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Numerical and Experimental Study of Wedge Elements Influence on Hydraulic Parameters and Energy Dissipation over Stepped Spillway in Skimming Flow Regime

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ABSTRACT: A stepped spillway is a hydraulic and cost-effective measure to dissipate the energy of large water flow over the spillway. Due to some limitations in stepped spillways, this study has intended a plan to increase and improve the effectiveness of energy depreciation. For this purpose, the effect of the wedge-shaped elements on the velocity and pressure changes over the steps, water level, and energy dissipation downstream the stepped spillway are evaluated. In this regard, several forms of wedge elements are studied with changes in wedge arrangement and the rate of discharge by using a numerical model of Flow-3D, and the appropriate models from the aspect of the most energy depreciation are selected and studied in the laboratory. In the laboratory, 25 experiments were performed on 5 physical models. Numerical and experimental results show that the addition of wedge elements on the stepped spillway has reduced the velocity and water depth downstream of the spillway to about 80% and 30%, respectively, and the energy dissipation over the stepped spillway increased by about 2.7 times. Also, by drawing the distribution profiles of pressure on the edge and the floor of steps, it was observed that the negative pressure in the horizontal section turned into a positive one. Also, negative pressure in the vertical section decreased up to 96% and positive pressure increased about 2 times. As well as increasing the density of the elements, the results that increase the energy dissipation are going to be more remarkable.

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1. INTRODUCTION

The purpose of the design and construction of stepped spillways is to increase the energy dissipation and reduce the dimensions of the hydraulic structures downstream. Stepped spillways, by providing an artificial rough bed, reduce the flow of kinetic energy and also significantly reduces the evaporation phenomena by conducting aeration in the flow .Several researchers such as Chanson [1], Chamani and Rajaratnam [2], and Kells [3] have analyzed energy dissipation on simple laboratory models of the stepped spillway (without adding elements on the steps). Tabbara et al. [4] by applying the finite element method evaluated flow over the stepped spillway. Razi et al. [5] studied the effect of slope and number of steps in numerical and laboratory methods.

One of the factors that cause fundamental changes in energy dissipation and hydraulic parameters in the stepped spillway is changes in shape and geometry of the spillway and steps. This study aims to investigate the effect of adding elements on the steps on changes in velocity and pressure on the steps, changes in the water level downstream of the spillway, and energy dissipation in the skimming flow regime.

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2. METHODOLOGY

2.1. Numerical studies

In this study, a finite-volume numerical method (Flow-3D) was used to investigate the effect of adding wedge-shaped elements on velocity and pressure changes in the floor and edges of the steps, the water level at the downstream, and the energy dissipation on the stepped spillway. The wedge-shaped elements are shown triangular in plan, in which two shapes of the triangle with four layers are investigated. The geometry and alignment of these wedges are shown in Fig.1.

To solve turbulence equations and numerical simulation of flow pattern in Flow-3D, the K-ε (RNG) turbulence model has been used. This model is more accurate than the Two-equation (K-ε) turbulence model for numerical simulation of the flow pattern on the stepped spillways, and the completion time of the simulation (uniformity of flow) in this model takes place sooner.

To validate the numerical model, the measured velocity values in the laboratory and the velocity in a numerical model for discharge of 60 liter/s were investigated that the mean relative error was obtained 8.57%.

2.2. Experimental study

In the present study, experiments were done in the hydraulic

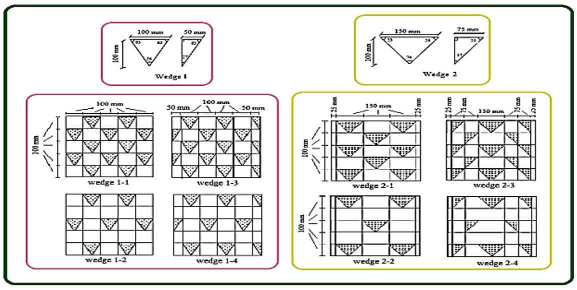

Fig. 1. Geometry and alignment of the wedges in the numerical study.

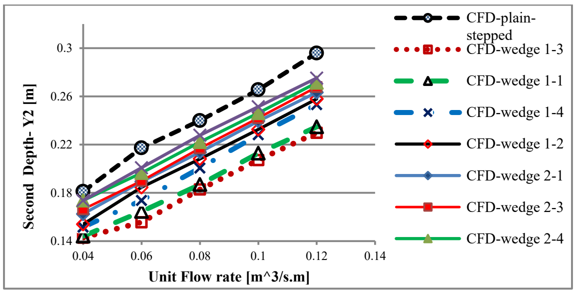

Fig. 2. Secondary water depth versus unit flow rate in the simple stepped spillway and stepped spillway with wedge elements.

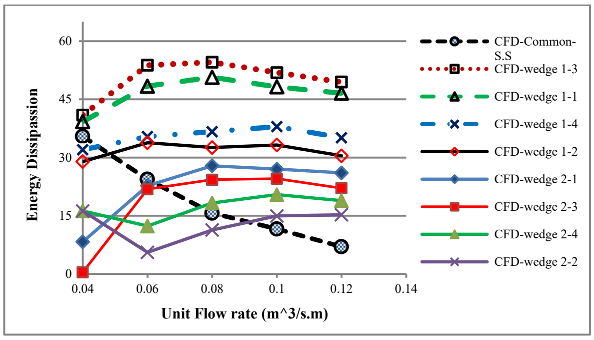

Fig. 3. Energy dissipation for simple stepped spillway and stepped spillway with wedge elements.

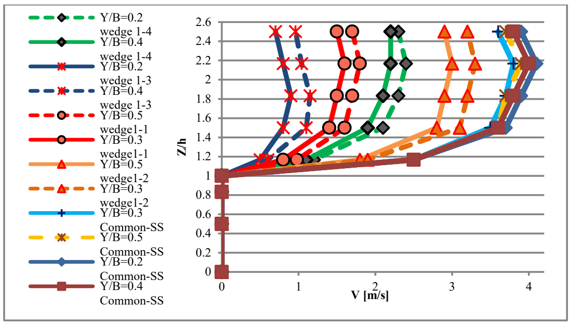

Fig. 4. Vertical profile of the flow velocity distribution in the vertical wall at x = 0 (*Z* is the distance from the floor of the step and *h* is the height of the step.

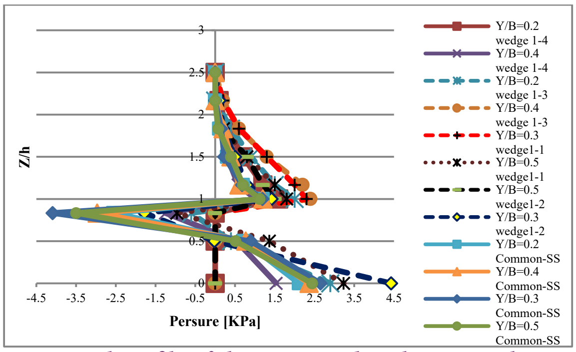

Fig. 5. Vertical profile of the Pressure distribution in the vertical wall at x = 0 (*Z* is the distance from the floor of the step and *h* is the height of the step).

laboratory of Tabriz University, Iran. The experiments were carried out in a Channel length=10 m, wide= 0.5 m, and high=0.8 m with a free-flow system. A laboratory model of a simple stepped spillway had 50 cm wide, 60 cm height, and which has 6 steps (w = h = 10 cm), four different layout modes of wedge elements were tested. The discharge range was 10 to 60 lit/s.

3. RESULTS AND DISCUSSION

3.1. Numerical studies

This study aims to investigate the effect of adding wedges elements on the steps on the velocity and pressure variations in the floor and vertical wall of the step, changes in the water level downstream of the spillway, and energy dissipation. Fig. 2 shows the results of the secondary water depth versus unit flow rate for simple stepped spillway (SSS) and stepped spillway with wedge elements (SSW) with different geometries and layouts. According to this figure, it is seen that the stepped spillway with wedge element types 1 and 2 has a lower secondary depth than a simple stepped spillway. So that the wedge element (3-1), (1-1), (4-1), and (2-1) reduced 30%, 21%, 14%, and 13% of the secondary depths relative to the simple stepped spillway, respectively.

Fig. 3 shows the energy dissipation values for SSS and SSW of types 1 and 2. It is observed that in SSW of type 1 and 2, energy is more lost than SSS. So according to the numerical results, it is deduced that SSW type 1 has the least amount of secondary depth and therefore the highest amount of energy dissipation compared to SSS and SSW type 2.

Fig. 4 shows the distribution profile of the flow velocity in the vertical wall (x = 0) for a flow rate of 60 lit/s. In the step wall, from the step stub (x = 0) to a height of 1 which is equivalent to the edge of the step, the surface is solid and the flow in the horizontal direction is not motion, so the velocity value is zero. After passing through the edge of the step a little bit from the wall, the velocity distribution increases, so that it reaches its maximum value at 0.3 from the free surface flow. Therefore velocity for the layouts 3-1, 1-1, 4-1 and 2-1 reduced (80% -72%), (61% -55%), (47-44%) and (23% -15%), respectively.

Fig. 5 shows the pressure variations in the vertical section of the step. By adding wedge elements type 1 with wedge1-1, wedge1-2, wedge1-3 and wedge1-4 layout, the negative pressure in the vertical wall was decreased about 72%, 56%, 96%, and 59%, respectively, and also positive pressure at the edge of the step increased 93%, 34%, 200%, and 37%, respectively.

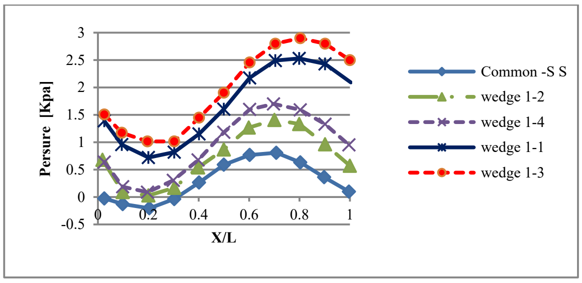

Fig. 6. Horizontal profile of the pressure distribution in the floor of the step (*X* distance from the step corner and *L* step length).

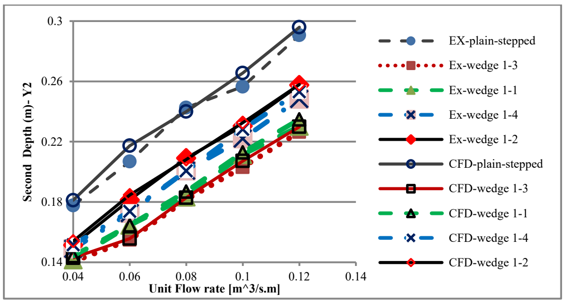

Fig. 7. Numerical and laboratory secondary water depth of a simple stepped spillway and stepped spillway with a wedge element type 1.

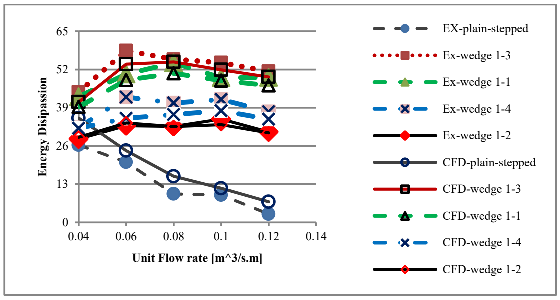

Fig. 8. Changes of the energy dissipation for simple stepped spillway and stepped spillway with wedge elements of type 1.

Fig. 6 shows the pressure changes in the floor of the step. The maximum pressure value for SSS and SSW 4-1 and 2-1 in 0.7 and for 1-1 and 3-1 at 0.8 in the floor of step occurs, and the minimum value in x / l = 0.2 occurs.

3.2. Experimental studies

Fig. 7 shows the secondary water depth versus unit flow rate for SSS and SSW of type 1. The error percentage of the secondary depth of flow in the numerical and experimental models is very small so that for SSS is 4/6%, and SSW with layout, 1-1, 1-2 1-3, and 1-4 is 3.28%, 3.02%, 3.29%, and 3.41%, respectively, which it indicates a good fit between numerical and laboratory data.

Fig. 8 shows energy dissipation changes for SSS and SSW type 1. According to this figure, energy dissipation for SSW has increased compared to SSS. The energy dissipation for wedge 1-1, 1-2, 1-3, and 1-4 compared to SSS is increased 2.4, 1.24, 2.7, and 1.62 times, respectively.

4. CONCLUSIONS

This study aims to investigate the effect of adding wedge elements on the stepped spillway on changes in velocity and pressure on the floor and edge of the steps, changes in the surface water level downstream of the spillway, and energy dissipation. Numerical studies of these models showed that SSW of type 1 with 4 different layouts had the least secondary depth and therefore they have the most energy dissipation compared to SSS and SSW type 2. Also, for the more density of the wedge elements, the better results are obtained. In fact, by reducing the distance between the elements, energy dissipation increases and the secondary depth decreases too. So that wedge elements in SSW with wedge1-3, wedge1-1, wedge1-4 and wedge1-2 layers reduced 30%, 21%, 14% and 13% secondary depths, respectively, and also (80% % 72), (61% -55%), (47-44%) and (23% -15%) reduced the velocity in the vertical wall of the step . As well as adding wedge-type 1 with the above-mentioned layouts, the amount of negative pressure in the vertical wall was decreased 96%, 72% 59%, and 56%, respectively, and the positive pressure at the edge of the step for the same arrangement was increased 200%, 93 %, 37%, and 34%, respectively.

The value of energy dissipation for SSW has increased compared to SSS so that wedge 1-1, wedge 1-2, wedge 1-3, and wedge 1-4 increased 2.4 times, 1.24 times, 2.7 times, and 1.62 times, respectively.

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