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The effects of step inclination and air injection on the water flow in a stepped spillway: A numerical study*

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Abstract: In this work, we perform a numerical study of a water flow over a stepped spillway. This flow is described by the Reynolds averaged Navier-Stokes equation (RANS) associated with the turbulence k - ε model. These equations are solved using a commercial software based on the finite volume scheme and an unstructured mesh. The air-water flow was modeled using volume of fluid (VOF) and multiphasic methods. The characteristics of the flow were investigated including the total pressure, the velocity profile, etc.. We analyze the effects on the flow structure of the steps and countermarch inclination, the air injection through the countermarch into the water flow and the dynamics water discharges. Results show that the inclination of the countermarch relative to the vertical and the air injection into the water flow increase the total pressure in the neighbourhood of the steps.

Key words: Stepped spillway, turbulence, air-water, air injection, volume of fluid (VOF) method, multiphasic method

Introduction

Water flow over spillway has been extensively studied because of its relevance in engineering problems such as in storage and detention dams. In a dam spillway, the water flow velocity reaches very high values causing the cavitation erosion of the spillway walls. Studies of water flows over a stepped spillway are very complex because these flows involve a number of phenomena such as air entrainment, cavitation, turbulent boundary layer, free surface flow and complex geometry[1]. In the following, we attempt to report some experimental and numerical studies on water flow along stepped spillway. Based on experimental works, Sánchez-Juny[2] showed the existence of four different zones inside which the flow occurs. In the first zone, immediately downstream of the crest of the spillway, the water is clear and without aeration process. In the second zone, adjacent to the preceding one, the water is clear and described by a typical U-shape and an aeration process occurs, starting from the edges of the channel. In the third area, the aeration process begins where the water is foamy and white. In the fourth zone, the flow is completely aerated and the white water phenomenon appears. In order to analyze the influence of the size of the countermarch on the flow structure, the air concentration and the rate of energy dissipation, Felder and Chanson[3,4] conducted a study on five stepped spillway configurations, two with countermarch of the same size and three with countermarch of different sizes. The results show that for low flow rates, the air concentration in the flow is, in the case of the configuration with countermarch of different sizes, superior to the one with the configuration for which the countermarch has the same size. For the stepped spillway with countermarchs of different sizes, the air concentration is superior to all those of other configurations. Moreover, the rate of energy dissipation does not really depend on the stepped spillway configuration considered in this study. Therefore, increasing the number of steps of the same size leads to a decreasing of the energy dissipation of the flow. It will be noted that in the case of the stepped spillway configuration for which steps have the same size, regardless of the flow regime, the rate of energy dissipation and the air

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concentration decreases as the discharge increases. The increase in the number of steps generates an increase in water thickness in the stilling basin and a reduction in the length of hydraulic jump[5]. For instance, for a stepped spillway made up of 32 steps, the water thickness in the stilling basin increased by 71% and the value of the length of hydraulic jump is reduced by 64% compared with a conventional spillway.

Numerous experimental studies based on the similarity of Froude (Fr) and Morton (Mo) numbers were performed to analyze the scale effect on the two-phase air water flows. These studies highlighted that the choice of the criteria to assess scale effects is critical because some parameters such as void fraction, turbulence intensity, or bubble size, are likely to be most affected by scale effects, even in relatively large laboratory models[6]. Based upon a literature review[7], Pfister and Chanson[6] have highlighted that the relevant scaling parameter of an air water flow is the air concentration, while the non-dimensional numbers Fr, We, Re, Mo, and some limiting values of Re or We reduce scale effects. No scale effect has been observed by these authors at full scale only, using the same fluids in prototype and model.

Numerical simulations of air-water flowing on stepped spillway were performed using the Reynolds Averaged Navier-Stokes equations (RANS)[1,8-12] or the Saint Venant equations[13] coupled with turbulent models such as standard k - ε [1,8,11,14,15], RNG k - ε [11] Reynolds stress[10,16], realizable k - ε [8,9], SST k - ω [9], v^2 - f [9] and LES[9]. These equations are very difficult to solve, so various works on this flow type were carried out by using a commercial code such as Fluent[8], or Flow-3D[10,11] and others. These software are based on the finite volume method, the volume of fluid (VOF) method[9,15], Tru VOF[10,17] or the mixture model[8,9]. Numerical studies showed that the skimming flow regime[1,8,9,12] is divided into a main flow described by a uniform stream over the outer edges of the steps[1,8,9] and a secondary flow characterized by eddies located in the space defined by the main flow, the step and the countermarch. For instance, a discharge value equal to 0.03 m^3/s, leads to negative pressure on the edges of the steps[8]. This negative pressure causes the cavitation phenomenon and consequently the deterioration of the stepped spillways. Qian et al.[9] analyzed the influence of four turbulence models: realizable k - ε, k - ω SST, v^2 - f and LES on the mean velocity of the water flow. The results are compared with those obtained by PVC. The turbulence model v^2 - f underestimates the mean velocity value of the iso-velocity cells, while the mean velocity values obtained by the realizable k - ε and the k - ω SST models are superior to those measured by the PIV system. The LES model leads to results different from the experimental results. Bombardelli et al.[11] simulated a non-aerated flow over a stepped spillway using the k - ε and RNG k - ε turbulence models combined with the Tru VOF method. Results of velocity field and water flow thickness obtained with these two turbulence models are close. Numerous studies[18-21] on water flows over stepped spillway showed that flows over stepped spillways can be classified into three regimes depending on the discharge value and the step geometry: nappe flow regime, observed for small discharge values, characterized by a succession of overfalls jumping from one step to another. The increase in the discharge value generates the development of eddies located in the space delimited by the main flow, the step and the countermarch. Between this type of skimming flow and the nappe flow regime, there exists a range of discharge values for which the flow is characterized by a significant aeration, splashing, and chaotic appearance and the flow properties vary from step to step.

Wei et al.[22] developed a diffusion model to predict the air concentration distribution in the self-aerated open channel flows. The air-water flow is regarded as consisting of the low flow region, where the air concentration is lower than 0.5 and the upper flow region, where the air concentration is higher than 0.5. They noted two different diffusion processes: one in which the air bubble diffuses in the water flow by turbulent transport fluctuations in the low flow region, in the other process the water droplets and free surface roughness diffuse in the air in the upper region.

In water flowing along a stepped spillway, the air quantity entrained by the flow and the air bubbles in the water flow contribute to the reduction of cavitation erosion. The air entrainment causes a reduction of the shear stresses in the fluid and on the wall of the spillway. Dong and Lee[23] indicated that friction factor in a stepped channel flow is considerably greater than that in a smooth channel flow. Moreover, the energy dissipated in the flow over a stepped spillway is superior to the one in a flow on a smooth spillway. Chen et al.[24] carried out a study in order to analyze the influence of the dam slop and of the ogee at the spillway toe on the energy dissipation rate. They showed that the energy dissipation rate increases as the dam slope decreases. In addition, the energy dissipation ratio of the stepped spillway without ogee is much greater compared with that of the stepped spillway with ogee. So, the ogee can improve the energy dissipation rate and consequently contribute to the reduction of the cavitation phenomenon. Many studies[18,21], mainly experimental, have shown that the resistance on the walls of spillway can be reduced by using, for example, special concrete or by air injection into the water flow.

Although the study of flowing water on stepped spillways have been the subject of various studies, it