during a time of 8.00 s was adopted, while, for the real scale case a variation 0.07 s during a time of 50.00 s was used. This methodology is called Table Data, and these data are inserted into FLUENT through a data entry in tables shape, called Boundary Profiles, enabling discrete transient data to be used as boundary conditions.

4.2 Volume of Fluid

The Volume of Fluid (VOF) method (Hirt & Nichols, 1981) is used in this paper. The VOF method is a multiphase model used for the solution of a flow composed by two or more phases. In this formulation, all stages are defined and the volume occupied by a phase cannot be occupied by another one. Thus, to represent the contained phases in each volume control, the volume fraction (α) concept is necessary. Therefore, the sum of all phases in each cell is necessarily equal to one. Only two phases are considered in the numerical model presented in this paper: air and water. Consequently, the cells with values of α_{water} between 0 and 1 contains the interface between water and air (in this case α_{air} = 1- α_{water}). Those cells with α_{water} = 0 have no water and they are full of air (α_{air} = 1); and, those cells that present α_{air} = 0 are full of water (α_{water} = 1).

Besides that, when the VOF method is used, only a single set of equations, formed by the momentum and continuity equations, is applied to all flow fluid components. Then, the volume fraction of each fluid in each cell (volume control) is considered in the whole computational domain, through the volume fraction transport equation. Thus, the model is composed by the continuity equation:

$$\frac{\partial(\rho)}{\partial t} + \nabla.\ (\rho\,\vec{v}) = 0 \tag{4}$$

the volumetric fraction equation:

$$\frac{\partial(\alpha)}{\partial t} + \nabla.\ (\alpha\,\vec{v}) = 0 \tag{5}$$

and the momentum equations:

$$\frac{\partial}{\partial t}(\rho\,\vec{v}) + \nabla.\ (\rho\,\vec{v}\,\vec{v}) = -\nabla p + \nabla.\ (\mu\,\bar{\bar{\tau}}) + \rho\,\vec{g} \tag{6}$$

where: ρ is the fluid specific pressure (kg/m³), t is the time (s), $\vec{v}$ is the velocity vector of flow (m/s), p is the static pressure (N/m²), μ is the viscosity (kg/(ms)), $\bar{\bar{\tau}}$ is the viscous stress tensor (N/m²) and $\vec{g}$ is the gravitational acceleration (m/s²).

Since the mass conservation and momentum equations are solved for the air and water mixture, it is necessary to calculate average values for the specific mass and viscosity, respectively (Srinivasan et al., 2011):

$$\rho = \alpha_{water}\rho_{water} + \alpha_{air}\rho_{air} \tag{7}$$

$$\mu = \alpha_{water}\,\mu_{water} + \alpha_{air}\,\mu_{air} \tag{8}$$

4.3 Other Procedures

As described earlier, the equations for mass and momentum conservation, associated with the volume fraction transport equation were numerically solved using a commercial code based on the Finite Volumes method (FVM) (Fluent, 2006). The first order upwind scheme for the treatment of advective terms was adopted in all numerical simulations, while pressure spatial discretization is performed using the PRESTO method. The GEO-RECONSTRUCTION method is applied to the volumetric fraction. Regarding the pressure-velocity coupling the PISO method was used. In addition, the sub-relaxation factors of mass and momentum conservation equations of 0.30 and 0.70 were employed, respectively. All solutions were performed through computers with an Intel Core I7 6800K of 3.40GHz clock and 32GB RAM.

5 RESULTS AND DISCUSSION

This section presents the results obtained for both studied cases throughout this paper. However, for the laboratory scale wave only the verification of the proposed wave generation methodology was performed, comparing its result with that presented in Machado (2016) which used the UDF methodology. Thereafter, for the laboratory scale wave a mesh quality study and a time step influence study were previously carried out. So, using the suitable mesh and time step the computational model verification procedure was performed. In addition, an analysis about the velocity inlet region fractionation was developed.

5. 1 Numerical Model of a Laboratory Scale Wave Tank

As described before, the initial verification of this new boundary conditions imposition methodology for the wave generation was held to a laboratory scale wave tank computational model. The numerical solution obtained with the boundary conditions imposition using the UDF, methodology that considers transient functions for the components of wave velocity (see Eqs. (1) and (2)), as in Machado (2016), was used as a reference. Therefore, the verification was performed by comparing the numerical results obtained by the Table Data application with the ones generated by UDF for the free surface elevation, as showed in Fig. (5). It should be emphasized that, for both studies, the generated wave has the same characteristics (see Table (1)).

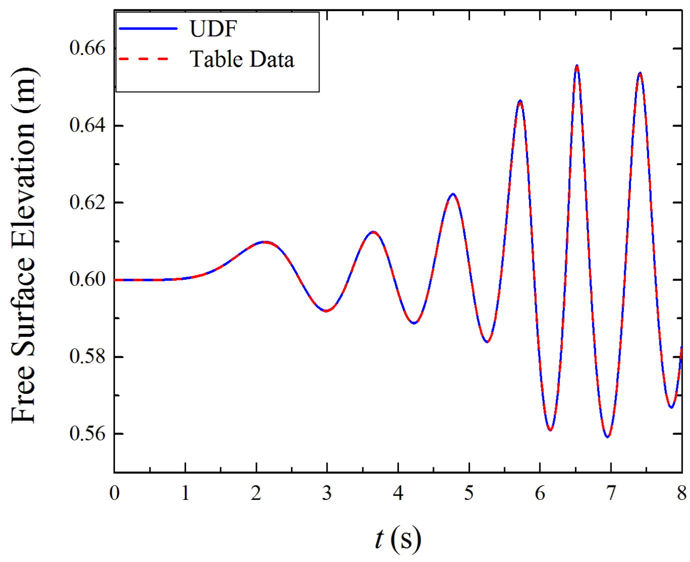

Figure 5. Computational model verification for a laboratory scale wave

It is observed in Figure (5), the numerical waves generated through the UDF and Table Data. It shows in the first few seconds of simulation that the first waves generated in the wave tank are more dampen, this happens because the wave flow comes from the rest. This damping due to flow inertia decreases with the simulation time advancement, which can be seen from around t = 6.00 s. It is also noted that the results obtained through the UDF and Table Data are in agreement, with a mean difference of approximately 0.01%. Moreover, a significant reduction in the total processing time from 14 h (UDF) to 4 h (Table Data) was observed, representing a reduction of approximately 71% in the time required to perform the numerical simulation.

5. 2 Numerical Model of a Real Scale Wave Tank

Mesh Quality Study

A very important aspect to be considered in numerical simulations is the spatial discretization used in the analyzed domain. The spatial discretization employed has great importance for an adequate prediction for the simulated flow, as well as, in the required computing power effort to perform these numerical simulations (Santos, 2008). Due to this fact, a mesh quality study was executed to ensure the accuracy of the results obtained in this paper. And, as mentioned earlier, a regular mesh composed of quadrilaterals was evaluated.

For the mesh quality study three mesh dimensions were evaluated, as can be seen in Table. (2), and took into consideration: the total number of computational cells (mesh elements) generated, the relative difference - calculated by comparing the RMS (Root Mean Square) elevation between the analytically calculated wave and the numerically calculated one - and, also, the total processing time. It should be emphasized that, for all analyzed cases the total simulation time was t = 50.00 s.

Tabela 2. Mesh Quality Study.

Δx (m)	Mesh Elements	Relative Difference (%)	Time (min)
0.30	73030	3.74	63
0.60	18530	12.16	38
0.90	7986	13.49	24

As seen in Table (2), the mesh with a greater refining, i.e., the mesh size Δx = 0.30 m presents the highest concordance with the analytically generated wave. And, since the meshes with Δx = 0.60 m and 0.90 m present a considerable difference from the analytical solution, the mesh with a larger number of cells was choose to use. It is noteworthy that the mesh used demands a greater computational effort, aiming at the total simulation time reduction, it was decided to conduct a study on the time step influence.

Time Step Study Influence

According to Barreiro (2009), the time step definition is an important parameter for results precision of a numerical simulation, because the use of inappropriate values can lead to information loss and solutions convergence incapability. Therefore, a study of time step influence over the wave free surface elevation was carried out, using the mesh defined in the quality study, i.e., with Δx = 0.30 m and evaluating the variation of the following time steps: Δt = 0.02 s, 0.04 s, 0.05 s, 0.06 s, 0.07 s, 0.08 s, 0.09 s and 0.10 s, as can be seen in Fig. (6). It is noteworthy that, for all cases the total simulation time was t = 50.00 s.

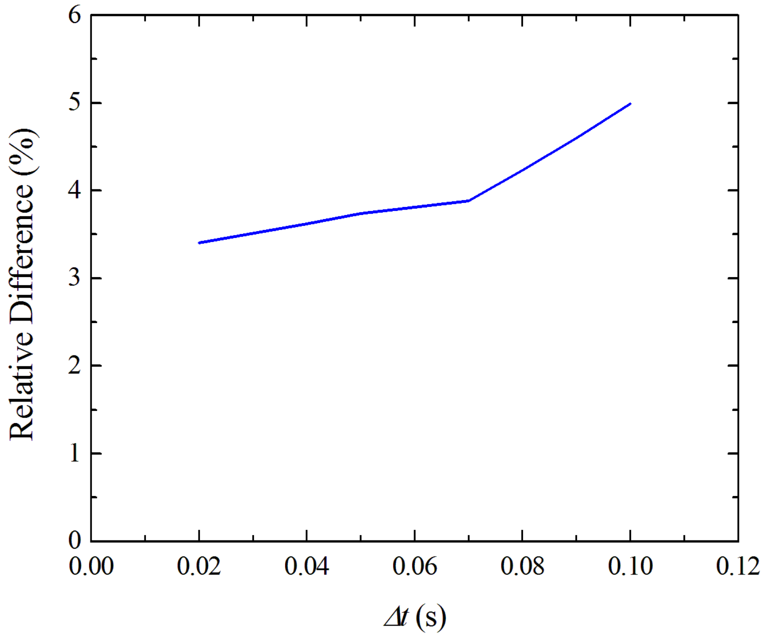

Figure 6. Time step study influence

As it is shown in Figure (6), for time steps from 0.02 s to 0.07 s, the curve representing the relative difference has a low growth, which indicates no significant variations of relative difference in these cases. While, from the time step of Δt = 0.08 s the curve shows a growing in its inclination, indicating a relative increase in the discrepancy between the numerical and analytics waves. Moreover, Table (3) shows the total processing time for each analyzed time step

As can be seen in Table (3), the time step which presented a lower relative difference (calculated by comparing the RMS (Root Mean Square) elevation between the analytically calculated wave and the numerically calculated one) was Δt = 0.02 s, however the processing time for this time step was around 120 min. Whereas, for Δt = 0.07 s, there was a decrease of 62.50% in the total simulation time and an increase of only 0.48% in the relative difference. Therefore, since the dissimilarity in relation to the total processing time, i.e., driving at a lower computational effort, and also the low difference in the results accuracy, it was chosen to use a Δt = 0.07 s.

Table 3. Time Step Study Influence.

Δt (s)	Relative Error (%)	Processing Time (min)
0.02	3.40	120
0.04	3.62	55
0.05	3.74	63
0.06	3.81	49
0.07	3.88	45
0.08	4.23	41
0.09	4.60	32
0.10	4.99	29

Velocity Inlet Region Fractionation Analysis

As already mentioned, the new procedure of wave generation proposed in this study is based on the insertion of horizontal and vertical components of wave velocity from an analytical database. Thereunto, the region where the velocity inlet is imposed (region of wave generation) is divided into sub-regions, where each of these receives the imposition of transient discrete data as a prescribed velocity boundary condition. Therefore, a study to investigate the discretization influence of this velocity inlet region was needed, where there were performed tests that assessed the simulated wave accuracy, besides the total processing time for the cases where the region was divided into regions with length: 2.00 m, 1.25 m and 1.00 m.

The Figure (7) presents the evaluation of spatial discretization on the velocity inlet region through discrete transient data. And, as can be observed, the case where fractioning in regions of 2.00 m had the major disagreement when compared with the wave obtained analytically. On the other hand, for the cases fractioned in regions with length of 1.25 m and 1.00 m, the results were similar to those found for the wave generated by the UDF, where there was a mean difference between the crests amplitude, calculated numerically and analytically, of approximately 1.20% and a mean difference between the cave amplitude, of approximately 5.00%. As both cases present similar results and processing time, the regions with 1.25 m were chosen to be used due to the fact that this discretization provides a lower number of discrete transient data tables.

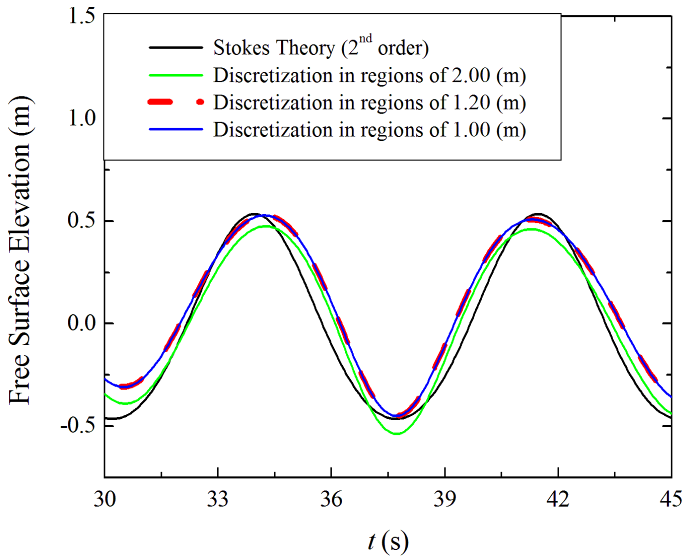

Figure 7. Analysis of discretization influence on the wave generation region

Numerical Wave Verification

To verify the proposed methodology, it was used the strategy of comparison between the analytical solution for the free surface elevation, given by Eq. (3), and the numerical solution, which consists in wave generation in a wave tank and observing the variation on the free surface vertical position, i.e., its amplitude, at a given location in the tank. It is worth to highlight that the numerically generated wave has the same characteristics that the analytically obtained one, as showed in Table (1).

The Figure (8) presents the comparison between the numerical wave obtained in this paper with the analytical wave predicted by Eq. (3) at position x = 100.00 m. For the phenomenon analysis, just time range of 30.00 s $\leq t \leq$ 45.00 s is considered, due to the fact that the wave flow starts from the repose and on account of the flow inertia, the first waves generated in the numerical tank are more dampen, leading to considerable deviations in comparison with the analytical results, as observed in Fig. (5). This damping tends to decrease with the advance of simulation time. Subsequently, from the time instant t = 30.00 s, the free surface elevation reaches the periodic state. In this time range of 30.00 s $\leq t \leq$ 45.00 s, it is observed a mean difference between the crests amplitude, calculated numerically and analytically, of approximately 1.20% and a mean difference between the cave amplitude of approximately 5.00%.

It is also noteworthy that, as it is a 2nd order Stokes wave, the crest amplitude and cave are distinct. Therefore, in a general way, it is possible to observe that the numerical model introduced in this study presents a satisfactory behavior when compared with the analytical solution.

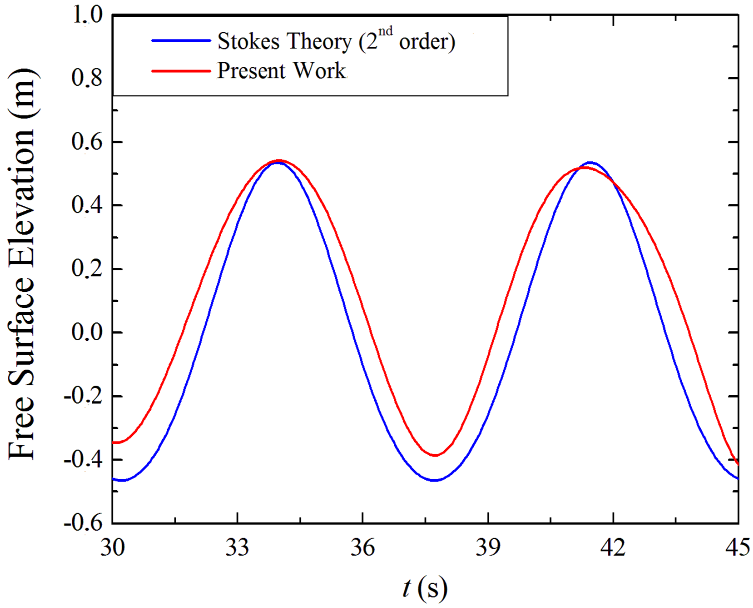

Figure 8. Numerical wave verification

Computational Model Verification

The solution to the numerical model of a real scale wave tank was obtained through the boundary conditions imposition using the UDF - used as a reference to evaluate this new procedure for wave generation - and the imposition of the same boundary conditions using the Table Data. The verification procedure occurred similarly to the case of a laboratory scale wave, i.e., by comparing the numerical results of free surface elevation obtained through the use of Table Data with the numerical results generated using the UDF.

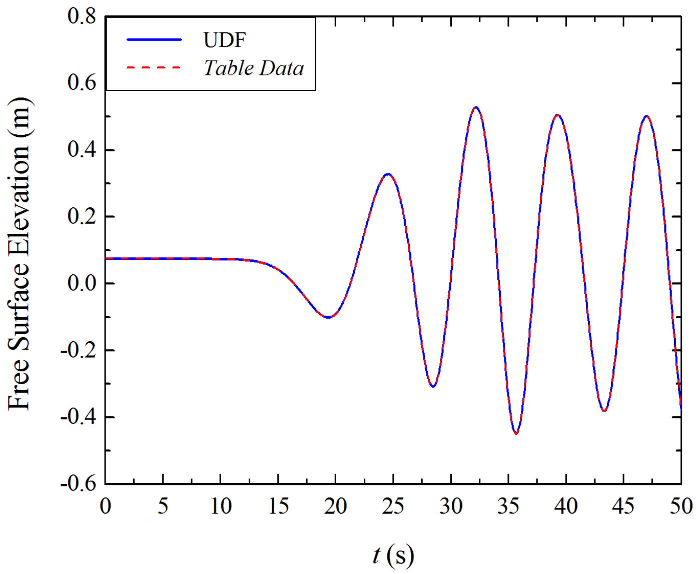

Figure 9. Computational Model verification for a real scale wave

It is observed on Fig. (9), that the waves generated through the UDF and Table Data methodologies are concordant, with a mean difference practically null (0.001%) between the wave amplitude. It is worth pointing out that, in both cases, the waves were monitored in the wave tank center (position x = 163.50 m). For the phenomenon analysis, two ranges of time are considered in the graph: in the first, 0.00 s $\leq t \leq$ 30.00 s, as previously mentioned, it is observed that the wave flow parts from the repose and due to the flow inertia, occurs a dampening of the first waves generated in the numerical tank. This damping tends to decrease with the advance of simulation time. Subsequently, to 30.00 s $\leq t \leq$ 50.00 s, the free surface elevation reaches the periodic state. There has not been employed a longer simulation time because, from the time instant of t = 50.00 s the first generated waves reach the wave tank end, i.e., from this time the wave free surface will be deviated due to the reflection phenomenon influence. It also highlights a reduction in the total processing time from 59 min (UDF) for 48 min (Table Data), representing a reduction of approximately 30% in total simulation time.

6 CONCLUSIONS

The contribution of this paper was to present a new methodology to the boundary conditions imposition of prescribed velocities for the regular wave generation in a wave tank. This procedure consists in the insertion of analytical horizontal and vertical data components of the velocity vector of wave propagation through the Table Data tool in FLUENT, instead of imposing through a user defined function, called the UDF, which, as shown here, has been widely used in previous studies. This new manner of imposing the boundary conditions adequately reproduces the analytical data and, also, faithfully reproduces the wave generation through the use of a UDF, besides, present a reduction in total processing time.

In future works it is intended to use this methodology to generate water free surface elevations which represent a realistic sea state condition. For this purpose, the methodology presented in this paper was studied. It also aims the application of this wave generation methodology in studies where Constructal Design method is used for geometrical evaluation of sea wave energy converters, aiming to improve the research for the study group which currently operates with Overtopping, Submerged Plate and the Oscillating Water Column devices.

6.1 Permission

The authors are the only responsible for the present material in this paper.

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