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Fluid-Structure Interaction between Broad Crested and Hydrodynamics Effects under Sand bed sediments

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Abstract. The present study intends to report the initial findings results in the hydrodynamic and sediment transport modeling with a study case of a broad crested weir considering a sediment bed made of sands. The adopted numerical model is the REEF3D, a Computational Fluid Dynamics tool, which is able to do sediment transport simulations, according to Bihs and Olsen [1]. The main objective is to examine the hydrodynamics effects of the flow around the structure in a movable sediment bed.

Keywords: Sediment Transport, Computational Fluid Dynamics (CFD), Fluid-Structure Interaction.

1 Introduction

The sediment transport phenomena occurs in distinctive conditions in the nature, can be seen in situations as sandstorms in the Sahara Desert or sedimentations in the reservoir of hydroelectric power stations. In the field of hydraulics engineering, there are well-established methods of considerer sediment transport, nevertheless those methods are commonly related to simplifications and empirical relations as a way to understood and represent the actual condition. To avoid those limitations, one of the alternatives is to develop reduced models in laboratories. Even so, these models have limitations associated primarily, to scalability and costs, and emerging as a viable alternative, there is the Computational Fluid Dynamics (CFD).

The REEF3D has been used to do CFD simulations in the sediments transport framework by Afzal et al. [4] to investigate the local scour around a pier under the action of waves. Ahmed et al. [5] did studies to assess the effects of local scour around a pipeline under the combined effect of waves and currents. And more recently, Afzal et al. [6] examine several characteristics of the REEF3D formulations by simulation and abutment scour under steady current.

The study case can be described as the analysis of the hydrodynamic effects in a solid structure with known dimensions, inside a multiphase domain, composed of air, water and sediments. For the fluid phase, the adopted initial conditions are constant water level in all the domain and the boundary conditions are a constant inflow rate with a controlled water level in the outflow, similar with the presented in Fleit [7]. The main objective is to examine the hydrodynamics effects of the flow around the structure in a movable sediment bed.

2 Numerical Approach

The numerical software used for the simulations is the open-source CFD tool REEF3D. The model is based in the resolution of the Navier-Stokes equation in the Reynolds-Averaged Navier-Stokes (RANS) framework, which base model has been presented by Olsen [2]. The discretization method of the software is the finite differences in structured meshes in three dimensions. Both interfaces, the air-water and the water-sediment is treat by an interface capturing method, the level-set method as given by Sussman et al. [3].

2.1 Fluid phase

The fluid phase is characterized as a free surface simulation and the equations for the fluid phase are defined in the eq. (1) and eq. (2).

$$\frac{\partial U_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left((v + v_t)\left(\frac{\partial U_j}{\partial x_j} + \frac{\partial U_j}{\partial x_j}\right)\right) + g_i \tag{2}$$

Where U represents the averaged speed in time, x is the carterisan spation coordinate, ρ is the fluid density, P represents the pressure term, v is the cinematic viscosity, v_t is the turbulent viscosity and g is the gravity acceleration. The indexes i and j refer to Cartesian components of vector variables.

Additionally, the domain is discretized on a structured, orthogonal computational grid. The advection term is solved by the method known as weighted essentially non-oscillatory (WENO) scheme, as presented in Liu et al. [8], while the temporal discretization adopts the 3nd order total variation diminishing (TVD) Runge-Kutta scheme, as presented by Gottlieb and Shu [9]. The pressure term is solved by the projection method [10] with the BiCGStab algorithm [11]. It is used a two-equation k-ω turbulence model to closed the RANS equation.

2.2 Sediment Transport

The sediment transport is solved by a series of equations that can be described as Suspended Transport, Bed load Transport and a bed morphology model that update the sediment boundary. The suspended load transport represents the particles that are lightweight, and are predominantly transported in the water column, they are threatened by an advection-diffusion transport equation as defined in eq. (3).

$$\frac{dc}{dt} + U_j \frac{\partial c}{\partial x_j} + u_s \frac{\partial c}{\partial z} = \frac{\partial}{\partial x_j} \cdot \left(\Gamma \frac{\partial c}{\partial x_j}\right) \tag{3}$$

Where c is the suspended sediment concentration, the diffusive coefficient is considered to be equivalent to the turbulence viscosity. And the u_s represents the settling velocity, defined by the formulation proposed by Soulsby [12], as seen in eq. (4).

$$u_s = \frac{\mathrm{v}}{\mathrm{d}}\left[(10.36^2 + 1.049\, D_*^3)^{\frac{1}{2}} - 10.36\right] \tag{4}$$

And the dimensionless grain size D_* is given by eq. 5.

$$D_* = D_{50}\left(\frac{gR}{v^2}\right)^{1/3} \tag{5}$$

In which D_{50} is the average particle size and R is the sediment submerged specific gravity, adopted as eq. 6.

$$R = \rho_s - \rho/\rho \tag{6}$$

The suspended transport flux is computed in function of two others relations, the deposition and entrainment rate. The deposition rate relates the concentration calculated by eq. 7 with the settling velocity (eq. 4).

$$D = u_s c \tag{7}$$

The entrainment rate is calculated as a function of the near bed concentration (eq. 8).

$$E = u_s c_b \tag{8}$$

The near bed concentration is calculated in by the empirical eq. 9, as presented in Van Rijn [13]

$$c_b = 0.015 \frac{D_{50}}{b} \frac{((\tau - \tau_c^*)/\tau_c^*)^{1.5}}{D_*^{0.3}} \tag{9}$$

The bed load transport is the sediment that moves near the bottom, by mechanisms of sliding, rolling or saltation. The transport is related to the shear stress by a method semi-empirical, known as Shields Method. In the method, it is defined a critical bed shear stress as function of hydrodynamics flow condition and sediments properties, if the calculated shear stress exceeds the critical value, will be bed-load transport. It is adopted a critical shear stress equal to 0.047. The intensity of the transport is calculated through an empirical equation of Van Rijn [14] as defined in eq. (10).

$$q_b^* = 0.053\frac{((\tau - \tau_c^*)/\tau_c^*)^{2.1}}{D_*^{0,3}} \tag{10}$$

The dimensionless bed-load transport rate is known as the Einstein number (eq. 11).

$$q^* = \frac{q}{D_{50}\sqrt{gRD_{50}}} \tag{11}$$

The mass balance flux from the sediment transport modes are computed by a bed morphology model named Exner Equation, presented in eq. 12, as given by Garcia [15].

$$(1-\rho_0)\frac{\partial \eta}{\partial t} = -\frac{\partial q_{bx}}{\partial x} - \frac{\partial q_{by}}{\partial y} - E + D \tag{12}$$

The ρ_0 term represents the sediment porosity, η is the movable boundary between the fluid and sediments, and q_b is the erosion rate.

The method of Shields is develop, and transformed in diagram, under the assumption of a flat bed, a situation related to laboratory set-ups although hard to be seen in the nature. To deal with the limitation, the software adopts a formulation that computes the effects of a sloping bed, and in the present study is used a reduction factor r based on the Dey [16] formulations, as given by eq. 13.

$$\tau_c = \mathrm{r} \, . \, \tau \tag{13}$$

It is also used another algorithmic to reduce the bed cell erosion, known as Sandslide. The algorithmic intends to reduce the bed shear stress during an erosion process, it works correcting the sloping bed when the angle became higher than the angle of repose of the sediments. In the present study it is used with value equal to -2, as presented in [6].

3 Study Case

The proposed case corresponds to a rectangular channel, with 5.25 m of length, 2.5 of with and 1.25 of height. It is adopted a sediment layer with 0.25 m thickness, and medium grain size (D_{50}) of 0.0001 m, equivalent of a fine sand. Between 1.5 m to 2.5 m, counting from the inflow boundary, there is an obstacle. The obstacle is a broad crest weir, with 1.25 m height in the sidewalls and 0.6 m in the center, the center section is slighter smaller than the side ones, respectively with 0.6 m and 1. 0 m. The dimensions of the obstacle and the experiment are show in Fig. 1 and Fig. 2.

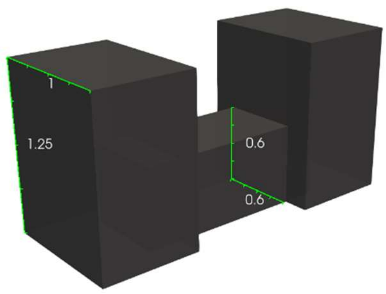

Figure 1. Isometric view of the obstacle.

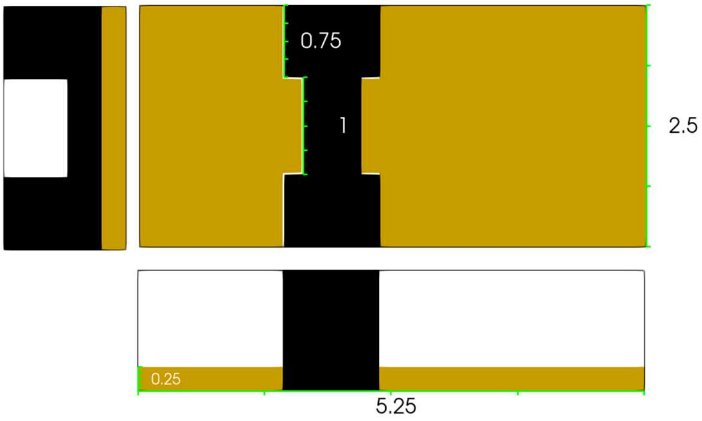

Figure 2. Top, front and side and side view of the experiment set.

The boundary conditions used from the fluid phase are constant discharge rate in the inflow, and constant water level in the outflow, this condition allows that the inflow water level is variable as the outflow discharge. The boundary conditions values are summarize in Tab. 1.

Table 1. Boundary Conditions used

Inflow Discharge [m³/s]	Inflow Water Elevation [m]	Outflow Discharge [m³/s]	Outflow Water Elevation [m]
0.4	-	-	0.6

The parameters and coefficients for the sediment module are summarized in Tab. 2.

Table 2. Parameters and coefficients.

Parameter	Value
Sediment D_{50}	0.0001 m-
Sediment density	2,650 kg/m³
Sediment Fall velocity	0.00789 m/s
Porosity	0.5
Angle of repose	30.0 º
Shield parameter	0.047

4 Results

It has been taken a slice in the middle of the domain to represent the final step (200 s) of the flow distribution and the change in the topography, given by Fig. 3. The Fig. 4 shows the top view of the same time step.

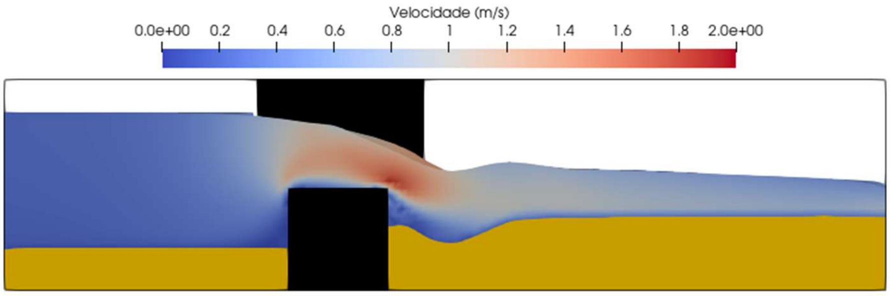

Figure 3. – Model results of the velocity distribution for the fluid phase.

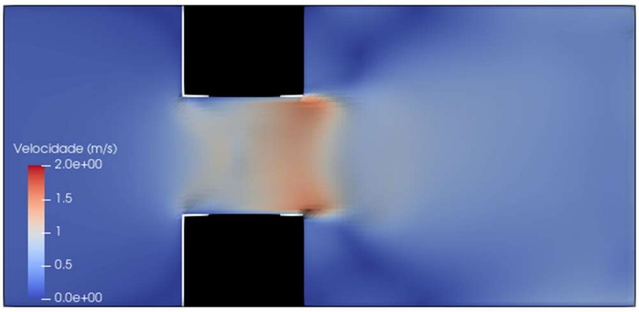

Figure 4. – Top view of the model results of the velocity distribution for the fluid phase.

As expected, the higher velocity values are concentrated right after the weir. It is expected that in this location would be seen a hole formation. But, as presented in the last step in Fig. 3, the sediment bed has increased after the weir. It is presented in Fig. 5 different time steps of the simulation.

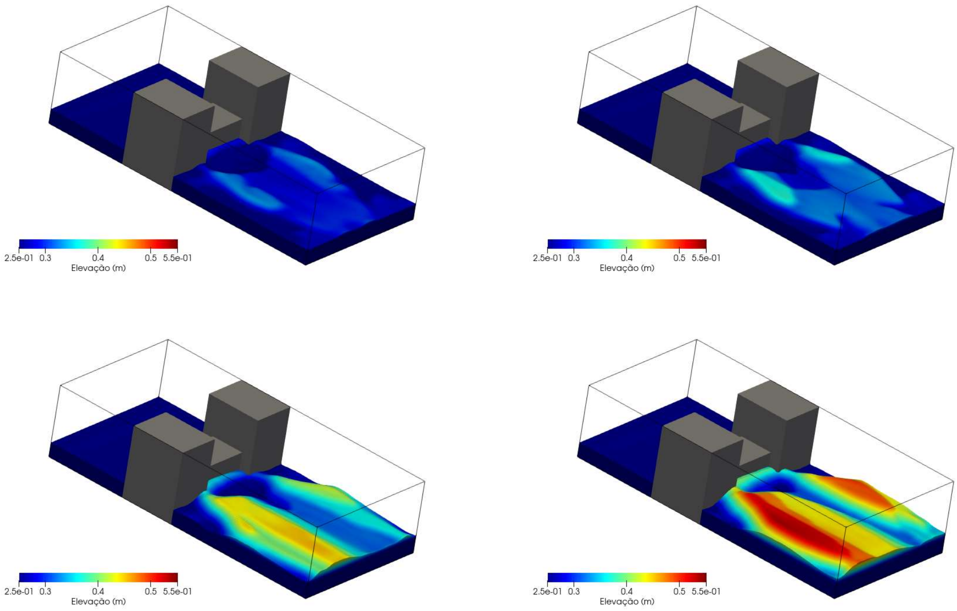

Figure 5. – Evolution of bed topography in the time steps, from left to right and top to bottom, 50 s, 100 s, 150 s and 200 s.

The hydrodynamic behavior of the experiment has develop a predominant flux in the middle, and higher banks depositions in the sides. In the initial moments of the simulation it has started and erosion in the middle, but scour pattern situation has changed between 100 s and 150 s, when the deposition has become an important factor. The maximal bed variation is show as a graph in Fig 6.

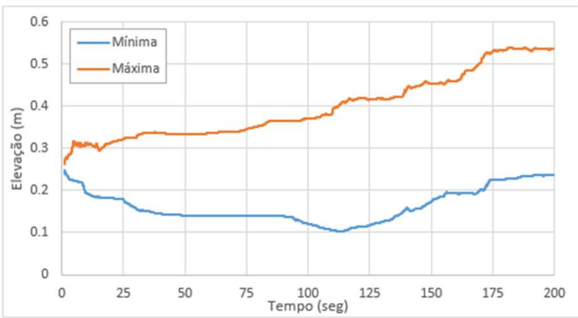

Figure 6. – Variation of maximum and minimum bed topography in the experiment.

The simulations have been made in an Acer® laptop with processor Intel i7-6700HQ, the domain contains 216,932 cells, and took 58.5 hours to be completed.

5 Conclusions

The study has investigated a study case of a broad crested weir with a movable sediment bed. The proposed case resamples a simple structure that is common to be presented in hydraulic structures. The methodology proposed has presented interesting results that can be evaluated with laboratory cases in order to improve the numerical predictions. Is expected that with the development of more capable computers, CFD simulations will became more of an alternative to be used in hydraulics studies.

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