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NUMERICAL SIMULATION OF WATER FLOW ALONG STEPPED SPILLWAYS WITH NON UNIFORM STEP HEIGHTS

SIMULATION NUMERIQUE DE L'ECOULEMENT DE L'EAU SUR UN COURSIER EN MARCHE D'ESCALIER AVEC DES MARCHES NON UNIFORME

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ABSTRACT

Stepped spillway is a good hydraulic structure for energy dissipation because of the large value of the surface roughness. The performance of the stepped spillway is enhanced with the presence of air that can prevent or reduce the cavitation damage. The flow over a stepped spillway can be divided into nappe flow regime, transition flow regime and skimming flow regime. This study aims to investigate the effects of the non uniform step heights on the air-water flow properties at stepped spillways. The numerical results of air concentration, air_water velocity and turbulence kinetic energy are presented in this research. Within this work flow over stepped chute is simulated by using fluent computational fluid dynamics (CFD). The volume of fluid (VOF) model is used as a tool to simulate air-water interaction on the free surface thereby the turbulence closure is derived in the $k-\varepsilon$ turbulence standard model. The found numerical results agree well with experimental results.

Key words: air-water flow, Fluent, VOF Model, Stepped Spillway, Standard k $-\varepsilon$ Model.

RÉSUMÉ

Le déversoir en marche escalier est un bon structure hydraulique pour la dissipation de l'énergie en raison de la grande valeur de la rugosité de surface. La performance du déversoir en marche escalier réside dans la présence d'air qui peut prévenir ou réduire la cavitation. Trois régimes d'écoulement distincts peuvent prendre place sur un coursier en marches d'escalier, appelés respectivement, régime d'écoulement en nappe, de transition et en mousse (extrêmement turbulent). L'objectif de cette étude est d'investiguer numériquement les propriétés de l'écoulement sur un coursier en marche d'escalier avec des marches non uniforme.

Les objectifs de cette étude sont valider la relation développée par Chanson et de présenter les contours de pression et vecteurs de vitesse à la surface d'escalier. Les résultats de simulation de la distribution de concentration d'air, de la vitesse du mélange eau-air et l'énergie cinétique turbulente sont présentés dans cette recherche. Dans ce travail, l'écoulement turbulent dans le canal en marche escalier est simulée à l'aide de logiciel FLUENT (CFD). Le modèle multiphasique VOF (Volume Of Fluid) est utilisé comme outil pour modéliser l'interaction eau-air près de la surface libre et le modèle (k-ε) est utilisé pour fermer le système d'équation. Les résultats trouvés numériquement sont en bon accord avec les résultats expérimentaux.

Mots clés : écoulement eau-air, FLUENT, méthode VOF, marche escalier, modèle (k-ε),

INTRODUCTION

Stepped spillway is a power full hydraulic structure for energy dissipation because of the large value of the surface roughness. The energy dissipated with steps was two to three times as great as the energy dissipated with a smooth surface (Charles and Kadavy 1996) and can reduce the size of stilling basin at the toe of the dam (Rajartman 1990; Christodoulou 1993; Chanson 2001). The performance of the stepped spillway is the presence of air which can prevent or reduce the cavitation erosion damage.

It is known that for minimum water discharge and for high length of step, nappe flow occur over a stepped spillway and can be characterized by a succession of free falling jets impinging on the steps and followed by a fully or partially developed hydraulic jump. For medium flow rates, the transition flow arises and is characterized by significant aeration, splashing, and chaotic appearance (Chanson and Toombes 2004). By increasing of water discharge, the skimming flow appears and is characterised by highly turbulence and the water flows as a coherent stream. In the skimming flow regime, air entrainment occurs when the turbulent boundary layer thickness coincides with the water depth (Chanson 1997). This location is called the inception point (e.g. figure 1). At the inception point upstream, the flow is smooth and glassy whereas at the downstream of the inception point the flow becomes uniform as the depth of the air-water mixture grows.

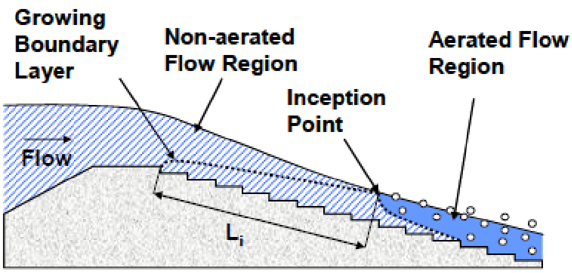


Figure 1: Position of the inception in stepped spillway

The topic of the flow over stepped spillway was the object of several experimental works, with the development of computational fluid dynamics (CFD) branch, flow over stepped spillway can be simulated to validate experimental results. The use of commercial CFD program has become very interesting in order to investigate flow over spillways using reasonable resources, time and expense (Chinnarasri et al 2012). Chen et al (2002), simulated flow over a stepped spillway using the k –ε turbulence model. Benmamar et al (2003) developed a numerical model for the two-dimensional flow boundary layer in a stepped channel with steep slope, which was based on the implicit finite difference scheme. Bombardelli et al (2010) Simulated non-aerated region of the skimming flow in steep stepped spillways using 3D-FLOW. Afshin and Mitra (2012) used FLUENT commercial software for examining the performance of the volume of fluid (VOF) and mixture models in simulating skimming flow over stepped spillway. Numerical study of Mohammed et *al.* (2012) was performed to simulate and investigate flow characteristics over a steeply sloping stepped spillway. They used VOF model to simulate interaction between air and water and Turbulence was encountered by both RNG k-ε and Large Eddy Simulation (LES).

Many experimental studies have focused on stepped spillways with uniform step height to quantify the energy dissipation and to study some characteristic flow regime. But some spillways are equipped with non uniform step heights (Felder 2013; Felder and Chanson2011). Stephenson (1988) observed an increase in energy dissipation of 10% in experimental test of non uniform step height with a slope of 45°. This study present the results of numerical simulation flow in stepped spillway with non uniform step height obtained by using Fluent computational fluid dynamics (2006) to show these effects on the air-water flow properties. The VOF model was applied to evaluate air-water flow hydraulic characteristics. The simulation results were compared with the experimental data of Felder (2013) and Felder and Chanson(2011),also with simulation results of flow along stepped spillway with uniform step height.

DESCRIPTION OF PHYSICAL MODEL

A physical model of stepped spillway provided by Felder (2013) is shown in figure 2. The non-uniform stepped spillways were equipped with a combination of steps with 5 & 10 cm step heights and is characterised by regular alternation of one 10 cm step followed by two 5 cm steps. The channel slope is 26.6°.

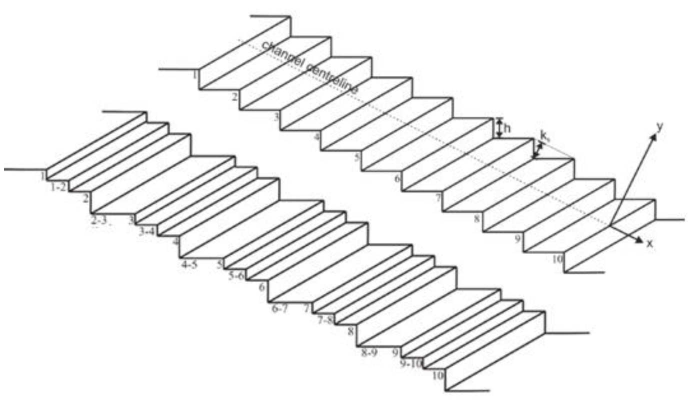


Figure 2: Uniform and non-uniform stepped spillway configuration

NUMERICAL MODEL

Fluent computational fluid dynamics (CFD) is used to solve Navier-Stokes equations that are based on momentum and mass conservation of the moving fluid. The standard $k - å$ model is used to simulate turbulence.

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

Momentum equation

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}\left\{(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right\} \tag{2}$$

Turbulence kinetic energy equation (k)

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k - \rho\varepsilon \tag{3}$$

Turbulence dissipation rate energy equation (ε)

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}G_k - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \tag{4}$$

Where, G_k is production of turbulent kinetic energy which can be given as

$$G_k = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{5}$$

μ_t is the turbulent viscosity that satisfies

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

C_μ=0.09 is a constant determined experimentally;

σ_k and σ_ε are turbulence Prandtl numbers for k and ε equation respectively, σ_k=1.0, σ_ε=1.3,

$C_{1\varepsilon}$ and $C_{2\varepsilon}$ are å equation constants, $C_{1\varepsilon}$=1.44, $C_{2\varepsilon}$=1.92.

The volume of fluid (VOF) method is applied to simulate the free surface between water and air. In this approach, the tracking interface between air and water is accomplished by the solution of a continuity equation for the volume fraction of water:

$$\frac{\partial \alpha_w}{\partial t} + \frac{\partial \alpha_w u_i}{\partial x_i} = 0 \, ; 0 \leq \alpha_w \leq 1 \tag{6}$$

Where, α_w is volume fraction of water.

In each cell, the sum of the volume fractions of air and water is unity. So, volume fractions of air denote α_a can be given as

$$\alpha_a = 1 - \alpha_w \tag{7}$$

MESHING THE GEOMETRY AND BOUNDARY CONDITIONS

The GAMBIT software was used to create and mesh the geometry. The physical model of Felder (2013) was divided into unstructured grids (triangular cell) that had a high adaptability to the complex geometry and boundary. Triangular meshes with 0.015 m^2 are used (figure 3). The boundary conditions in this study are shown in figure 3.

The boundary conditions in this study are pressure inlet as water inlet and air inlet, outlet as a pressure outlet type. All of the walls as a stationary, no-slip wall. The viscosity layer near to the wall dealt with the standard wall function. The boundary conditions for the turbulent quantities such as k and ε can be calculated from (Fluent Inc 2006):

$$k = \frac{3}{2}\left(U_{avg} I\right)^2 \tag{8}$$

$$\varepsilon = C_u^{3/4} \frac{k^{3/2}}{0.07 D_H} \tag{9}$$

Where, *I* is turbulence intensity can be estimated from the following formula derived from an empirical correlation for pipe flows:

$$I = 0.16 (Re_{DH})^{-1/8} \tag{10}$$

U_{avg} is the mean velocity of water flow inlet and D_H is the hydraulic diameter.

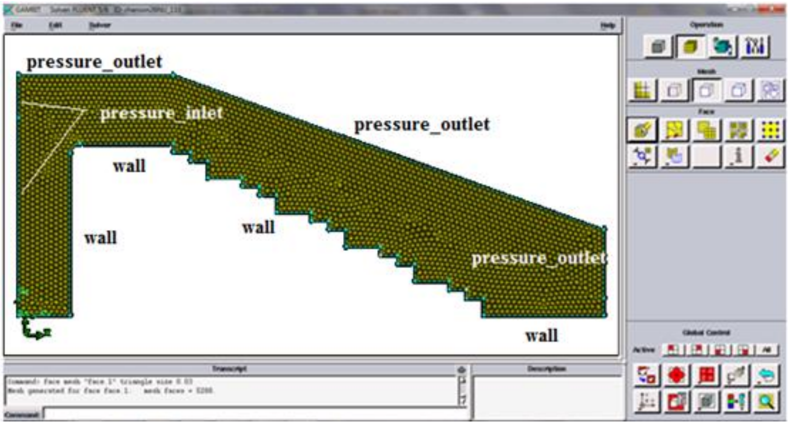
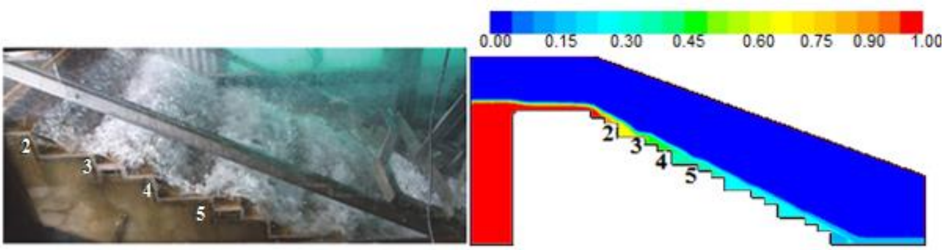


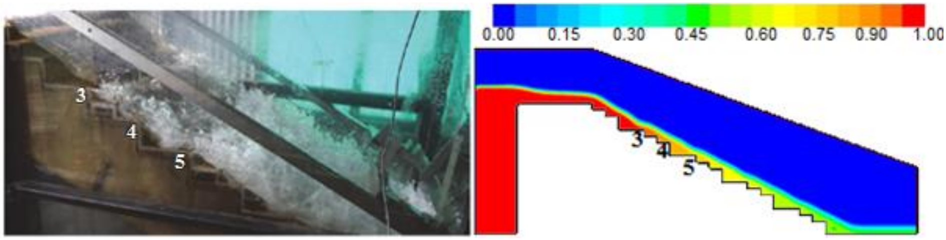
Figure 3: Grid and boundary condition

RESULTS AND DISCUSSIONS

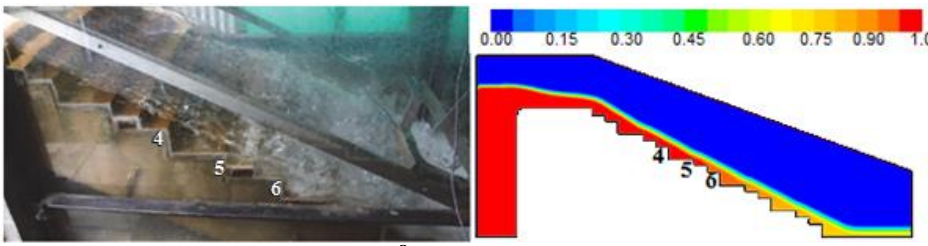
On uniform stepped spillway, nappe flow occurs for the smallest flow rates. For an intermediate range of flow rates, a transition flow regime is observed. For higher discharge value, the water skims over the pseudo-bottom formed by the step edges as a coherent stream. Beneath the pseudo-bottom, intense recirculation vortices fill the cavities between all step edges. The aim of this work is assess the effects of non-uniform step heights on the air-water flow properties down a stepped chute. Three flow regimes over non-uniform steps are shown in figure 4.



(A) Nappe flows: q = 0.025 m^2/s;



(B) Transition flows: q = 0.069 m^2/s



(C) Skimming flows: q = 0.133 m^2/s

Figure 4: Observed and computed flow regime on non uniform step height

Seen from these figures, good agreement between observed and computed flow regime, also the simulated inception point is well agreed with that of measurement. Figure 4 indicates that, the air entrainment started on step edge N°2, for nappe flow and on step edge N° 3 for transition flow. In skimming flow, the location of the inception point is clearly shown between step N° 5 and N°6. It is clear that, the inception point moves toward the basin floor when the discharge increases.

Figure 5 gives numerical void fraction of water on the uniform and non uniform stepped spillways with 26.6° slope.

The observations of the air-water flow patterns on the non-uniform stepped spillways showed that the non uniform configurations were close to the uniform stepped spillway with 10 cm high steps. These results proved that the non uniform stepped configurations have no influence on the location of the inception point of air entrainment.

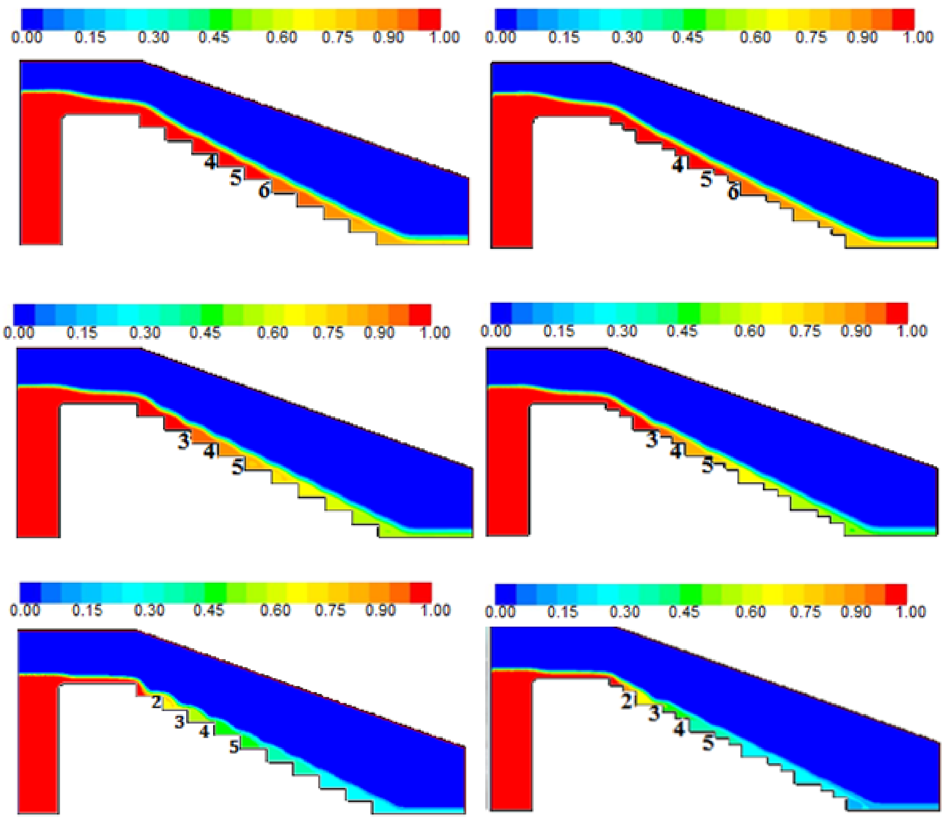


Figure 5 : Numerical void fraction of water on the uniform and non uniform stepped spillways

Void fraction and velocity profile

Downstream of the inception point of free-surface aeration, air and water are fully mixed, forming a homogeneous two-phase flow. In figure 6, the distribution of concentration of air on non uniform configuration is compared with those obtained in uniform configuration. The comparison is satisfactory, but scatter of the void fraction distribution shapes was observed for the non-uniform stepped spillways. We observed some larger air concentration on non uniform configuration when y/Y_{90} <0.25 which might be caused by stronger instabilities of the flow.

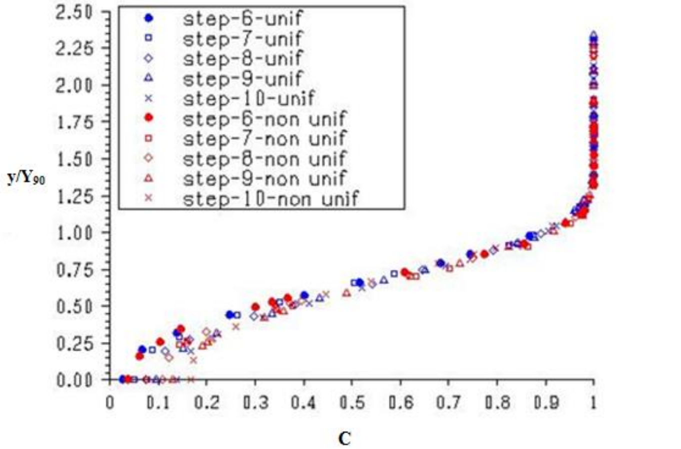


Figure 6 : Computational air concentration distribution on uniform and non uniform configurations

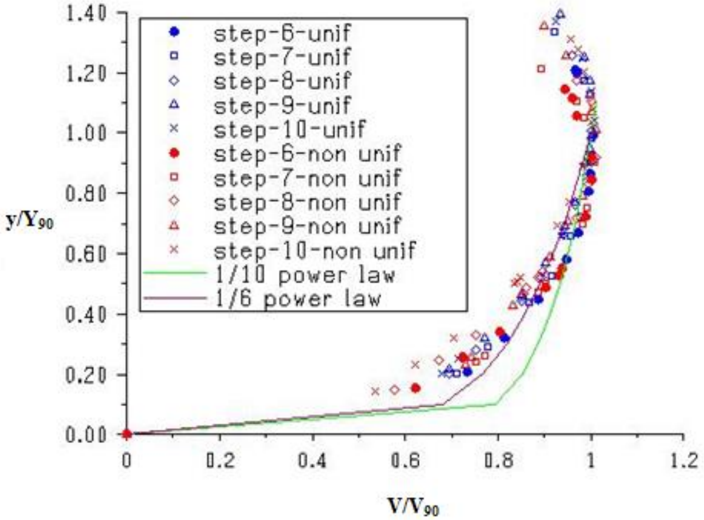


Figure 7 : Dimensionless velocity on uniform and non uniform configurations

The air- water velocity profile at step edge is presented in figure 7 for q=0.122 m^2/s. This figure show same profile of velocity on the uniform and the non uniform configurations and it increases from the pseudo bottom at the free surface flow. Felder and Chanson (2011) compared the velocity profile with $1/10^{th}$ power law correlation for $y/Y90 < 1$ and a uniform profile for $y/Y90 \geq 1$. From figure 7, the Velocity profile matched well with one-sixth power law.

Air concentration distributions and velocity profile, measured by Felder and Chanson (2011) is presented in Figure 8. The air concentration distributions obtained by simulation (e.g. figure 6) agree with measurement results.

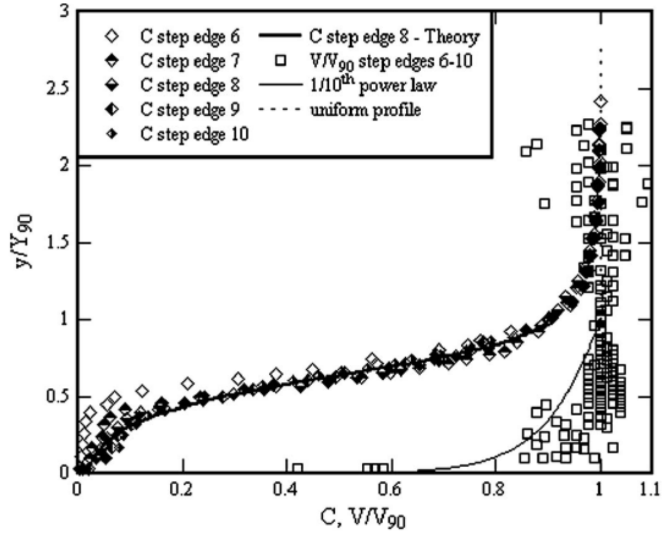


Figure 8 : Dimensionless velocity and air concentration measured by Felder and Chanson (2011)

For the velocity profile, there is some difference between the simulation and measurement when $y/Y_{90}<0{,}5$. The numerical solution seems to produce slightly more uniform velocity profiles than those observed which may be due to the nature of turbulence models. Thus, the difference may also come from the three-dimensional structure of the flow and the anisotropy is not captured in 2D. (Bombardelli et al 2010).

Velocity distribution

The velocity distribution on the uniform and the non uniform stepped spillway are compared in figure (9). The maximum velocity from non uniform configuration is some great than in uniform configuration which the recirculating vortices are more developed (seen figure 10). Thus, the stepped spillway with uniform step heights is more efficient than with non uniform step heights in reducing the flow velocity and in dissipation of energy. Felder and Chanson (2011) showed from experiment that, the configuration with non-uniform step heights did not yield any advantages in terms of energy dissipation performances.

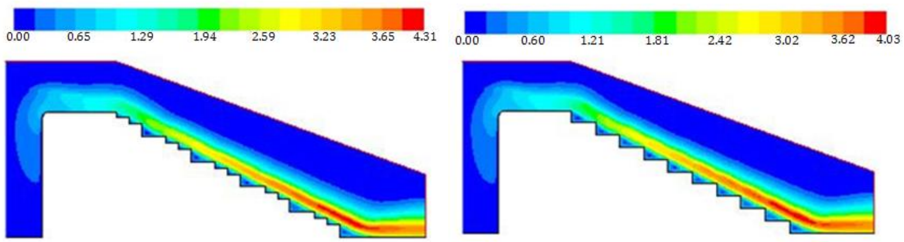


Figure 9 : Velocity distribution on uniform and non uniform configurations

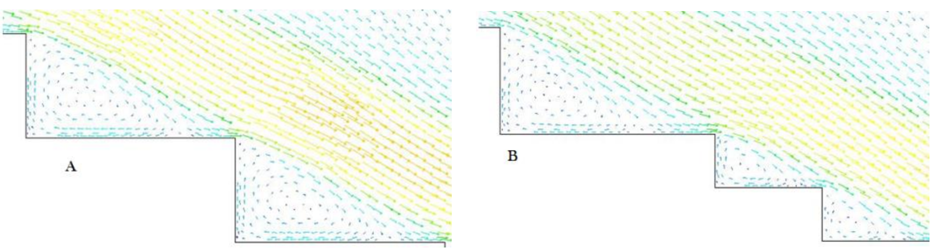


Figure 10 : Recirculation flow in step corner, A: uniform configuration, B: non uniform configuration

Turbulence kinetic energy

Figure (11) present a comparison of turbulence kinetic energy on the uniform and non uniform stepped spillway.

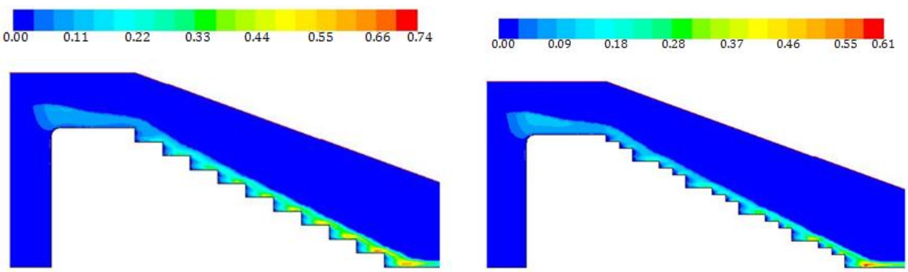


Figure 11 : Turbulence kinetic energy on uniform and non uniform configurations

The kinetic energy of turbulence on the uniform stepped spillway was largest for most step edges. The roughness height which is $k_s = h\ \cos\theta$ is great on uniform configuration and the kinetic energy of turbulence increased with the surface roughness. It means that, the recirculating vortices located in the triangular zone of the step corner are higher in uniform stepped spillway.

Pressure distribution

In order to evaluate the risk of cavitation in stepped channel; figure (12) and figure (13) show the contour of pressure on the uniform and non uniform stepped spillway for q=0.133 m^2/s. According to figures (12) and (13), the maximum value of negative pressure is appeared in non uniform configuration and is located in the steps edges for the 5 cm high. The cavitation on chutes is initiated for high velocity flows and it is known that the velocity in non uniform configuration is higher than the uniform configuration. Thus, the stepped spillway with uniform step heights is more protect than with non uniform step heights in risk of cavitation.

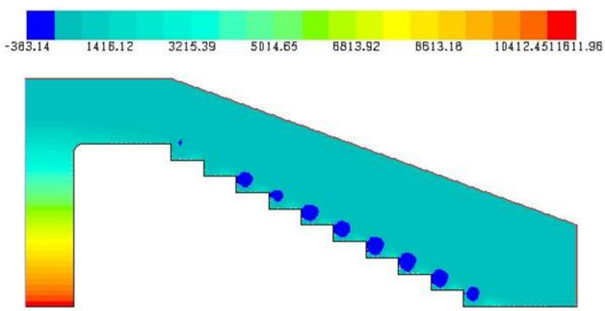


Figure 12 : Contour of static pressure on uniform stepped spillway

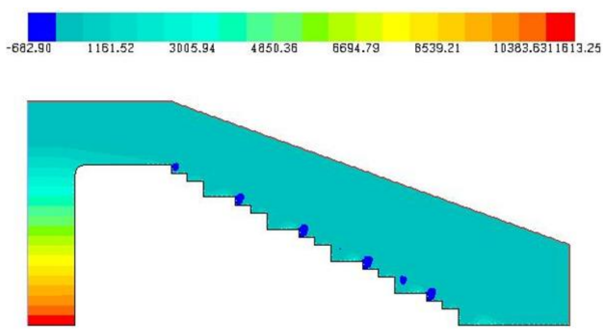


Figure 13 : Contour of static pressure on non uniform stepped spillway

CONCLUSIONS

In the present numerical study, flow over stepped spillway was simulated by using fluent. Free surface was treated by VOF model and turbulence flow was estimated by k-å Standard Model. This work focused on the uniform and non uniform steps height. The experimental studies are used to validate the numerical results of the air-water two-phase flow over the stepped spillway. Good agreement is found between numerical and experimental results. On the basis of results, the following conclusions can be drawn:

1. The non uniform stepped configurations did not have any impact on the location of the inception point of air entrainment;
2. The configurations with the non-uniform step heights showed some larger air concentration compared to the uniform stepped spillways which might be caused by stronger instabilities of the flow;
3. The maximum velocity from non uniform configuration is some great than in uniform configuration;
4. The configuration with non-uniform step heights did not yield any advantages in terms of energy dissipation performances;
5. The maximum value of negative pressure is appeared in non uniform configuration and is located in the small steps edges, so, the stepped spillway with uniform step heights is more protect than with non uniform step heights in risk of cavitation;
6. The kinetic energy of turbulence on the uniform stepped spillway was largest for most step edges.

REFERENCE

AFSHIN EGHBALZADEH, MITRA JAVAN, 2012. Comparison of Mixture and VOF Models for Numerical Simulation of Air–entrainment in Skimming Flow over Stepped Spillways .J. of Science Direct. Procedia engineering (28) 657 – 66.

BENMAMAR, S. KETTAB, A., THIRRIOT, C., 2003, Numerical simulation of turbulent flow upstream of the inception point in a stepped channel. Proceedings, 30th IAHR Congress. Auth, Thessaloniki, Greece: 679-686.

BOMBARDELLI FA, MEIRELES I, MATOS J, 2010. Laboratory measurements and multi-block numerical simulations of the mean flow and turbulence in the non-aerated skimming flow region of steep stepped spillways. Environ. Fluid Mech 11(3):263-288.

CHANSON, H, 1997. Air Bubble Entrainment in Free-Surface Turbulent Shear Flows. Academic Press, London, UK, 401 pages ISBN 0-12-168110-6.

CHANSON, H., 2001. The Hydraulics of Stepped Chutes and Spillways. Steenwijk, the Netherlands: A. A. Balkema Publishers.

CHANSON, H., TOOMBES, L. 2004. Hydraulics of stepped chutes: the transition flow. Journal of Hydraulic Research, Vol 42, N°1, pp 43–54.

CHARLES E.RICE, KEM C.KADAVY, 1996. Model of A roller compacted concrete stepped spillway. Journal of Hydraulic Engineering, ASCE, 122(6):292-297.

CHEN, Q., G.Q. DAI AND H.W. LIU., 2002, Volume of Fluid Model for Turbulence Numerical Simulation of Stepped Spillway Over Flow. Journal of Hydraulic Engineering, ASCE 128 (7): 683-688.

CHINNARASRI, C., KOSITGITTIWONG, K. JULIEN. PY. 2012. Model of flow over spillways by computational fluid dynamics.Proceedings of the Institution of Civil Engineers, pp 1-12

CHRISTODOULOU, G.C. 1993. Energy dissipation on stepped spillways. Journal of Hydraulic Engineering, ASCE 119 (5): 644-650.

FELDER, S. 2013. Air-Water Flow Properties on Stepped Spillways for Embankment Dams: Aeration, Energy Dissipation and Turbulence on Uniform, Non-Uniform and Pooled Stepped Chutes. Ph.D. thesis, School of Civil Engineering, The University of Queensland, Australia.

FELDER, S., CHANSON, H. 2011. Energy Dissipation down a Stepped Spillway with Non- Uniform Step Heights." Journal of Hydraulic Engineering, ASCE, Vol. 137, N° 11, pp. 1543- 1548 .

Fluent, 2006, Manuel and user guide, Fluent Inc

IMAN NADERI RAD, MEHDI TEIMOURI., 2010. An Investigation of Flow Energy Dissipation in Simple Stepped Spillways by Numerical Model. European Journal of Scientific Research. ISSN 1450-216X Vol.47 No.4:544-553.

MOHAMMAD S, JALAL. A., MICHAEL. P, 2012. Numerical Computation of Inception Point Location for Steeply Sloping Stepped Spillways" 9th International Congress on Civil Engineering, Isfahan University of Technology (IUT), May 8-10,Isfahan, Iran

RAJARATNAM, N, 1990. Skimming flow in stepped spillways. Journal of Hydraulic Engineering, ASCE 116 (4): 587-591.

STEPHENSON, D. 1988. Stepped Energy Dissipators. Proc. International Symposium on Hydraulicsfor High Dams, IAHR, Beijing, China, pp. 1228-1235.