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PRESENCE OF ROLL WAVES IN CHANNEL AND SPILLWAY OF BARRAGE

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Abstract: Instabilities such as pulsating waves on the free surface are commonly called roll waves (shock waves), which propagate in both Newtonian and non -Newtonian fluid flows, in a laminar or turbulent regime. Such a phenomenon can arise in artificial channels, in natural environments due to disasters, transport in gas pipelines, etc. When they occur in natural disasters, roll waves, due to the amplitude and speed of propagation, end up increasing the damage created. In this work, a study on roll waves in Newtonian fluid in turbulent flow with free surface is carried out using the commercial software Ansys fluent. Two case studies are analyzed : the classic literature experiment carried out by Brock and the spillway of the azad dam in Iran, initially studied by Aghebatie et al. For both studies, the standard turbulence models are analyzed. **k - ε** and *standard* **k - ω** in addition to analyzing the velocity profile and the shear stress at the bottom of the channels. The model **k - ω** proved to be more effective for the Brock experiment, but not for the spillway case. the signifier increase in shear stress was observed in both cases, either in the presence of stabilized roll waves (Brock's case) or in the presence of instabilities that appeared in the azad spillway.

Keywords: Roll waves; flow turbulent ; Spillway of Dam.

INTRODUCTION

Roll waves are waves that can appear in shallow water flows (Balmforth and Mander, 2004; Dressler, 1949; Brock 1969), propagating with well-defined speed, length and amplitude, in the shape of a wave train. roll waves can occur in both Newtonian and non -Newtonian fluid flows. (Liu and Mei, 1994; Coussot, 1994, Balmforth and Liu, 2004, Di Cristo et al., 2013, Tamburrino and Ihle, 2013, Maciel et al. 2017, Ferreira et al, 2021, Maciel et al., 2021). These instabilities, when under favored conditions, appear both in channels with free surface and in closed channels, for example, in gas pipelines (Gaspari, 2013). So, the study of *roll waves* is of both environmental and industrial interest. although the phenomenon occurs more frequently in artificial channels, the *roll waves* they can also ok found in natural flows such as rivers, those produced by disasters such as debris flows, mudflows and avalanches. in the event of natural disasters, the presence of these waves pass an aggravating factor, since the wave fronts potentiate the destructive power of the disaster, whether in non - Newtonian or Newtonian fluids. In the case of Newtonian fluids, such as water, waves can have significant propagation speeds, in addition, the flow is notably turbulent.

The study of the phenomenon *roll waves* in free surface flow began with Cornish (1910), when hey visualized the phenomenon in the Merligen channel in turbulent flow. Jeffreys (1925) determined the first condition of there of the phenomenon for turbulent flows, based on the Froude number, in which for Fr > 2, would occur *roll waves.*

Dressler (1949developed a work that became classic within the context of *roll waves* He described the phenomenon as a series of waves of well-defined lengths and interconnected by discontinuities through shock conditions. The theoretical foundation of dressler's work (1949) is still widely used by researchers. in the context of roll waves in turbulent flows, studies have been carried out both with an experimental approach (Brock, 1969; Miao et al., 2017; Miao et al., 2020), as a mathematical and numerical approach (Zanuttigh and Lamberti, 2002; Richard and Gavrilyuk, 2012; Cao et al., 2014; Ivanova et al., 2018) where the authors have been proposing changes in the k-ε turbulence model to better represent the evolution of the phenomenon. It is known in the literature that the presence of the phenomenon affects the shear stress at the bottom of the channel, which, depending on the flow conditions, such an increase can ok up to 30%. (Liu et al., 2005; Toniati, 2018, Maciel et al., 2018) compared to the uniform regime.

This increase in shear stress is significant in natural disasters as it directly affects sediment transport, as well as in pipelines or dam spillways, due to eventual cavitation effects.

The study on roll waves in dam spillways was carried out by barzagan and Aghebatie (2015) as well as Aghebatie and Hosseini (2016) who used the commercial software ANSYS Fluent for the simulation of roll waves in the spillway of the azad dam. For the simulation, the volume of Fluid (VoF) model and the Standard k-ε turbulence model were used, the results were compared with experimental results obtained in a prototype spillway built in Hydraulic structures department of Iran Water Research Institute (IWRI) for model calibration. in the work, the authors state that the k-ε model was the closest to the experimental results, but did not present comparisons between the results of the different turbulence models. Furthermore, the work does not discuss the velocity field or the shear stress at the bottom of the spillway, during the presence of *roll waves.*

Within this context, these authors revisit those works and simulate (as a test case)) *roll waves* in turbulent flows based on classic Brock experiments, using turbulence models and and verify that the k-ω model showed better agreement with the Brock experiment (Peres et al., 2019). Thus, the proposal of this work extends and also at to analyze and compare the numerical results for the spillway of the azad dam using the turbulence model *Standard* , in addition to discussing the implications of changing the velocity field and the shear stresses, parameters that were not addressed in previous works and are still little discussed in the literature.

NUMERIC MODELING

STUDY OF CASE 1: EXPERIMENT OF BROCK

Brock's (1969) experiment used clean water as the test fluid initially, flowing through a channel 39.6 m long and 0.1175 m wide, with slopes of 2.87° and 4.83°. with these experiments, Brock made these of the *roll waves* said natural, which are waves generated without the control (imposition) of a disturbance frequency and also the roll waves generated from a disturbance imposed on the system, by an articulated plastic blade connected to a variable speed motor, enabling the generation of *roll waves* periodic (forced system). Brock verified in his experiments the roll wave generation criterion established by Jeffreys (1925), i.e. $Fr > 2$.

Subsequently, the length of the channel tested by Brock (1969) was reduced to 24.4 m and sand was added to the bottom and side walls, uniformly (average diameter of 0.6 mm), in order to study the influence of roughness. wall on the generation of *roll waves,* the slope used in this test was 6.85°, varying flow rates and disturbing frequencies. In this work, the simulations under experimental conditions used by Brock (1969) are presented, according to Table 1.

tanΘ	**channel**	h_0**[mm]**	***Fr***	**T(s)**	**Re**
0.05011	Straight	7.98	3.71	1,218	$3.11\ 10^{4}$

Table 1- Parameters used by Brock in the experiment of *roll waves* stabilized in a 36.9 m channel.

Where θ is the slope of the channel; the normal depth of flow; *Fr* the Froude number $Fr = \frac{\bar{u}}{(gh_o cos\theta)^{1/2}}$, T the period of the imposed disturbance., Re the Reynolds number $Re = \frac{4\, R_h\, \bar{u}}{\upsilon}$, R_h the hydraulic radius, $\bar{u}$ the average velocity of uniform flow, the kinematic viscosity of the fluid.

For the numerical simulation, the software ANSYS Fluent was used, the mesh is 2D composed of rectangular elements. A mesh sensitivity analysis was performed using the Grid Coefficient Index (GCI) method with three different mesh sizes, the coarsest mesh (437,745 elements) was not adequate for the representation of the phenomenon, while the intermediate mesh (750,650 elements) and the most refined mesh (1,138,735 elements) proved to be adequate, showing a difference in wave properties of less than 3%. The results presented here are for the intermediate mesh. The boundary conditions used are shown in figure 1.

The *software* Fluent (version 14.5.7) offers several options for discretization models and solvers containing variables that can affect convergence and the desired solution. The multiphase model used was the VoF (Volume of Fluid), the viscous models were *Standard* k-ω and *Standard* k-ε, for pressure and velocity coupling Simplec was used, and for pressure, Presto, the momentum is solved by Third Order MUSCL (Monotonic upwind Scheme for Conservation Laws) and the volume fraction obtained by Modified HRIC (High Resolution Interface Capturing).

CASE STUDY 2: AZAD SPILLWAY

The physical prototype of the Azad spillway built at IWRI in scale 1:33.33 in acrylic, using inlet discharges of 500 m^3/s and 800 m^3/s, the main hydraulic characteristics, such as flow depth, pressure and velocity, were measured at about 50 points across the prototype. Figure 2 shows a schematic of the spillway.

The mesh is two-dimensional (2D) and composed of 250,000 rectangular elements and without discontinuities, there is a greater refinement at the bottom of the channel in order to adapt to the turbulence model. The boundary conditions to be used are represented in figure 3. Wall condition is applied at the top of the inlet and at the bottom of the spillway, pressure outlet condition at the top and at the outlet of the spillway, and inlet condition of mass flow at the bottom of the inlet, the dry bottom condition is also applied.

The same *solvers* as in the Brock case (case 1) were used, with the difference that in case 2 only the *Standard model was analyzed* k-ω, since the *Standard model* k-ε had already been tested by Aghebatie and Hosseini (2016) and Bazargan and Aghebatie (2015). It is worth noting that the flow studied was 800 m^3/s and that for the spillway none upstream disturbance has been imposed, or that is, the occurrence or no instabilities on the spillway free surface it came naturally.

RESULTS

CASE STUDY 1: BROCK'S EXPERIMENT

Roll stabilization *waves* occurred after 30m of channel for properties such as speed, amplitude and well-defined wavelength, such experimental properties and the result of the simulations of the different turbulence models are presented in table 2.

Another way to compare the results obtained is through Figure 4 which shows the profile of the stabilized waves in a dimensionless way, being the total length of the wave.

Standard turbulence model k-ω proved to be more effective in determining the properties of *roll waves* obtained experimentally by Brock (1969), presenting an error in the wave amplitude of 4.4%, while the *Standard model* k-ε proved to be more effective in relation to

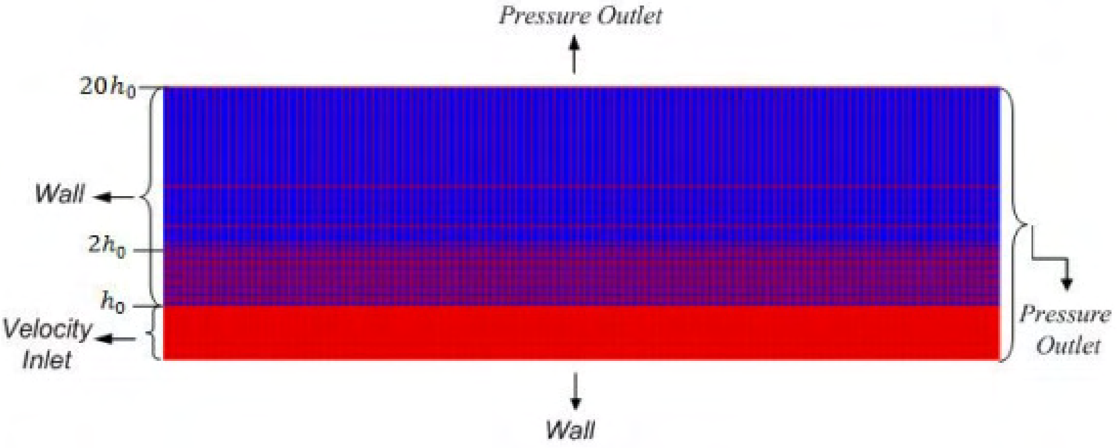

Figure 1.- **Boundary** Conditions Adopted to simulate Brock's experiment.

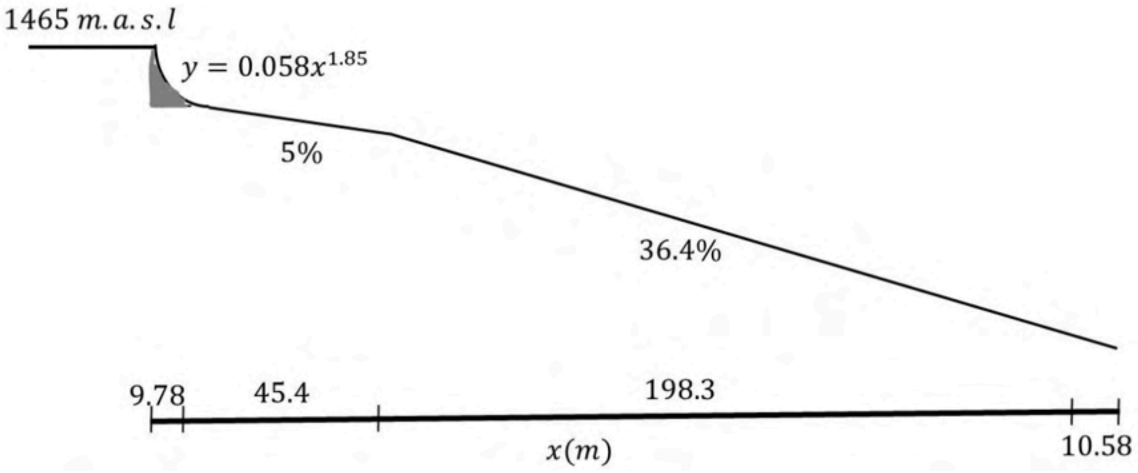

Figure 2.- Longitudinal Section of the Spillway Azad Source: Adapted from Aghebatie and Hosseini (2016).

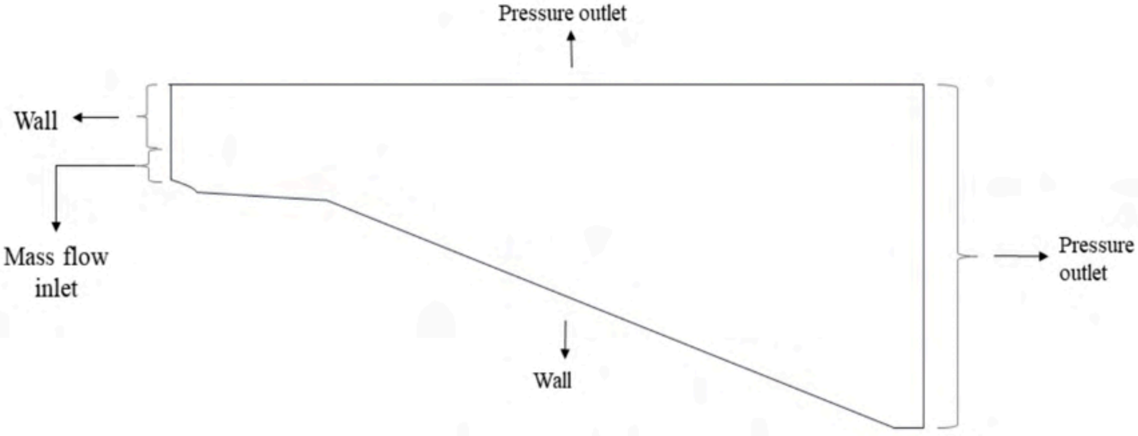

Figure 3.- Boundary conditions adopted. Azad spillway

Results	length [m]	Amplitude [m]	propagation speed [m/s]	Frequency $[s^{-1}]$
Experimental	1.81	0.0130	1.50	0.83
Model k - ε	1.87	0.0147	1.55	0.82
Model k - ω	1.73	0.0136	1.44	0.82

roll properties stabilized *waves.*

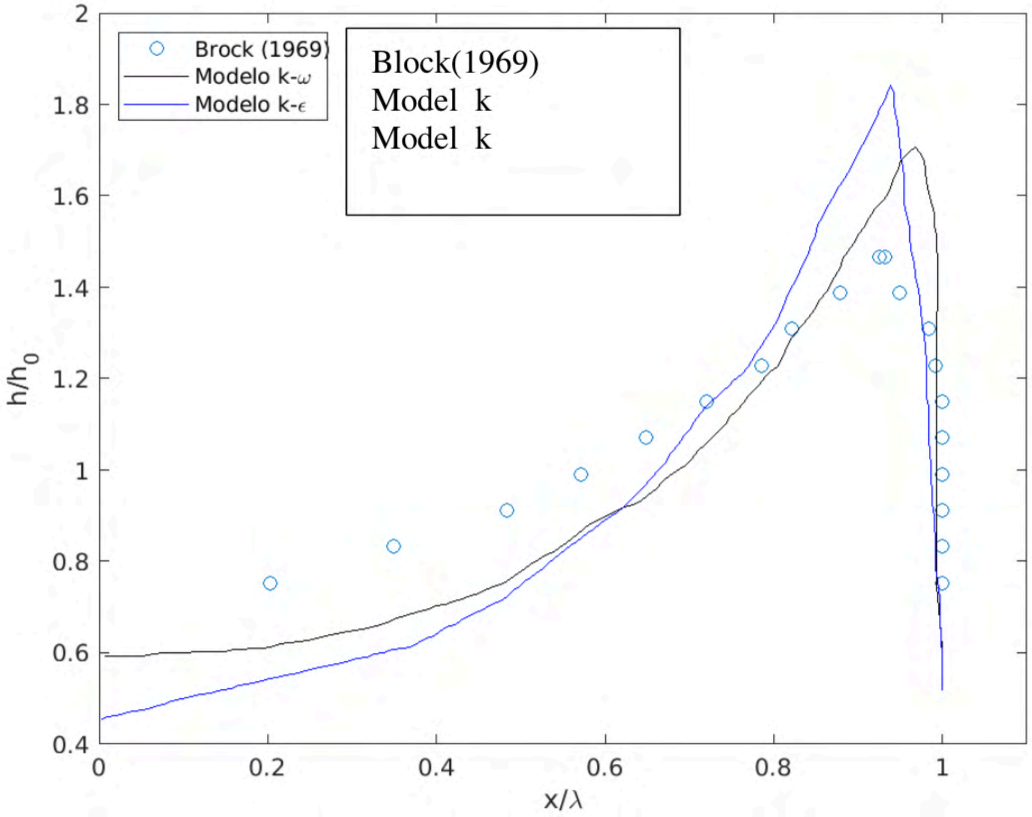

Figure 4.- Comparison of experimental wave profile and simulations.

the point (x/λ) where the peak of the wave occurs, still in figure 4 it is interesting to note how the wave profile is typical of a shock wave as proposed by Dressler (1949).

Figure 5 shows the velocity field in the presence of *roll waves.* The shear stress at the bottom of the channel in the region where the *roll waves* are already developed and stabilized is shown in Figure 6.

Analyzing figures 5 and 6 it is possible to realize that the occurrence of the phenomenon *roll wave* in the flow led to a 63 % speed increase over speed average of the uniform flow in the regions close to the wave shock (larger depth of flow) and 28% in the maximum shear stress at the bottom of the channel in relation to the uniform flow shear stress, which corroborates the results of Toniati (2018) and Liu *et al.* (2005).

CASE STUDY 2: AZAD SPILLWAY

In figure 7 are contours of the water -air interface are presented for different points of the channel, where it is possible to visualize instabilities in the free surface propagating through the spillway. In figure 8 we have the variation of the free surface as a function of time, obtained with the insertion of "monitors" (numerical probes) in 15 measurement points along the spillway.

Through figure 7, it is possible to observe the existence of instabilities in the free surface, however, it is not possible to visualize the propagation in the form of a stabilized train of waves, as observed in the Brock channel and in the simulations carried out in this work whose *roll waves* were generated with the imposition of a disturbance. For the Azad spillway, the free surface variation is more evident through monitors that capture the free surface variation as a function of time (Figure 8). Through of these monitors, however, instabilities are observed at points x=134.94 m and x = 159.67 m, which present standards similar, with differences in the wave amplitudes, the same observation can be made between the points x=184.40 and x=209.12 m.

In addition Furthermore, it is possible to see that in the initial part of the spillway (up to 55 meters in length) the instabilities present maximum amplitudes of the order of 0.4 m, and that after one sudden change in Spillway slope (from 5% to 36.4%) there is a wave with a very steep profile (shock wave type) with amplitude of 1.20 m (point x=60.54 m), still in this slope the waves reach 1.40 m in amplitude.

Comparisons between the experimental results (Aghebatie ; Hosseini, 2015; Bazargan; Aghebatie, 2016), the numerical results obtained by the same authors using the turbulence model and those presented here for the k-ε *standard* turbulent model k-ω, can be seen in figure 9 for the depths of flow along the spillway and for surface velocities (figure 10). In addition Furthermore, data interpolations were performed to identify the behavior of depth and velocity. superficial along the length of the spillway.

The interpolations were carried out with 95% confidence limit for the adjustment coefficients. Through figure 9, it can be seen that the depth of the flow along the spillway it presents one significant decrease up to the first 90 m in length, with exception of measurement at x = 72.30 m. The depth behavior adjusts well to a _ occupation logarithmic In figure 10 it is observed that the surface velocity increases along the length of the spillway, the behavior fits well to a 2nd degree polynomial.

It is also observed that for both depth and surface velocity, the simulation with the model it shows results closer to the experimental ones when compared to the model , which in this analysis seems to underestimate the depth of flow. However, the behaviors are similar along the spillway, with coefficients that can be adjusted to the experimental model. It is

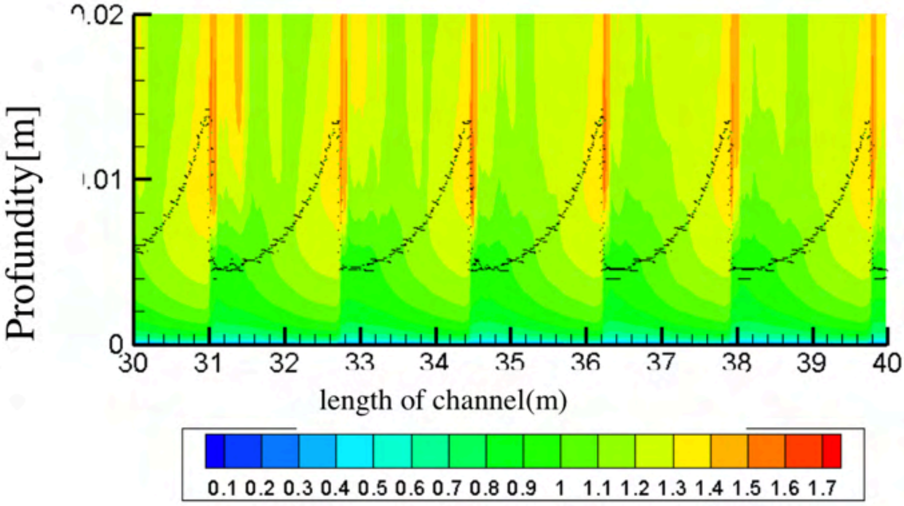

Figure 5.- Velocity field in (m/s) in presence of *roll waves.*

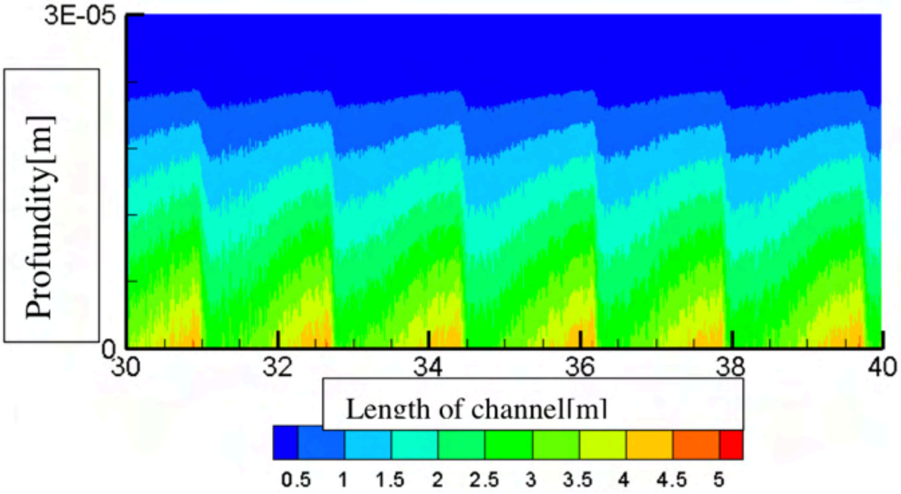

Figure 6.- Channel bottom shear stress (in Pascal) at presence of stabilized *roll waves.*

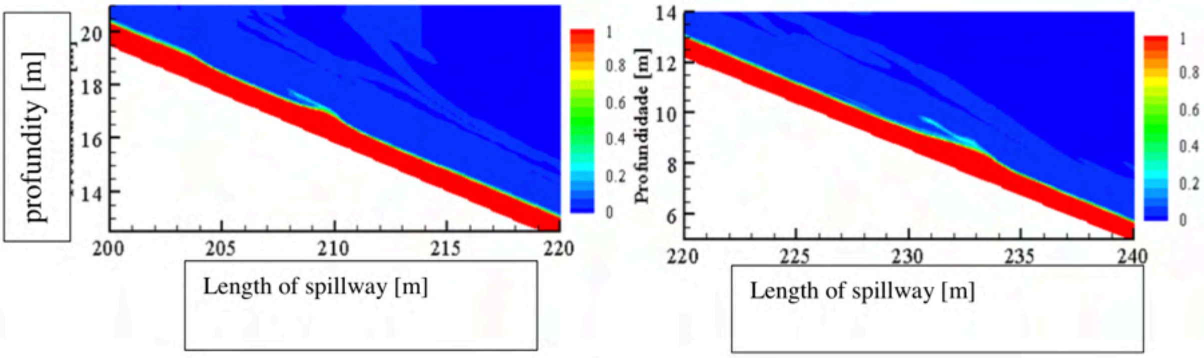

Figure 7.- Contour of the free surface along the spillway channel. For a flow time of 35 s.

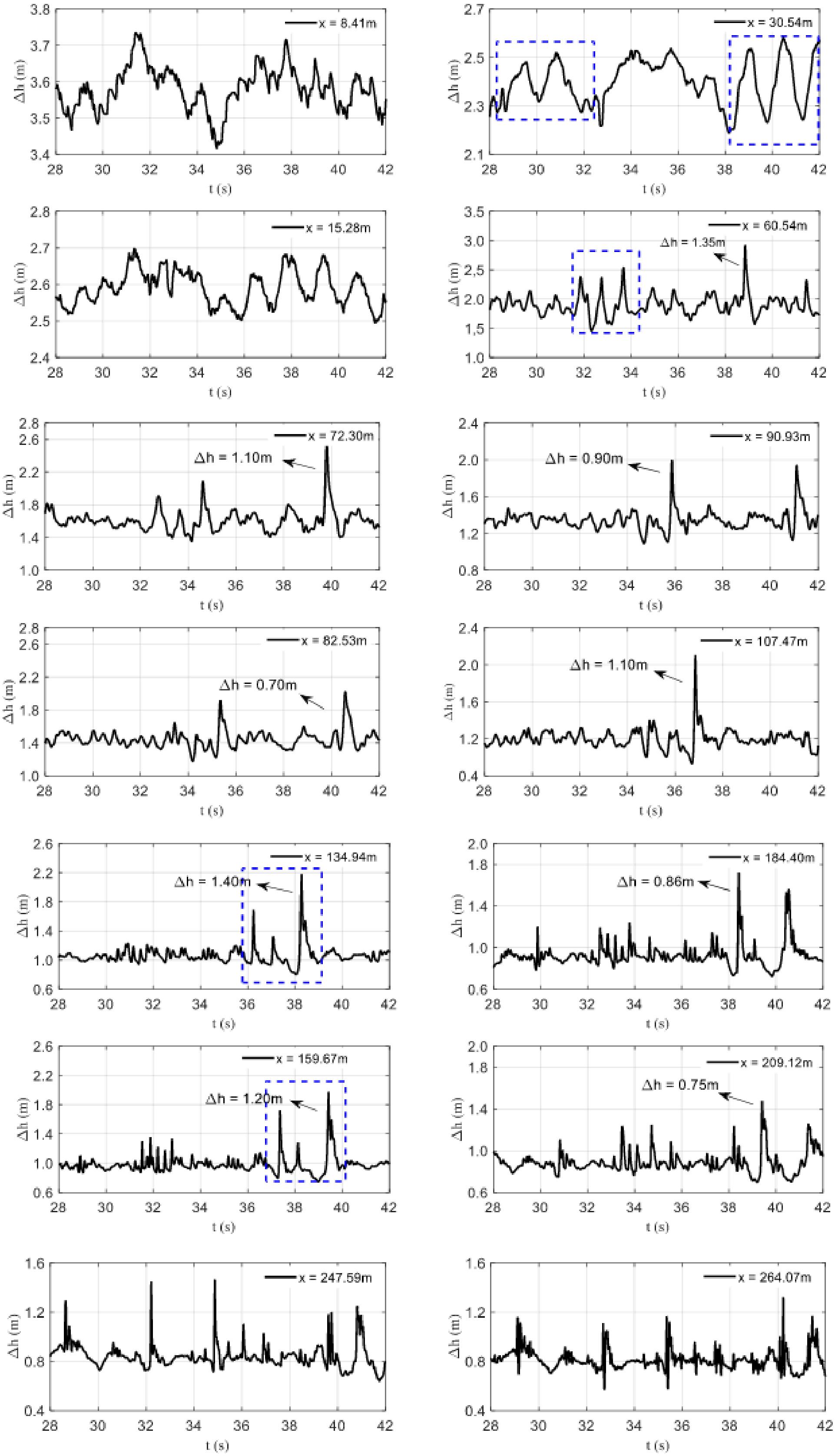

Figure 8.-Free surface variation as a function of time.

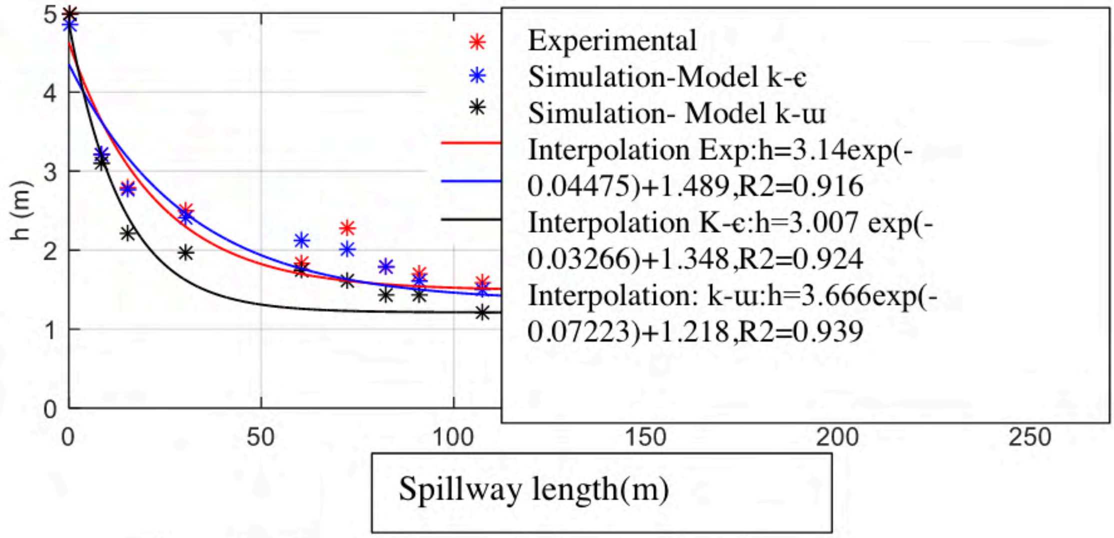

Figure 9. - Free surface variation as a function of time.

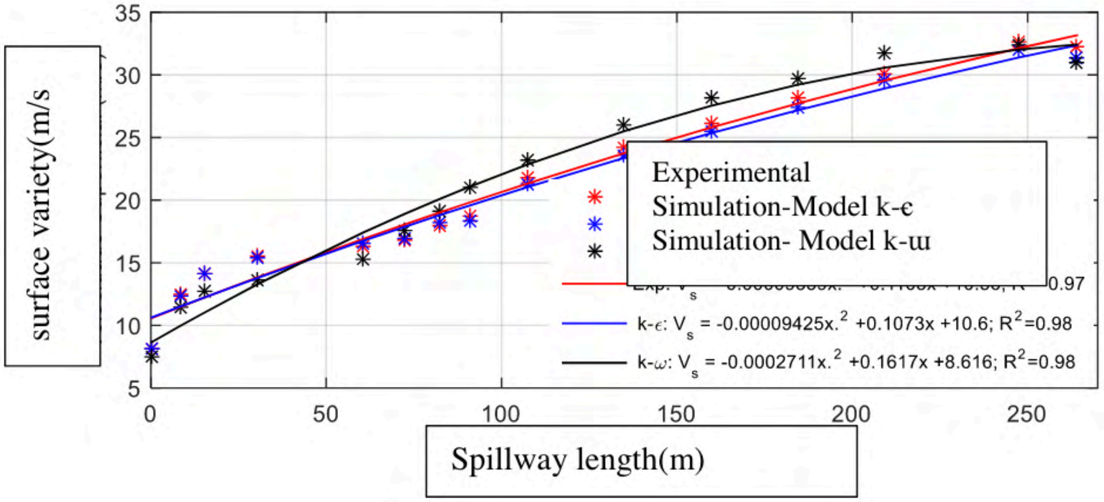

Figure 10. - Surface runoff velocity.

worth mentioning that there was no access to the analysis of experimental errors.

Figure 11 shows the shear stress values at the bottom for the different measurement points. along the length of the spillway. In figure 12 the shear stress is related to the depth of flow and in figure 13 the shear stress is related to the surface velocity.

Through the analysis of Figure 11, we can see that the shear stress at the bottom of the spillway as a function of the length of the channel approaches the behavior of a quadratic equation, similar to the analysis of the surface velocity as a function of the length of the channel (figure 10), the shear stress growth rate is higher in the region of greater slope (36.4%), showing a small drop when reaching the region of low slope.

Analyzing figures 12 and 13, it can be seen that the highest values of shear stress and consequently of friction velocity do not occur in the regions of greater amplitudes, in this case, they occur in the regions of greater surface velocities, it is then concluded that for this case study, velocity proved to be a predominant factor on the shear stress at the bottom of the channel and not the depth of flow, as seen in the case study of Brock (1969). It is worth mentioning that the Brock channel has a constant slope and the flow velocity presented small variations due only to the *roll formation. waves.*

CONCLUSION

In this work, numerical simulations of *roll waves* in turbulent flows based on the experiments of Brock (1969) and on the Azad spillway, using the *software* fluent. The simulations were performed for two turbulence models: *standard* $k-\varepsilon$ and *standard* $k-\omega$, the latter being less recurrent in the literature.

For the case study carried out, the results pointed to waves with a profile of typical shock waves, according to the results of the literature (Dressler, 1949). Furthermore, the $k-\omega$ turbulence model proved to be more effective than the $k-\varepsilon$, since it was the numerical result that best approached the classic experimental result of Brock (1969). With regard to the properties of the *roll waves,* it was observed that the fundamental frequency of the waves is identical to that of the disturbance applied upstream of the flow, which confirms theoretical and numerical results in the literature (Kranenberg, 1992; Needham ; Merkin, 1987; Maciel, 2001). For this case study, a mesh sensitivity study (GCI) was performed.

In the case study of the Azad spillway, it was possible to visualize free surface disturbances occurring along the channel, however, such disturbances do not present stability as seen in the case study of Brock (1969). no disturbances upstream of the flow, so the instabilities arose naturally. For this case study, the simulations using the model $k-\varepsilon$ performed by (Aghebatie; Hosseini, 2016, Bazargan; Aghabatie, 2015) showed a result closer to the experimental results than the model $k-\omega$, even though these analyzes were performed without the presence of information about experimental errors, and that the mesh sensitivity test is not finished. With the analyzes presented here, it can be concluded that the spillway geometry influences the emergence of instabilities naturally, without imposing a disturbance frequency. In addition, it can be seen that the waves of greater amplitude (1.4m) occurred in the steepest region of the channel. In terms of shear stress, it can be concluded that it has a higher growth rate also in the steepest region of the channel.

Thus, the *roll study waves* becomes indispensable from a design point of view, not only due to the eventual overflow of the spillway chute (due to the high wave

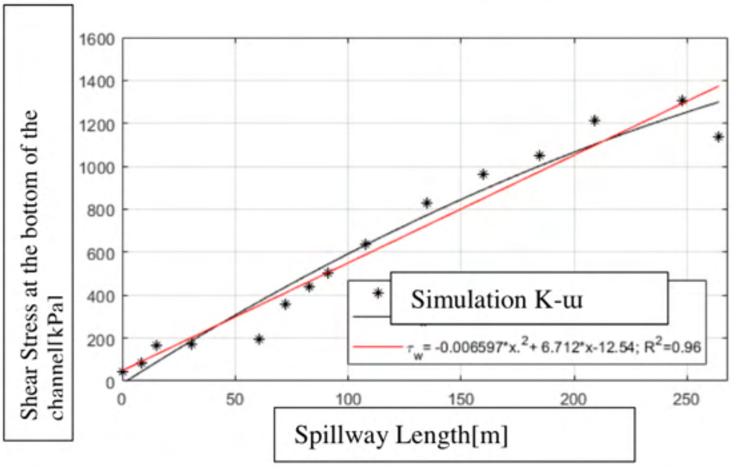

Figure 11.- Shear stress as a function of the length of the spillway at the instant of 35 s.

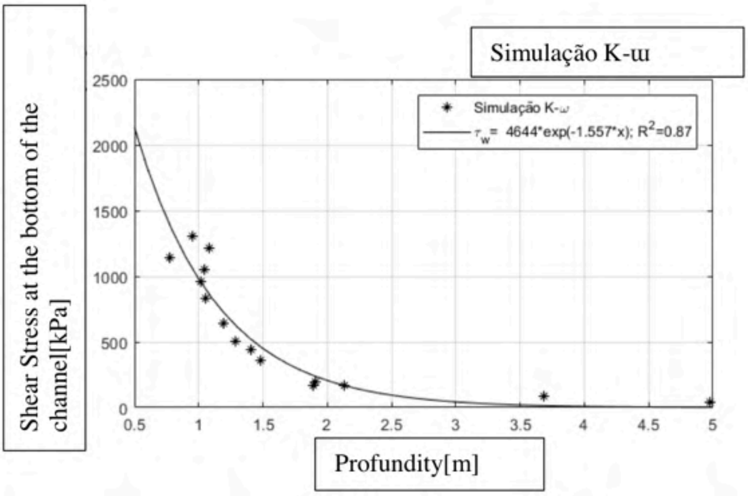

Figure 12.- Shear stress as a function of depth of flow at 35 s.

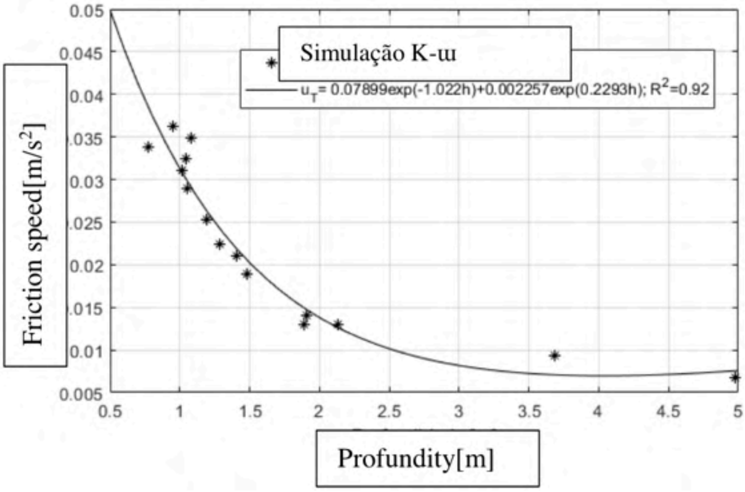

Figure 13.- Friction velocity as a function of the depth of flow at 35 s.

amplitude) but also to the possible increase in sediment transport as a result of the increase in shear stress, but also due to the possibility of occurrence of water hammer (hydraulic transients) resulting from pressure and flow variations.

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