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Study of mesh sensitivity and temporal discretization influence on the generation of realistic irregular waves through the WaveMIMO methodology

Estudo da sensibilidade de malha e influência da discretização temporal na geração de ondas irregulares realísticas através da metodologia WaveMIMO

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ABSTRACT

The present study addresses the investigation of mesh sensitivity in the free surface (FS) region and the discretization of the time step (Δt) used in the generation of irregular waves through the WaveMIMO methodology. In this study, this methodology treats data that comes from the TOMAWAC spectral model to obtain realistic orbital velocity profiles of wave propagation, which are subsequently imposed as inlet boundary conditions in the wave channel. Therefore, realistic data are considered relating to a point close to Molhes da Barra in Rio Grande, Rio Grande do Sul. The numerical simulations were carried out in Fluent, a computational fluid dynamics software based on the finite volume method. The volume of fluid multiphase model was used to treat the water-air interface. For the discretization of the FS, four cases were investigated, the first was suggested in the literature, and the other three cases subdivided the region into 4 segments, which presented different discretizations among them. Regarding temporal discretization, 4 different cases were compared, relating the time step to the mean period (T_m) of the sea state considered. The best results were obtained for the combination of 60 mesh elements in FS and $\Delta t = T_m/120$.

Keywords: WaveMIMO methodology; Irregular waves; Realistic sea state; Mesh sensitivity; Time step independence

RESUMO

O presente estudo aborda a investigação da sensibilidade de malha na região de superfície livre (SL) e a discretização do passo de tempo (Δt) empregados na geração de ondas irregulares através da metodologia WaveMIMO. Nesse estudo, essa metodologia trata dados que provém do modelo espectral TOMAWAC para obtenção de perfis de velocidade orbital de propagação de ondas realísticas, que posteriormente são impostos como condição de contorno na entrada do canal de ondas. Para tanto, são considerados dados realísticos referentes a um ponto próximo aos Molhes da Barra, em Rio Grande, no Rio Grande do Sul. As simulações numéricas foram realizadas no Fluent, software de dinâmica dos fluidos computacional baseado no método de volumes finitos. O modelo multifásico *Volume of Fluid* foi utilizado no tratamento da interface água-ar. Para a discretização da SL foram investigados quatro casos, o primeiro, sugerido na literatura e os outros três casos, subdividem a região em 4 segmentos, que, apresentam distintas discretizações entre si. Quanto à discretização temporal, comparou-se 4 casos distintos, relacionando o passo de tempo com o período médio (T_m) do estado de mar considerado. Os melhores resultados foram obtidos para a combinação de 60 elementos de malha na SL e $\Delta t = T_m/120$.

Palavras-chave: Metodologia WaveMIMO; Ondas irregulares; Estado de mar realístico; Sensibilidade de malha; Independência de passo de tempo

1 INTRODUCTION

Aiming to decouple energy production from non-renewable sources as much as possible, Hernández-Fontes et al. (2020) indicate the ocean's energy resources as an alternative, both on a large scale, where there is high availability of resources, and on a smaller one, where the needs of towns in coastal regions can be met. According to Pecher and Kofoed (2017), through the extraction and conversion of energy contained in waves, the ocean is capable of supplying a significant part of the global demand for electric energy.

That energy might be extracted by different types of converters, devices such as: oscillating water column, oscillating bodies, overtopping, and submerged horizontal plate (Pecher & Kofoed, 2017; Seibt et al., 2023), among other models. Both experimental and numerical studies are carried out to improve these converter devices. Regarding the numerical studies, Machado et al. (2021) presented and verified the WaveMIMO methodology, in which discrete transient wave propagation data is obtained and used as a prescribed velocity boundary condition (BC) in a wave channel, to numerically simulate the generation of irregular waves based on realistic sea states, reproducing the natural phenomenon.

Thus, to contribute to the improvement of the WaveMIMO methodology (Machado et al., 2021), the present study aims to evaluate the discretization of the free surface (FS) region and the influence of temporal discretization upon the generation of realistic irregular waves. Thereby, realistic sea state data referring to the municipality of Rio Grande (RG), in the state of Rio Grande do Sul (RS), Brazil are considered.

2 MATHEMATICAL AND NUMERICAL MODELLING

To carry out the study, numerical simulations of the generation of irregular waves in a channel were developed using Fluent, which is a computational fluid dynamics (CFD) software based on the finite volume method. The multiphase model volume of fluid (VOF), proposed by Hirt and Nichols (1981), is used to treat the interface of the phases, water and air, which are represented using the concept of volumetric fraction (α). The sum of the phases in each control volume must be unity, therefore, each computational cell might be in three different states, filled with water, where:

$$\alpha_{water} = 1 \tag{1}$$

filled with air, where:

$$\alpha_{air} = 1 \tag{2}$$

or containing both phases, where:

$$\alpha_{water} + \alpha_{air} = 1 \tag{3}$$

Furthermore, as these fluids are immiscible, *i.e.*, they do not mix, it is worth that:

$$\alpha_{water} = 1 - \alpha_{air} \tag{4}$$

When using the VOF model, there is a single set of equations, which is composed of the conservation of mass, volumetric fraction, and momentum equations. According to Versteeg and Malalasekera (2007), the rate of mass increase in the element is equal to the net rate of mass flow in the element:

$$\frac{\partial\rho}{\partial t}\Delta x\Delta z = [-\frac{\partial\rho u}{\partial x} - \frac{\partial\rho w}{\partial z}]\Delta x\Delta z \quad (5)$$

where:
ρ is the fluid specific mass (kg/m^3);
t is time (s);
u and w are, respectively, the flow velocities (m/s) in the horizontal (x) and vertical (z) directions of the coordinate system (m), which make up the velocity vector ($\vec{v}$).

Thus, carrying out simple algebraic manipulations, the mass conservation equation is obtained:

$$\frac{\partial\rho}{\partial t} + \nabla(\rho\vec{v}) = 0 \quad (6)$$

Similarly, replacing ρ with α, we obtain the volumetric fraction conservation equation:

$$\frac{\partial\alpha}{\partial t} + \nabla(\alpha\vec{v}) = 0 \quad (7)$$

Furthermore, still according to Versteeg and Malalasekera (2007), Newton's second law states that the rate of change in momentum of a fluid particle is equal to the sum of the forces on the particle. This results in the conservation of momentum equation:

$$\rho\frac{\partial\vec{v}}{\partial t} + \rho\nabla(\vec{v})\vec{v} = -\nabla p + \nabla(\bar{\bar{\tau}}) - p\vec{g} + S \quad (8)$$

where:
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).

Also, it should be noted that S is the sink term, referring to the numerical beach tool, used to avoid wave reflection, which is given by (Lisboa et al., 2017):

$$S = -[C_1 V + \frac{1}{2}C_2|V|V](1 - \frac{z - zf_s}{z_b - zf_s})(\frac{x - x_s}{x_e - x_s})^2 \quad (9)$$

where:
C_1 and C_2 are, respectively, the linear (s^{-1}) and quadratic (m^{-1}) damping coefficients, respectively, defined as 20 s^{-1} and 0 m^{-1} (Lisboa et al., 2017);
V is the fluid velocity module at the analyzed point (m/s);
z_{FS} and z_b are the vertical positions of the FS and the bottom (m);
x_s and x_e are the horizontal start and end positions of the numeric beach (m).

2.1 Realistic Irregular Waves Generation

To generate realistic irregular waves in Fluent, it was used the WaveMIMO methodology, presented by Machado et al. (2021), which imposes discretized orbital velocity profiles of wave propagation in horizontal (u) and vertical (w) directions as inlet BC. Therefore, realistic sea state data were treated, which, in the present study, come from the TOMAWAC spectral model, which, in turn, are obtained by solving the equation that represents the general situation of wave propagation in an unstable and non-homogeneous given by (Awk, 2017):

$$\frac{\partial N}{\partial t} + \frac{\partial(\dot{x}N)}{\partial x} + \frac{\partial(\dot{z}N)}{\partial x} + \frac{\partial(\dot{K}_x N)}{\partial K_x} + \frac{\partial(\dot{K}_z N)}{\partial K_z} = Q(K_x, K_z, x, z, t) \tag{10}$$

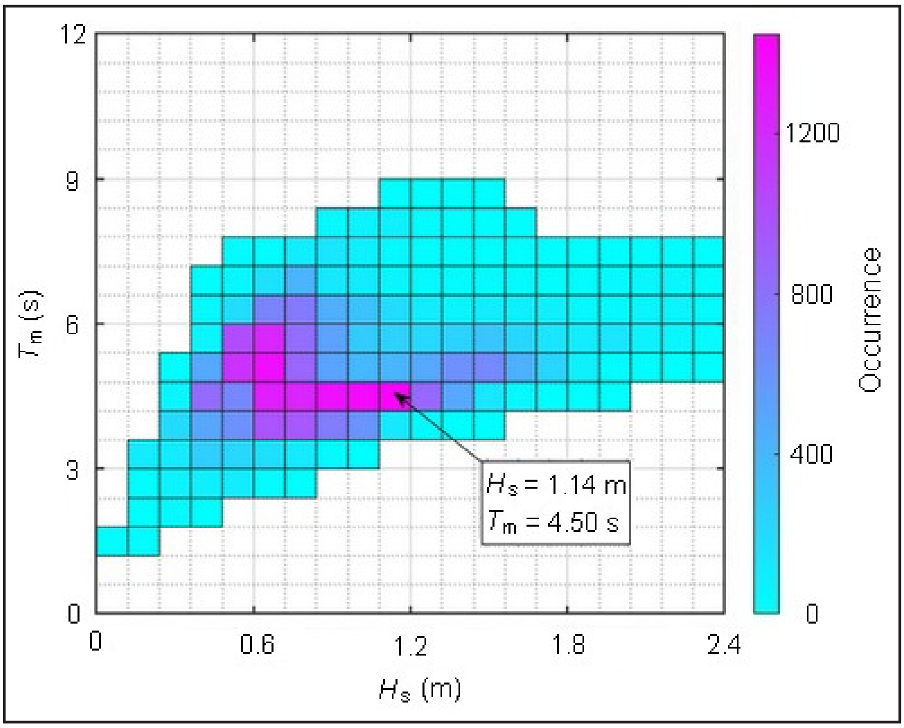
where:
N represents the directional spectrum of wave action density (m^2/Hz/rad);
K_x is the x component of the wavenumber vector (m^{-1});
K_z is the component in z of the wavenumber vector (m^{-1});
Q is the source term (m^2/rad).

After the sea state data are obtained, the wave spectrum is transformed into a time series of FS elevation, through the procedure proposed in Oleinik et al. (2021). Thus, the spectral data are approximated by a finite sum of monochromatic waves, described individually, according to Airy's Linear Wave Theory (Airy, 1845), which allows to obtain the velocity profiles necessary for the generation of realistic irregular waves.

2.2 Realistic Sea State Data

The realistic sea state data considered in the present study refers to the point with geographic coordinates -52°4' 45.08" W, -32°11' 24.92" S, located 171.06 m from the Molhes da Barra breakwater, in RG. To determine the most frequent sea state occurred in the study region, the realistic data of significant height (H_S) and mean period (T_m) referring to the year of 2018 were analyzed. Therefore, Figure 1 shows the bivariate histogram that relates the occurrences of H_S and T_m and points out the most frequent combination, which occurred in November 9, 2018 at 07:15.

Figure 1 – Bivariate histogram of H_S and T_m combinations



Source: the authors (2023)

Afterward, aiming to establish the regular waves representative of this sea state, which is used as a reference for the spatial and temporal discretization of the computational domain, the wavelength (λ) was calculated. Therefore, the dispersion relation was used, which is given by (McCormick, 2010):

$$\omega^2 = gk \tanh(kh) \tag{11}$$

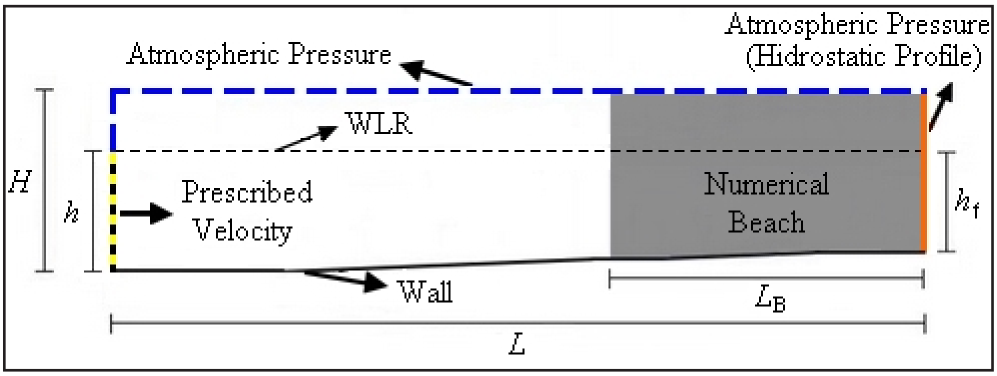
Thus, the characteristics of the representative regular waves are: height $H_S = 1.14$ m; length $\lambda = 31.50$ m; period $T_m = 4.50$ s; and depth $h = 13.29$ m. Furthermore, it should be highlighted that h refers to the depth found at the location of the selected point.

3 PROBLEM DESCRIPTION

The wave channel used (Figure 2) has length $L = 171.06$ m, which is the distance found between the selected local and the Molhes da Barra breakwater; height $H = 16.00$ m; and depth that varies from $h = 13.29$ m, at the point region, up to $h_f =$

10.54 m, at the breakwater region, following bathymetric data from the Hydrography and Navigation Directorate of the Brazilian Navy, digitized by Cardoso et al. (2014). Moreover, in accordance with Lisboa et al. (2017), the numerical beach has a length (L_B) of 2λ. Finally, Figure 2 also illustrates the computational domain, where the boundary conditions are presented. Furthermore, WLR represents the water level at rest.

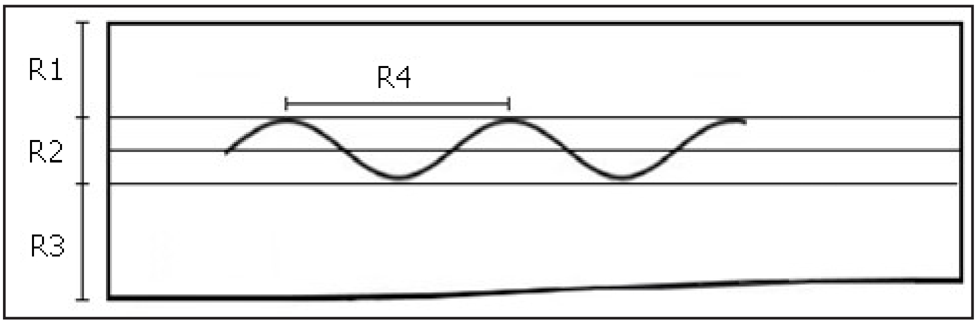
Figure 2 – Computational Domain Illustration



Source: the authors (2024)

For the computational domain spatial discretization, the recommendation of Gomes et al. (2012) was considered for the stretched mesh (Figure 3). Thus, there are three vertical regions in the computational domain: R1, containing only air, discretized into 20 computational cells; R2, the FS region, investigated in the present study; and R3, containing only water, discretized into 60 cells. Horizontally, it was applied 50 computational cells per λ. Furthermore, a time step of 0.05 s was used, as in Machado et al. (2021).

Figure 3 – Stretched mesh configuration



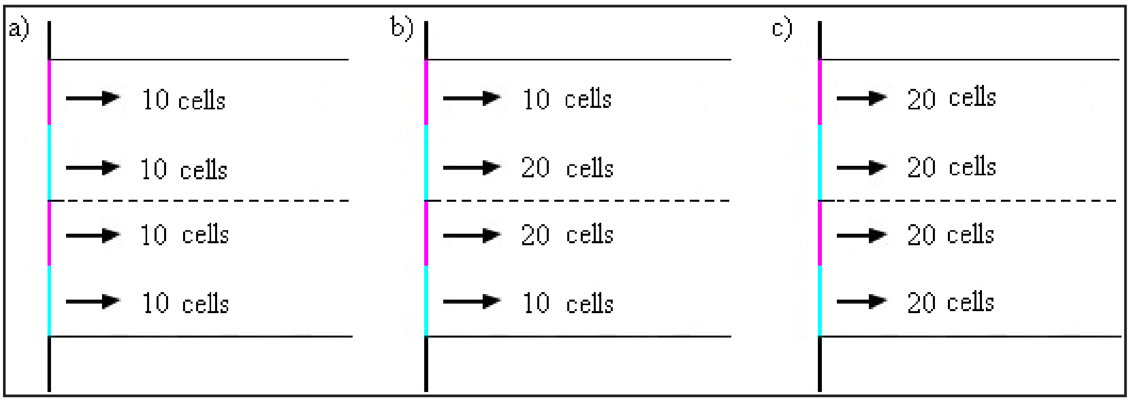
Source: the authors (2024)

Thus, the first study carried out is the one that investigates the mesh sensitivity, in the first case investigated (Case 1), the Machado et al. (2021) recommendation was used, which subdivides the region where the prescribed velocity BC is imposed into 14 segments of size $h/14$. Therefore, the FS region has two segments, one below and one above the WLR, discretized according to the recommendation of Gomes et al. (2012).

In addition to the aforementioned case, three other discretization approaches were considered, in which the segments that make up the FS region were divided into 2 of size $h/28$, while the remaining 13 segments of the prescribed velocity imposition region were maintained with size $h/14$. Thus, the evaluated cases, illustrated in Figure 4, are defined as:

- Case 2: each segment was discretized with 10 computational cells, totaling 40, as in Gomes et al. (2012);
- Case 3: the segments close to the WLR were discretized into 20 computational cells, while in the others it was used 10, totaling 60 cells, in a manner analogous to that suggested in Romanowski et al. (2019), which indicates the need for greater refinement in the area of greatest concentration of wave elevations;
- Case 4: each segment was discretized with 20 cells, totaling 80, twice the refinement adopted in Case 1.

Figure 4 – FS Discretization: (a) Case 2; (b) Case 3; (c) Case 4



Source: the authors (2023)

As for the temporal discretization investigation, the time step (Δt) influence was analyzed. Therefore, Δt was related to the T_m in order to evaluate four distinct cases: Case 5: $\Delta t = T_m/60$, where $\Delta t = 0.0750$ s;

- Case 6: $\Delta t = T_m/90$, where $\Delta t = 0.0500$ s;
- Case 7: $\Delta t = T_m/120$, where $\Delta t = 0.0375$ s;
- Case 8: $\Delta t = T_m/150$, where $\Delta t = 0.0300$ s.

Regarding the total simulation time, it was considered 900 s of generation and propagation of waves for all analyzed cases. Therefore, aiming to determine the best case tested in each analysis carried out, a probe was used to monitor the FS elevation $x = 0$ m, *i.e.*, in the wave generation zone. Then, the results obtained in the simulations were compared, individually, with the FS elevation from the TOMAWAC spectral model through the metrics MAE (Mean Absolute Error) and RMSE (Root Mean Square Error) represented, respectively, by (Chai & Draxler, 2014):

$$\mathrm{MAE} = \frac{\sum_{i=1}^{M} |O_i - P_i|}{M} \tag{12}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{M} (O_i - P_i)^2}{M}} \tag{13}$$

where:
O_i represents the value found numerically in Fluent (m);
P_i the data from TOMAWAC (m);
M represents the total amount of data.

4 RESULTS AND DISCUSSIONS

To carry out a quantitative evaluation of the results found in the mesh sensitivity study, Table 1 presents the metrics MAE and RMSE calculated, as well as the processing time required in each case. It is possible to observe that the approach of dividing the segments that make up the FS proves to be assertive, since even Case 2, which has the same number of computational cells in the FS region (40) and presents little difference in the metrics and in processing time, it has better results than Case 1, which is based on recommendations from the literature.

Table 1 – Results of the mesh sensitivity in the FS region study

Case	MAE (m)	RMSE (m)	Processing Time (h)
1	0.110010	0.143264	8.22
2	0.109854	0.143104	8.05
3	0.107813	0.140381	9.17
4	0.108386	0.141013	10.3

Source: the authors (2024)

As seen in Table 1, another assertive approach is the one adopted in Case 3, the best case analyzed, where the central segments of the SL, those closest to the WLR, are discretized with greater refinement than the other segments. Despite having 60 computational cells in the FS region, Case 3 presents smaller metrics than Case 2, which has 80 cells in the same region, indicating that further refining the FS region where most elevations occur leads to more accurate results than greater refining in the FS region as a whole.

Furthermore, it should also be noted that the processing time is directly proportional to the refinement applied to the evaluated meshes. Thus, the mesh configuration from Case 3 was adopted for the subsequent study, where the influence of temporal discretization was evaluated, being the quantitative results presented in Table 2.

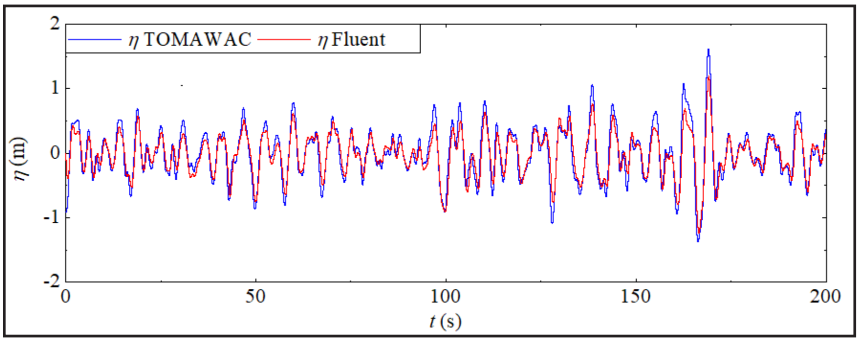
Table 2 – Results of the temporal discretization study

Case	Time Step (Δt)	MAE (m)	RMSE (m)	Processing Time (h)
5	$T_m/60$	0.110460	0.143543	6.15
6	$T_m/90$	0.107813	0.140381	9.17
7	$T_m/120$	0.106848	0.139250	12.3
8	$T_m/150$	0.119071	0.157183	16.13

Source: the authors (2023)

As can be seen in Table 2, Case 7 presented the best results, with metrics MAE and RMSE, respectively, 3.27% and 2.99% smaller than Case 6, which coincides with the recommendation in Machado et al. (2021) of $\Delta t = 0.05$ s. Furthermore, Case 7 presents metrics MAE and RMSE, respectively, 10.27% and 11.40% smaller than Case 8, the worst case analyzed. Finally, it is worth to highlight that the processing time is inversely proportional to the time step analyzed.

Figure 5 – Qualitative comparison of the results obtained for the best combination evaluated



Source: the authors (2023)

In all cases evaluated, the realistic irregular waves generated through the WaveMIMO methodology reproduced the elevations of the irregular waves that came from the spectral model accordingly. However, as the FS elevations present little difference, it would not be possible to distinguish them qualitatively. Thus, in Figure 5 the FS elevations monitored in Case 7 are presented and compared with the data coming from TOMAWAC, where, to facilitate the visualization of the results, only the first 200 s are displayed.

As shown in Figure 5, despite the differences that occur in the troughs and, especially, in the crests, it was possible to accurately reproduce the realistic irregular behavior of the sea state in the study region using the WaveMIMO methodology. Furthermore, considering the MAE and RMSE metrics presented in Tables 1 and 2, it is noted that it was possible to improve the performance of the WaveMIMO methodology through adjustments on the mesh and the time step employed. When Case 7, the best case evaluated, is compared with Case 1, the recommendation on Machado et al. (2021), there are reductions on the metrics of 2.87% (MAE) and 2.80% (RMSE).

5 CONCLUSIONS

The present study sought recommendations for the use of the WaveMIMO (MACHADO et al., 2021) methodology, thereunto, studies of mesh sensitivity and time step influence were carried out. Regarding mesh sensitivity, the best results were obtained when each segment that makes up the FS region was divided into 2 segments of size $h/28$, and the greater mesh refinement is applied to the segments close to the WLR, discretizing these in 20 computational cells each and the remaining segments in 10 cells, totaling 60 cells in the FS region, which is in accordance with the recommendation of Romanowski et al. (2019).

As for the temporal discretization study, the best results were obtained when the relation between the Δt and the is $\Delta t = T_m/120$. Thereby, for future investigations, it is suggested similar studies to be carried out considering the wave climate found in other regions of the RS coast.

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