



# Numerical modeling of the hydraulic jump location using 2D Iber software

Mohammed Amin Hafnaoui<sup>1,2</sup> · Mahmoud Debabeche<sup>1</sup>

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## Abstract

In the recent years, numerical modeling of free surface flows has experienced a rapid and important development. Several programs and software have been used to simulate free surface flows. Transition from supercritical to subcritical flow regime leads to formation of hydraulic jumps. Numerical modeling of hydraulic jumps has taken an important part in this domain. This work aims to assess the efficiency of Iber software in the simulation of hydraulic jump in a rectangular channel. The location and displacement of the hydraulic jump were simulated by 2D Iber software. The data of these simulations were obtained from the experimental tests carried out at the laboratory. The results of the simulated hydraulic jump surface profiles showed a good agreement with those measured experimentally. The velocity distribution is presented in this study. Numerical simulation results satisfactorily predicted the hydraulic jump location, which gives confidence using of Iber software in the simulation of hydraulic jump.

**Keywords** Hydraulic jump · Iber software · Rectangular channel · Numerical modeling · Free surface flows

## Introduction

The hydraulic jump is considered part of the free surface flows; rapid transition from supercritical to subcritical flow regime leads to formation of the hydraulic jump. This transition causes simultaneously a decrease in the flow velocity and an increase in the water level downstream. Hydraulic jumps can be found in stilling basins, channels, and rivers. Obstacles and change of slopes or cross-sections contribute to the formation of the hydraulic jump and play an important role in overflow of rivers or channels, which leads to flooding (Hafnaoui et al. 2009). Floods cause major disasters in different parts of the world and are responsible for the extreme number of human losses and material damages (Hafnaoui et al. 2013; Hachemi and Benkhaled 2016; Kumar et al. 2017). Flood modeling helps to determine flood-prone areas and understand the flow behavior in rivers (Hafnaoui

et al. 2020). Prediction of flood depth is also important for controlling floods and reducing their damage. Therefore, it is important to predict the flood depth and peak discharge for the design of flood control projects (Roohi et al. 2020). The effect of the hydraulic jump instability on the flood risk in natural rivers was studied by De Leo et al. (2020). A case study was carried out in the laboratory for two rivers. The results indicated that hydraulic jump instability might play an important role in realistic conditions of river confluence, which requires to carry out flood protection works. Determining the location of the hydraulic jump is of great importance to reduce flooding risk.

The hydraulic jump is utilized to dissipate the kinetic energy of a supercritical flow to avoid important modifications of the stilling basin bed (Debabeche et al. 2009). Numerical modeling of the hydraulic jump was studied by several researchers. Gharangik and Chaudhry (1991) analyzed the effect of the Boussinesq term on the formation of the hydraulic jump using Mac–Cormack and the two–four schemes to resolve the 1D Saint-Venant equations. Rahman and Chaudry (1995) used the same numerical schemes with grid adaptation to improve the resolution of the solution. The Mac–Cormack and two–four schemes were used also by Sakarya and Tokyay (2000) and Tokyay et al. (2008) to simulate the A-type hydraulic jump at a

✉ Mohammed Amin Hafnaoui  
hafnaoui.amine@gmail.com

<sup>1</sup> Research Laboratory of Civil Engineering, Hydraulics, Environment and Sustainable Development, LARGHYDE, University of Biskra, Biskra, Algeria

<sup>2</sup> Scientific and Technical Research Center on Arid Regions, CRSTRA, Biskra, Algeria

positive step and minimum B-jumps at abrupt drops. The numerical model was verified by comparing the results with the available data and analytical methods.

Carvalho et al. (2008) studied the characteristics of the hydraulic jumps through a comparative study between a numerical model based on 2D Reynolds-averaged Navier–Stokes equations and a physical model. Padova et al. (2013, 2018) used SPH technique 2D and 3D based on the Navier–Stokes equations to study the formation of the hydraulic jump. Daneshfaraz et al. (2017) assessed the perforated screens and the effect of baffles on energy dissipation using Flow 3D software. This software was also used by Azimi et al. (2017) to study the characteristics of hydraulic jump in U-shaped channels. Arjenaki and Sanayei (2020) studied different geometry of stepped spillways using the standard k- $\epsilon$  and RNG turbulence models of Flow 3D software. Five types of spillways were proposed for this study, and the results showed that the type-D spillway was the best experimental model for energy dissipation. The numerical simulation with RNG model gave better results and the error index was minimal. Adding barriers to type-D spillway increases energy dissipation by 15%.

Iber is a free software package for simulating unsteady free surface turbulent flow and transport processes in shallow water flows based on 2D Saint-Venant Equations (Cea et al. 2019). It is designed to be useful in several domains, including the simulation of free surface flow in rivers, assessment of flood-prone areas and their risks, calculation of tidal currents in estuaries, erosion, and sediment transport (Corestein et al. 2010). This software was used in numerous researches; Bladé et al. (2014), Cea et al. (2018) and Cueva et al. (2018) presented Iber software with some applications of the flows in rivers. Muñoz and Kenyo (2014) and Ortiz et al. (2017) made a comparative study between IBER and HEC-RAS to compare the benefits and disadvantages of these two programs.

The location of the hydraulic jump was treated experimentally by Achour et al. (2002) through a study of the sill position in a rectangular channel. Behrouzi-Rad et al. (2013) evaluated the effect of a sill with circular holes on the location of a hydraulic jump and its length.

The location and the displacement of the hydraulic jump were numerically analyzed by Hafnaoui et al. (2016, 2018) in triangular and rectangular channels, through a numerical model developed by MATLAB<sup>®</sup> software based on the Mac–Cormack scheme with TVD extension.

The objective of this work is to assess the efficiency of the 2D Iber software in simulating the location and displacement of a hydraulic jump. The study relies on the data of the experimental tests carried out by Gharangik and Chaudhry (1991) and Hafnaoui (2018) in a rectangular channel.

## Materials and methods

### Experimental model

This research work was based on two experimental models. The tests using the first experimental model were conducted by Gharangik and Chaudhry (1991) in a horizontal rectangular channel 14 m long and 0.46 m wide. The values of the Froude number obtained vary from 2.30 to 7.0 and the values of the roughness coefficient  $n$  are in the range 0.008 and 0.011  $s/m^{1/3}$ . Figure 1 shows a simplified diagram of the first experimental model; more details could be found in Gharangik and Chaudhry (1991).

In the second model, the experiments were carried out at the Research Laboratory of Civil Engineering, Hydraulics, Environment and Sustainable Development (LARGHYDE) of Biskra University. The experimental model comprises a main channel 11 m long, in which is inserted a measuring rectangular flume 0.2 m wide and 0.2 m high (Hafnaoui 2018). Figure 2 shows a photograph of the main channel and locations of the hydraulic jump in the measuring flume. The hydraulic jump was controlled by a sill placed downstream of the flow and takes a distance  $L$  of 4 m from the flume length. The displacement distance of the hydraulic jump  $L_c$  is measured after each increase in the sill height or the flow  $Q$ . Figure 3 shows the procedure to measure the displacement  $L_c$  of the hydraulic jump. Many sills were employed to measure the hydraulic jump locations; the height  $h_s$  of the sills used varies between 0.028 and 0.071 m. The values of the Froude number obtained vary from 2.9 to 5.5. Table 1 shows the test conditions.

### Numerical model

In this study, a hydrodynamic module of Iber 2.5.1 software was used. This module calculates the depth-averaged two-dimensional shallow water equations (Cea et al. 2019). Iber 2.5.1 software downloaded from (<https://www.iberaula.es/54/iber-model/downloads>) website.

### Hydrodynamic equations

In the hydrodynamic module, the conservation equations of mass and momentum in the two horizontal directions are written as follows (Manual de referencia hidráulico IBER 2014):

$$\frac{\partial h}{\partial t} + \frac{\partial hU_x}{\partial x} + \frac{\partial hU_y}{\partial y} = M_s, \quad (1)$$

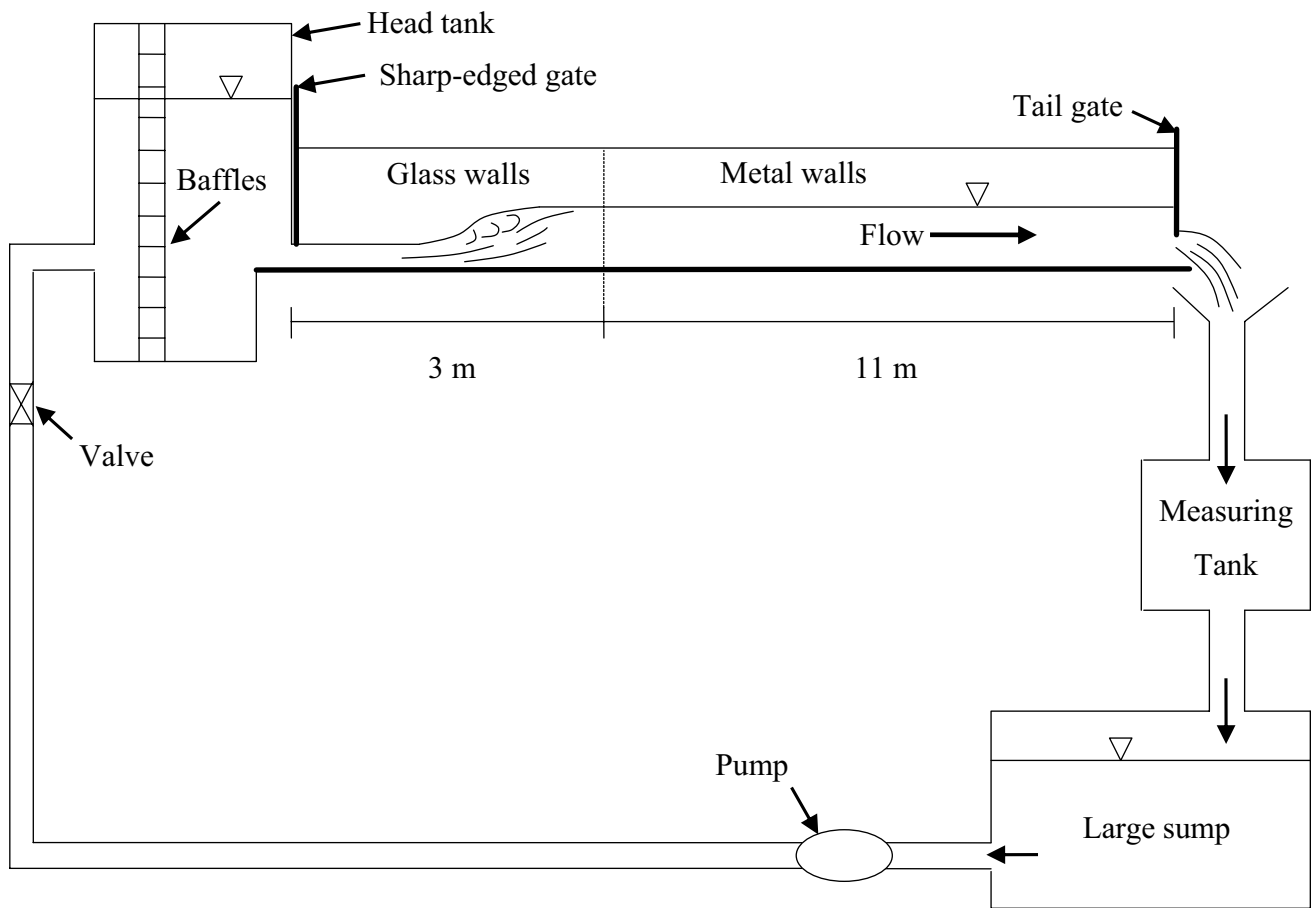


Fig. 1 Simplified diagram of the first experimental model according to Gharangik and Chaudhry (1991)



a Main channel



b Locations of the hydraulic jump

Fig. 2 Photograph of the main channel and locations of the hydraulic jump

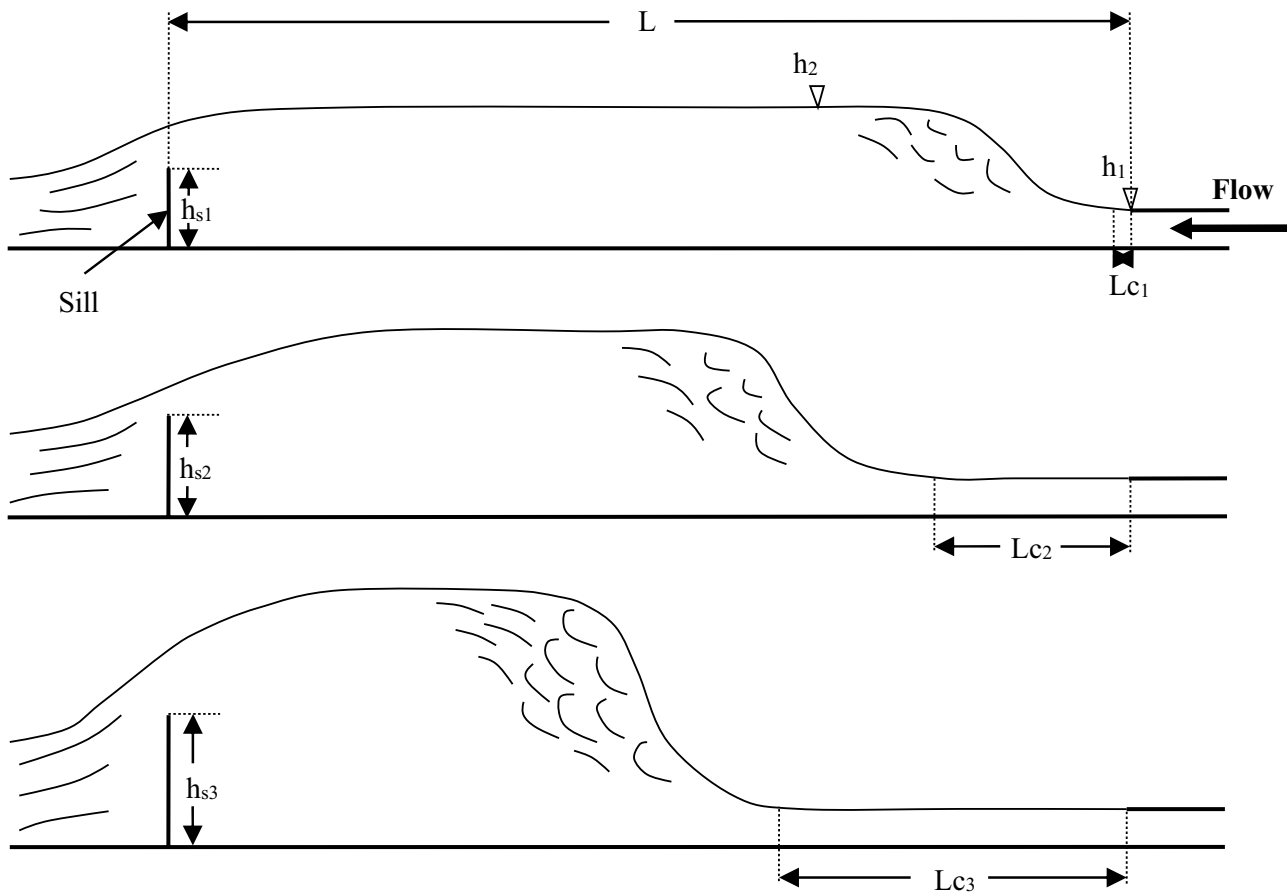


Fig. 3 Simplified diagram of the hydraulic jump displacement

Table 1 Test conditions

Experimental model	Test Number	Froude Number $F_1$	Specific discharge $q$ (m <sup>2</sup> /s)	Initial depth $h_1$ (m)	Final depth $h_2$ (m)
1st Experimental model	1	4.23	0.11815	0.043	0.222
	2	6.65	0.07744	0.024	0.195
2nd Experimental model	3	3.86	0.06915	0.032	0.15
	4	3.86	0.06915	0.032	0.139
	5	3.86	0.06915	0.032	0.128
	6	4.67	0.08372	0.032	0.183
	7	4.67	0.08372	0.032	0.174
	8	4.67	0.08372	0.032	0.167

$$\begin{aligned} & \frac{\partial h U_x}{\partial t} + \frac{\partial h U_x^2}{\partial x} + \frac{\partial h U_x U_y}{\partial y} \\ &= -gh \frac{\partial Z_s}{\partial x} + \frac{\tau_{s,x}}{\rho} - \frac{\tau_{b,x}}{\rho} - \frac{g h^2}{\rho} \frac{\partial \rho}{2 \partial x} \\ & \quad + 2\Omega \sin \lambda U_y + \frac{\partial h \tau_{xx}^e}{\partial x} + \frac{\partial h \tau_{xy}^e}{\partial y} + M_x, \end{aligned} \tag{2}$$

$$\begin{aligned} & \frac{\partial h U_y}{\partial t} + \frac{\partial h U_x U_y}{\partial x} + \frac{\partial h U_y^2}{\partial y} \\ &= -gh \frac{\partial Z_s}{\partial y} + \frac{\tau_{s,y}}{\rho} - \frac{\tau_{b,y}}{\rho} - \frac{g h^2}{\rho} \frac{\partial \rho}{2 \partial y} \\ & \quad - 2\Omega \sin \lambda U_x + \frac{\partial h \tau_{xy}^e}{\partial x} + \frac{\partial h \tau_{yy}^e}{\partial y} + M_y, \end{aligned} \tag{3}$$

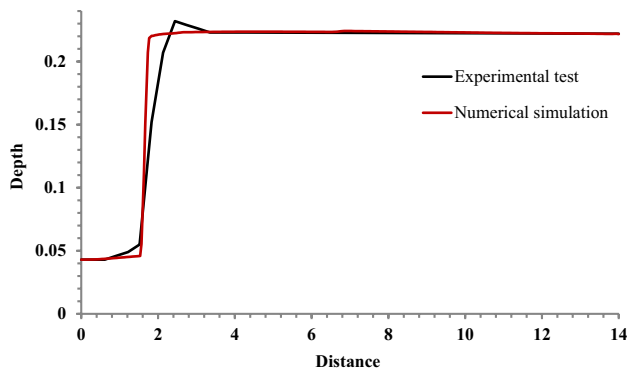


Fig. 4 Hydraulic jump profile for  $F_1 = 4.23$

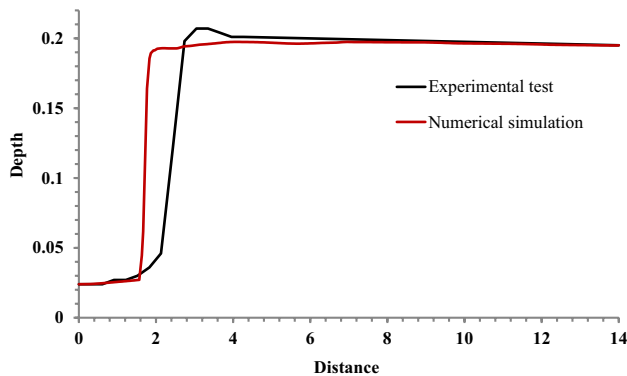


Fig. 5 Hydraulic jump profile for  $F_1 = 6.65$

where  $h$  is the water depth,  $U_x$  and  $U_y$  are the mean horizontal velocities,  $g$  is the acceleration of gravity,  $Z_s$  is the elevation of the free surface flow,  $\tau_s$  is the friction on the free surface,  $\tau_b$  is the friction of the bottom,  $\rho$  is the density of the water,  $\Omega$  is the angular speed of rotation of the earth,  $\lambda$  is the latitude of the considered point,  $\tau_{xx}$ ,  $\tau_{xy}$ ,  $\tau_{yy}$  are the effective horizontal tangential tensions, and  $M_s$ ,  $M_x$ ,  $M_y$  represent source terms of the mass and momentum.

The hydrodynamic equations are solved by the finite volume method, which is one of the most widespread and commonly used in computational fluid dynamics. The second order Roe scheme was also used to simulate the hydraulic jump.

### Results and discussion

The general conditions of the numerical simulations were assumed as follows: the initial flow depth  $h_1$  and the specific discharge  $q$  were considered as upstream boundary conditions and the final flow depth  $h_2$  was considered as the downstream boundary condition. The final time of the simulation is equal to 300 s and the mesh is considered as triangular elements.



Fig. 6 Mesh with triangular elements

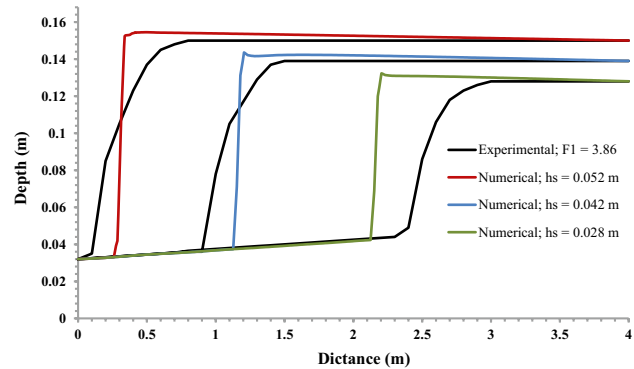


Fig. 7 Hydraulic jump profiles for  $F_1 = 3.86$

### Numerical simulation of the first experimental model

The numerical simulations of the first experimental model were made for two Froude numbers  $F_1 = 4.23$  and  $6.65$ . The values of the proposed roughness coefficient  $n = 0.008$ . The results of the numerical simulations are presented in Figs. 4 and 5.

Comparison of the simulated and measured hydraulic jump profiles shows a good agreement for the Froude number  $F_1 = 4.23$ . For  $F_1 = 6.65$ , the numerical simulation of the hydraulic jump profile is located slightly upstream of the hydraulic jump profile measured experimentally. The hydraulic jump location is better simulated for  $F_1 = 4.23$ .

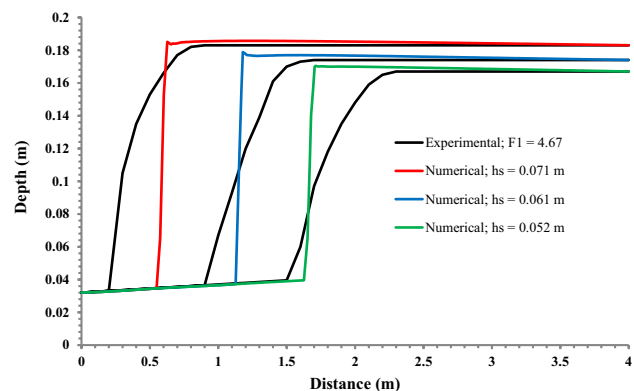


Fig. 8 Hydraulic jump profiles for  $F_1 = 4.67$

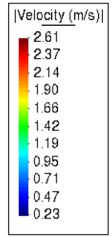
**Numerical simulation of the second experimental model**

Numerical simulations of the second experimental model were made for different locations  $L_c$  of the hydraulic jump. The values of the proposed roughness coefficient  $n=0.01$  and the values of the Froude numbers obtained were equal to

$F_1=3.86$  and  $4.67$ . The height  $h_s$  of the sills used to control the hydraulic jump are  $0.028, 0.042,$  and  $0.052$  m for the Froude number  $F_1=3.86$ . For  $F_1=4.67$  the height  $h_s$  are  $0.052, 0.061$  and  $0.071$  m. Figure 6 shows the mesh used for these simulations, whereas Figs. 7 and 8 show those of the numerical simulations.



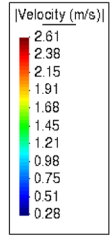
Hydraulic, step 300  
Smooth Contour Fill ( Mean) of Velocity (m/s), |Velocity (m/s)|.



**a** Velocity distribution for  $F_1 = 4.67$  and  $h_s=0.071$  m



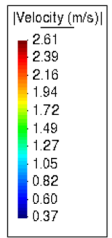
Hydraulic, step 301  
Smooth Contour Fill ( Mean) of Velocity (m/s), |Velocity (m/s)|.



**b** Velocity distribution for  $F_1 = 4.67$  and  $h_s=0.061$  m



Hydraulic, step 300  
Smooth Contour Fill ( Mean) of Velocity (m/s), |Velocity (m/s)|.



**c** Velocity distribution for  $F_1 = 4.67$  and  $h_s=0.052$  m

**Fig. 9** Velocity distribution for  $F_1=4.67$

Comparison of the computed and measured results generally shows that the hydraulic jump locations give approximately the same results for the Froude numbers tested. For  $F_1 = 3.86$  and  $h_s = 0.028$  m, the hydraulic jump profile is located slightly upstream from the measured one. The simulated hydraulic jump profiles show a good concordance with the experimental tests.

The results of the numerical simulations with Iber software generally compare well with the experimental data.

Velocity distributions for the hydraulic jump displacements for the Froude number  $F_1 = 4.67$  are presented in Fig. 9. Three sill heights  $h_s$  were used to create different locations of the hydraulic jump,  $h_s = 0.052$ ,  $0.061$ , and  $0.071$  m.

Figure 9 shows the velocity distribution for the locations of three simulated hydraulic jumps; the maximum velocity value is upstream of the channel before the formation of the hydraulic jump, and then it begins to decrease suddenly after the formation of the hydraulic jump and levels off at a minimum value.

The analysis of velocity distribution allows determining the locations where velocity is high, which enables us to make the necessary arrangements to protect the hydraulic structures against erosion or collapse.

## Conclusion

In this work, the numerical modeling of the hydraulic jump location using 2D Iber software was studied. Two experimental models were used to simulate the location and the displacement of the hydraulic jump in a rectangular channel.

For the first experimental model, the hydraulic jump locations were predicted extremely well with the experimental data. The hydraulic jump profile for the Froude number  $F_1 = 4.23$  is better simulated than  $F_1 = 6.65$ . For the second experimental model, the results of the numerical simulations for the Froude numbers tested generally compare well with the experimental data for the profiles and locations of the hydraulic jumps.

The comparison of the simulated and measured hydraulic jump profiles showed that the numerical simulations using Iber software gave approximately the same results for all measured hydraulic jump profiles. The analysis of the hydraulic jump profiles allows to determine the characteristic of the hydraulic jump and helps to design the stilling basins. It also allows to determine the locations where the depth is high, which enables us to make the necessary arrangements to protect the rivers or channels from the overflow or flooding.

Velocity distribution was shown for different locations of the hydraulic jump. Determining the high velocity locations

helps to protect the hydraulic structures from erosion or collapse.

The results of the numerical simulations via Iber software satisfactorily predicted the hydraulic jump location.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that there is no conflict of interest regarding the publication of this paper.

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