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STEPS NUMBER EFFECT ON HYDRAULIC PARAMETERS OF FLOWS IN STEPPED SPILLWAYS

EFFET DU NOMBRE DE MARCHES SUR LES PARAMETRES HYDRAULIQUES DES ECOULEMENTS DANS LES COURSIERS EN MARCHES D'ESCALIERS

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ABSTRACT

Spillways are one of the most important parts of dams. There are several types of spillways, but they all play the same role. The flow through these structures is quite complicated hydraulically. The main focus of this study is the free surface flow in stepped spillways. Thus, the objective is to determine the influence of the steps number on the hydraulic parameters of the flow through this type of spillway. Taking into account the complexity of the equations of motion governing the flow through these structures, the use of Ansys-Fluent software was chosen in order to carry out the desired numerical models. It is to be noticed that this software is based on the finite volume method. The basic equations of the phenomenon treated are those of an incompressible fluid given by Navier-Stokes, while for modelling the turbulence the k-ε equations were used. The VOF model coupled with Level-Set was also used in order to take into account the biphasic flow characteristics. The influence of the steps number on the energy dissipation, on the water level, and also on the shear stresses acting on the walls was analyzed.

Keywords: Stepped spillways, Turbulent flow, Navier-Stokes, k-ε model, Energy dissipation, VOF, Level-Set.

RESUME

Les évacuateurs de crue représentent l'une des parties primordiales dans les barrages. Ces aménagements hydrauliques sont de plusieurs types, mais jouent tous le même rôle. L'écoulement à travers ces structures est assez compliqué de point de vue phénomène hydraulique. Dans cette étude, on s'intéresse essentiellement aux coursiers à surface libre en marches d'escaliers. Ainsi, l'objectif est la détermination de l'influence du nombre de marches sur les paramètres hydrauliques de l'écoulement à travers ce type d'évacuateurs de crues. Tenant compte de la complexité des équations du mouvement régissant l'écoulement traversant ses structures, on a opté pour l'utilisation du logiciel Ansys-Fluent afin de réaliser les modèles numériques nécessaires. Il est à signalé que le logiciel en question est basé sur la méthode des volumes finis. Les équations de base du phénomène traité sont celles d'un fluide incompressible données par Navier-Stokes, tandis que pour la modélisation de la turbulence, on a utilisé les équations k-ε. Le modèle VOF couplé avec Level-Set a été aussi utilisé afin de tenir compte du caractère diphasique de l'écoulement. L'analyse de l'influence du nombre de marches sur la dissipation d'énergie, sur la hauteur d'eau, et également sur les contraintes agissant au niveau des parois a été réalisée.

Mots clés : Coursier en marches d'escaliers, Ecoulement turbulent, Navier-Stokes, modèle k-ε, Dissipation d'énergie, VOF, Level-Set.

INTRODUCTION

Erosion of the stream bed downstream of spillways in dams makes it essential the construction of efficient energy-dissipating structures. The emergence of roller compacted concrete (RCC) gave rise to a new design of stepped spillways which allow for an increase in the rate of energy dissipation and a reduction in the size downstream stilling basins.

Numerous investigations on the effect of the geometry variation on the flows hydraulic characteristics in stepped spillways, and more specifically on energy dissipation, have been carried out in recent years. For instance, the work by Sroensen (1985) in which he showed that the dissipated energy in stepped spillways depends on the flow rate, the chute inclination angle, and the steps number and their geometry. The steps form plays a very important role in energy dissipation. Chinnarasri and Wongwises (2006) showed that the dissipation rate is very important for steps with thresholds. This result was confirmed later by Jahad et al. (2016). Based on the Rassaei and Rahbar (2014) study whom evaluated the effect of different parameters (number, length and height of steps) on energy dissipation in a chute stepped spillways, they have shown that energy increases with increasing steps' height and length, and also with decreasing chute spillways slope.

In addition, the simulation of free surface flows in smooth stepped spillways canals was undertaken by Lebdiri et al. (2017). The longitudinal velocity profiles analysis was carried out. The motion equations resolution was performed using the Ansys-Fluent code. Also, in 2017, Bentalha and Habi carried out a purely numerical study whose purpose is to analyze the effects of the non-uniform step heights on the air-water flow properties at stepped spillways. The aim was to examine the formulae developed by Chanson, and to determine the pressure contours and velocity vectors at the step surface.

Furthermore, Lebdiri et al. (2018) provided research work on numerical computation via the Ansys-Fluent code of the water-air interface with the VOF (Volume Of Fluid) and the MMF (Mixture Multiphase Flow) models. The two models are based on Navier-Stokes for an incompressible fluid flow and the k-ε equations to account for turbulence. This study made it possible to simulate two-phase flows, and the obtained free surface profiles showed a high degree of agreement between the two models. Also, Lebdiri et al (2019) presented a numerical simulation study of flows in spillways in which discretization of the motion equations was performed using two methods, namely finite element and finite volume. A comparative study of the obtained results was carried out. This comparison mainly concerns the free surface, mean velocity and velocity profiles. A very high degree of agreement was observed.

It was found through the examined references related to the purpose of this study, that most of the research works that have dealt with the effect of the steps number, have been carried out on stepped spillways with very close number of steps. Consequently, there are actually not available results on great variation in the size of steps. It is thus interesting to examine the effect of changing the steps size on energy dissipation in the spillway by varying the steps number from 12 to 122.

GOVERNING EQUATIONS

The flow covered in this study is governed by the continuity and the Navier-Stokes equations, also named the momentum equation for an incompressible Newtonian fluid. Taking the average turbulent flow velocity, these equations are written under Reynolds' conditions, as follows (Chassaing, 2000):

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + g_{x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \tag{2}$$

where:

$\bar{u}_i$: The average part of the velocity component in the x_i direction and $\bar{u}_i'$ is the corresponding fluctuating part,

ρ : The fluid density,

$\bar{P}$: Average pressure,

ν : Kinematic viscosity,

g_{x_i}: Fluid particle acceleration in the x_i directions.

The $\overline{u_i' u_j'}$ term represents the turbulent stress tensor components given by $\nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$, with ν_t is the turbulent kinetic viscosity.

In the present study we used the k-ε model based on the concept of turbulent viscosity concept to close the equations system to be solved. These are given as follows (Chassaing, 2000; Lebdiri et al., 2018):

$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) - \varepsilon \tag{3}$$

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = C_{\varepsilon 1}\nu_t \frac{\varepsilon}{k}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

with:

k : Turbulent kinetic energy,

ε : Turbulent kinetic energy dissipation,

$$\nu_t = C_u \frac{k^3}{\varepsilon}, C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.92, \sigma_\varepsilon = 1.3, \sigma_k = 1.0, C_u = 0.09$$

The free surface is tracked using the VOF (Volume Of Fluid) model coupled with the Level-Set method. The VOF model is used to locate the two fluids, while the Level-Set is used to capture the interface between the two fluids. The VOF model uses the volume fraction notion to distinguish the two fluids. For this purpose, a volume fraction equation is solved in the domain. This volume fraction is advected by the following transport equation (Merrouche, 2010):

$$\frac{\partial \alpha_q}{\partial t} + \frac{\partial (\alpha_q \bar{u}_i)}{\partial x_i} = 0 \tag{5}$$

where α_q is the volume fraction field of the q phase.

In the case of two fluids, equation (5) is solved only for a single phase in order to locate each of the two fluids in the whole space; the other phase is deduced by complementarity. The α_q value varies between 0 and 1. If $\alpha_q = 1$, the cell of the studied geometry is completely occupied by one of the two fluids, and if $\alpha_q = 0$ it's the other fluid that occupies it. On the other hand, if $0 < \alpha_q < 1$, the cell is in the presence of both fluids separated by an interface. In the case of the presence of water and air this interface represents the free surface. To account for both fluids in the computational domain, the density and kinematic viscosity presented by ρ and ν in the governing equations are given as a function of the density fraction as follows (Merrouche, 2010; Lebdiri et al., 2019) :

$$\rho = \alpha_q \rho_e + (1 - \alpha_q)\rho_a \tag{6}$$

$$\nu = \alpha_q \nu_e + \left(1 - \alpha_q\right) \nu_a \tag{7}$$

where, the subscripts e and a denote water and air respectively.

To capture the interface, the Level-Set method uses a function F constituting an infinite number of contour lines on either side of the interface which correspond to the zero level line. This method uses a transport equation equivalent to the volume fraction equation to predict the function F, it is given by the following expression (Merrouche, 2010; Lebdiri et al., 2019):

$$\frac{\partial F}{\partial t} + \frac{\partial (\bar{u}_i F)}{\partial x_i} = 0 \tag{8}$$

APPLICATION

For numerical investigation undertaken in the present work, a stepped spillway of 2.85m height with chute slope of 30° is considered. Six cases of steps number varied from 12 to 122 as reported in Table 1 are examined. These geometries were discretized using elements with 0.008 m maximum size and with a refinement in the area around the steps.

Table 1: Steps number in studied cases

Case	1	2	3	4	5	6
Steps number	12	34	52	78	100	122

As boundary conditions at the inlet of the flow the average longitudinal velocities of water and air are imposed as follows: $u_{water} = 4.119\, m/s$ and $u_{air} = 0.001\, m/s$. Their transversal components being zero: $v_{water} = v_{air} = 0\, m/s$. The turbulence intensity and scale length are set as follows: $I_{\ell,water} = 0.048048\, m$, $I_{t,water} = 3.4\%$, $I_{t,\mathrm{air}} = 0.001\%$, $I_{\ell,\mathrm{air}} = 0.001m$. At the outlet and at the free surface the zero pressure condition is applied to represent the atmospheric pressure. The pressure in the model is calculated relatively to atmospheric pressure. Finally, the adaptive "scalable wall function" law is applied on the walls. Figure 1 shows the geometry and boundary conditions of the studied domain.

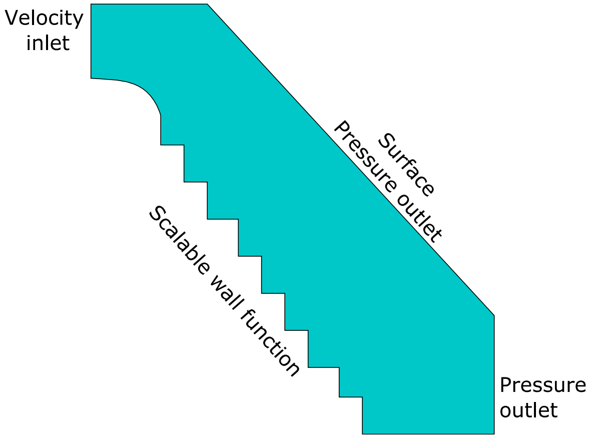

Figure 1: Geometry and boundary conditions

RESULTS AND DISCUSSIONS

Figure 2 is obtained by performing several simulations on the geometry cases listed in Table 1. For each simulation, the total energy E_s at the flow output is determined and the dissipation rate is calculated in relation to the input available energy E_0, i.e. : $\Delta E/E_0 = (E - E_0)/E_0$. According to this figure which represents the energy dissipation rate variation as a function of the steps number, it can be seen that the dissipation rate decreases with the increase in the steps number to reach a minimum value for the case of a chute with 87 steps. From this value, the energy dissipation rate increases slightly.

According to the literature, a small steps number causes appearance of nappe flow which is characterized by high energy dissipation; this justifies the decrease in energy dissipation with an increase in the steps number. Also, as the steps number increases the flow turbulence increases and the length of the turbulent uniform flow area increases, in this case the turbulent flow dissipates more energy than the nappe flow. This result was confirmed by Chanson (Chanson, 1994; Musavi-Jahromi et al., 2008) who hypothesized that in some cases turbulent flow in a stepped spillway can cause significant energy dissipation, and this can occur in the case of long chutes with turbulent uniform flow.

Stepped spillway with an optimal geometry must ensure maximum energy dissipation with minimal downstream water height and minimal wall stress. For this reason, the variation in the downstream water height of the chute spillway and the acting stress on the bottom walls were evaluated for the six cases studied. From Figure 3, it can be seen that the variation in the basin water height as a function of the steps number follows the same form as the variation in the energy dissipation rate. The water height in the downstream basin decreases as the steps number increases until it reaches a minimum value at which the height increases slightly.

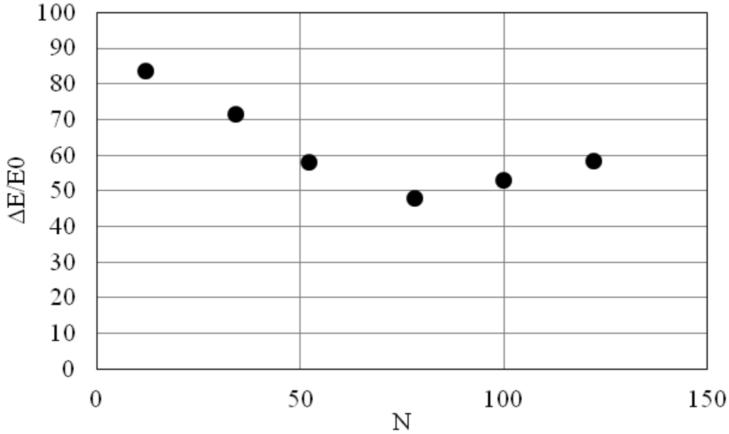

Figure 2: Variation of the energy dissipation rate versus the steps number

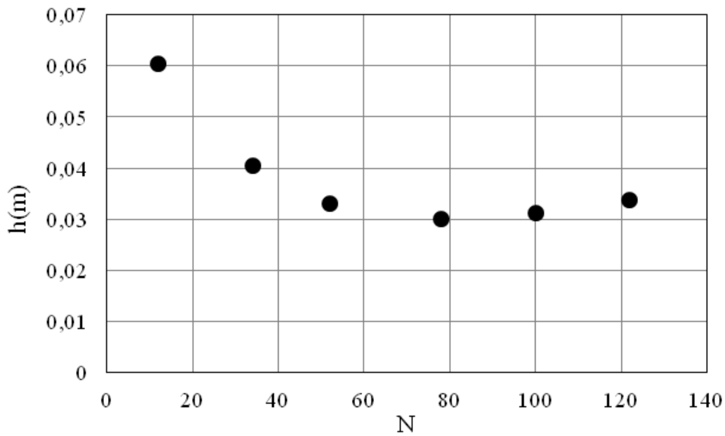

Figure 3: Variation of water height in the stilling basin versus steps number

From Figure 4 which represents the variation of the shear stress on the spillway chute bottom as a function of the steps number, it can be seen that the increase in the steps number causes a decrease in the stress on the wall along the spillway chute, and an increase in this stress in the downstream basin. This was confirmed by Figure 5 which illustrates the variation in wall stress for the two cases of 12 and 122 steps.

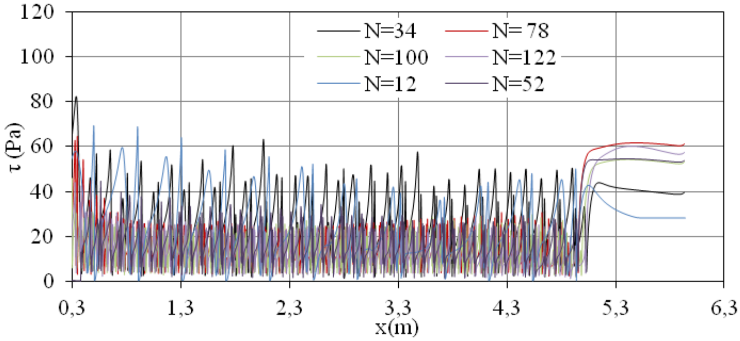

Figure 4: Distribution of shear stresses along the wall for the various studied cases

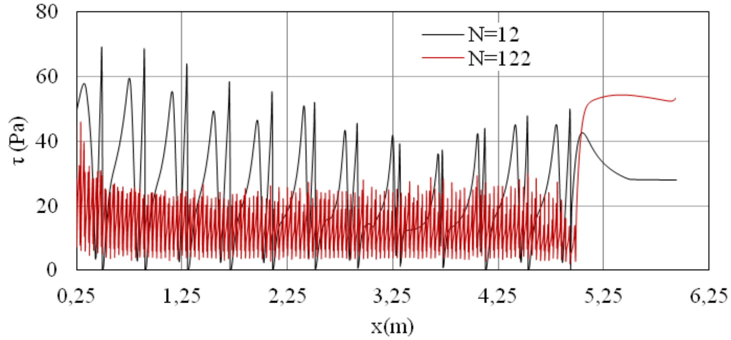

Figure 5: Distribution of shear stresses along the wall - comparison between the two cases of 12 and 122 steps

CONCLUSIONS

The present research work was focused on turbulent flows in stepped spillways. Several numerical simulations with a varied steps number were performed using the Ansys-Fluent code which is based on the finite volume method. We investigated the effect of the steps number on the energy dissipation rate, on the downstream water height, and on the bottom acting stress. The obtained results showed that the steps number choice influences not only the energy dissipation rate, but also the basin water height and the shear acting stress on the canal walls. These constraints must be minimal to avoid bottom erosion. To do this, it is necessary to build steps that ensure a longer uniform turbulent flow area as this geometry ensures a high dissipation rate with a high downstream water height and minimal stress on the spillway chute.

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