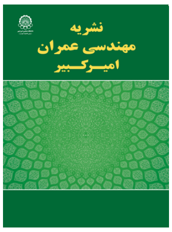

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Experimental Investigation of Nappe Flow Domain on Stepped Spillways

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ABSTRACT: Stepped spillways are used to discharge the floods flow entering the reservoirs. Along these spillways, the energy is highly dissipated. It consists of a series of arranged steps along the spillway to ensure a uniform flow depth and velocity. Stepped spillways improve the rate of longitudinal energy dissipation on the spillway. The energy dissipation affects the flow characteristics and the energy dissipaters at downstream. The flow over stepped spillways is divided into three regimes of nappe, transition and skimming flows. So far, limited numbers of studies have been performed on the basis of analytical and empirical information to check the features and complicated nature of nappe flows. Limitations on physical model studies are also important to mention. As a result, few relationships have been suggested to describe nappe flow characteristics over stepped spillways. In this study, a set of experiments were performed on three large-scales hydraulic spillway models of Siahbisheh upper and lower dams and Zhaveh spillway dam. The data cover six spillway slopes and 24 flow rates. Measurements of depth, velocity, and static pressure were made at 40 different cross sections along the chutes. Major effective geometrical and hydraulic parameters on energy dissipation in nappe flow regime over stepped spillways were analyzed, based on present measurements. A relationship was then suggested to calculate the rate of energy dissipation in nappe flow regime. This study showed that the ratio of critical depth to height of spillway is the most important dimensionless parameter in predicting energy dissipation, the increase of which reduces the relative energy dissipation in the nappe flow regime.

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1.INTRODUCTION

In this study, dependent variables are used to introduce a dimensionless form of energy dissipation in stepped spillways. These variables are: height of the step (h), step length (l), discharge per unit width (q), height spillway (vertical distance from the crest to the bottom of stilling basin) (H_D), acceleration due to gravity (g), number of steps (N), maximum head over spillway (H_{max}). Given that the flow is the free surface type and ignoring the effect of the Reynolds and Weber numbers, the relative energy dissipation is expressed in the following dimensionless equations:

$$\frac{\Delta H}{H_{max}} = f\left(\frac{y_c}{Nh}.\frac{h}{l}.\frac{H_D}{y_c}\right) \quad \text{or}$$

$$\frac{\Delta H}{H_{max}} = f\left(\frac{y_c}{Nh}.\frac{h}{l}.\frac{H_D}{y_c}.N\right) \qquad (1)$$

The present study was carried out in the hydraulic laboratory of the Water Research Institute on three hydraulic models (Upper Siahbisheh Dam, Lower Siahbisheh and Zhaveh dams) and six spillways with six different slopes. The upper Siahbisheh spillway with three slopes, the lower Siahbisheh spillway with two slopes and the Zhaveh spillway with one slope are the physical models used in this research. Figure 1 shows Siahbished and Zhaveh models.

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2.METHODOLOGY

A literature review was carried out on relative research, specifically on the nappe flow regime, in detail. Zhang and Chanson (2016) investigated the development of a boundary layer on stepped overflows via a laboratory study. The results of their research showed that in stepped spillway with a steep slope of 1V:1H, the development of a turbulent boundary layer occurs faster than a smooth chute with the same discharge and slope [1]. Hasanalipour et al. (2019) tested four physical models on the spillway of the upper and lower Siahbisheh

SiahBisheh (D, E Model)   *Zhavel (F Model)*

Fig. 1. lower Siahbisheh dam spillway (model D & E) and Zhaveh dam (model F)

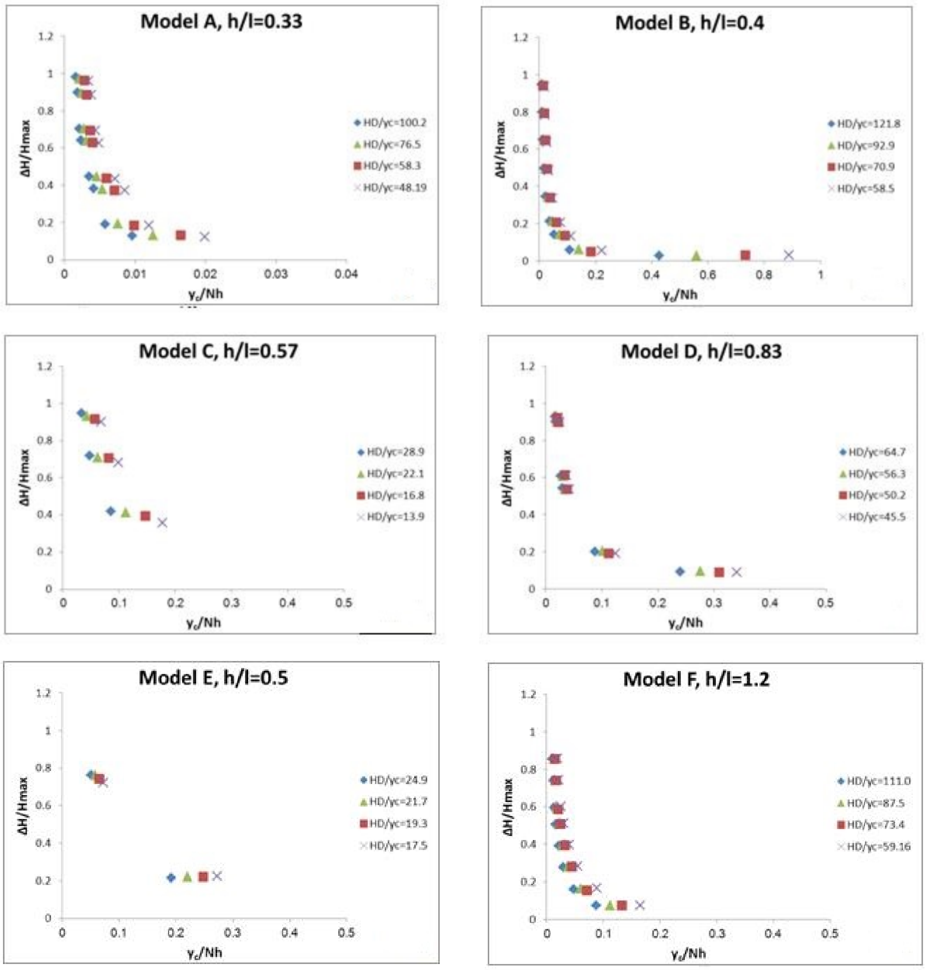

Fig. 2. Variation of $\frac{\Delta H}{H_{max}}$ in terms of $\frac{y_c}{Nh}$ for different models of the present study

dam with scales of 1:15 and 1:20 and slopes of 18.44, 26.56, 74.29 and 38.81 degrees. Results show that in the nappe flow regime, an increasing trend of pressure is observed from the heel to the edge of the step. This trend is gentle to the middle of the step but continues to increase sharply. Also, in the nappe flow regime, with increasing spillway slope, extreme pressures occur near the edge of the step [2].

3.RESULTS AND DISCUSSION

The present research is based on physical model and laboratory results. Experiments were performed on six spillways with six different chute slopes and four discharges to measure hydraulic parameters and nappe flow profile. The results were analyzed and the effect of the geometric parameters (geometry, slope, height and length of the steps) was investigated. Nappe and transition flow regime have been recognized by observations and checked by previous results.

According to results, for spillway with a certain height and a specified number of steps (N), with decreasing $\frac{H_D}{y_c}$, the relative energy dissipation decreases. Figure 2 shows the variation of $\frac{\Delta H}{H_{max}}$ in terms of $\frac{y_c}{Nh}$ for different models.

According to the dimensionless analysis, the proposed relationship to calculate the relative energy dissipation of nappe flow in stepped spillways was obtained by the logarithmic method. The general relationship on relative energy dissipation was considered as follows:

$$\frac{\Delta H}{H_{max}} = a \times \left(\frac{h}{l}\right)^{b} \times \left(\frac{H_D}{y_c}\right)^{c} \times \left(\frac{y_c}{Nh}\right)^{d} \qquad (2)$$

where, a, b, c and d are unknowns, which are defined by optimization techniques, so that the final equation was determined as follows:

$$\frac{\Delta H}{H_{max}} = 1.11 \times \left(\frac{h}{l}\right)^{-0.30} \times \left(\frac{H_D}{y_c}\right)^{-1.07} \times \left(\frac{y_c}{Nh}\right)^{-1.021} \quad R^2 = (0.98) \qquad (3)$$

Equation (3) provides the relative energy dissipation from the crest to the Nth step for the spillway with the height H_D and slope $\theta(\frac{h}{l})$. Based on the model characteristics, Equation 3 is applicable considering the following conditions:

$$0.33 < \frac{h}{l} < 1.2,\ \ 13.92 < \frac{H_D}{y_c} < 121.84 \ \text{ and } 0.00163 < \frac{y_c}{Nh} < 0.8875$$

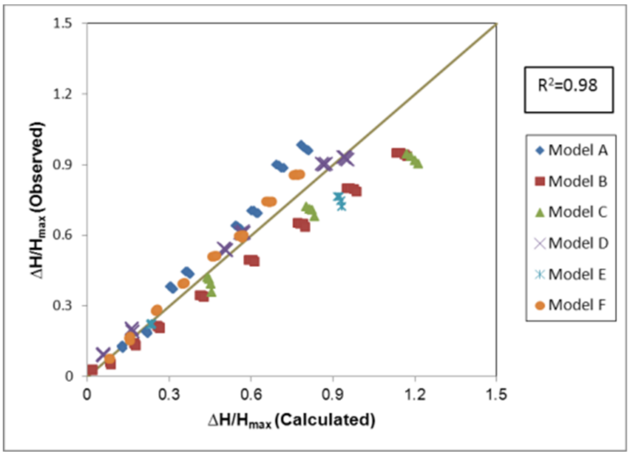

Fig. 3. Validation of proposed equation for calculating relative energy dissipation (logarithmic solution method)

To validate Equation 3, variation in $\frac{\Delta H}{H_{max}}$ from the measurements and estimations was plotted and compared in Figure 3. The figure shows reasonable agreements between the measured and the estimated results.

To ensure the accuracy of the proposed equation in calculating energy dissipation, the results of this equation were compared and shown with the results of other researchers in Table 1.

Table 1. Evaluation of energy dissipation equations for nappe flow regime

Researcher	Equations	R^2
Chanson (1994)	$\frac{\Delta H}{H_{max}} = 1 - \frac{0.54\left(\frac{y_c}{h}\right)^{0.275} + 1.715\left(\frac{y_c}{h}\right)^{-0.55}}{1.5 + \frac{H_D}{y_c}}$	0.61
Fratino (2000)	$\frac{\Delta H}{H_{max}} = 1 - \frac{H_r}{H_{max}} = 1 - \frac{y_1 + \frac{1}{2}\frac{y_c^3}{y_1^2}}{H_D + \frac{3}{2}y_c} = 1 - \frac{\lambda + \frac{1}{2}\lambda^{-2}}{\frac{H_D}{y_c} + \frac{3}{2}}$	0.77
Salmasi (2000)	$\frac{\Delta H}{H_{max}} = 1 - \frac{H_r}{H_{max}} = 1 - \frac{y_1 + \frac{1}{2}\frac{y_c^3}{y_1^2}}{H_D + \frac{3}{2}y_c} = 1 - \frac{\lambda + \frac{1}{2}\lambda^{-2}}{\frac{H_D}{y_c} + \frac{3}{2}}$	0.90
Present Study	$\frac{\Delta H}{H_{max}} = 1.11 \times \left(\frac{h}{l}\right)^{-0.30} \times \left(\frac{H_D}{y_c}\right)^{-1.07} \times \left(\frac{y_c}{Nh}\right)^{-1.021}$	0.98

4. CONCLUSION

According to the studies on stepped spillways, in the nappe flow regime, the best hydraulic performance occurs at low discharges with the hydraulic jump on every step. In this condition, maximum energy dissipation is expected. Based on the present results, in the nappe flow regime, the larger h/l and the spillway slope leads to lower energy dissipation. With increasing dimensionless parameter $\frac{q^2}{gH_D^3}$, the relative energy loss $\frac{\Delta H}{H_D}$ also decreases.

For a given discharge, the relative energy dissipation increases with increasing the number of steps (N). The relative energy dissipation improves with increasing dimensionless parameter for all slopes and steps conditions. The present results show that the most important dimensionless parameter in energy $\frac{H_D}{y_c}$ dissipation is $\frac{y_c}{Nh}$, which has a greater impact on the relative energy dissipation in the nappe flow regime. Besides, for stepped spillway with constant discharge per unit width, by increasing the step roughness (K_s), the location of nappe flow moves upstream. Based on the present results, an equation for calculating the relative energy dissipation in the nappe flow regime was also introduced.

REFERENCES

[1] G. Zhang, C. H., Hydraulics of the Developing Flow Region of Stepped Spillways, I: Physical Modeling and Boundary Layer Development, Journal of Hydraulic Engineering (ASCE), 142(7) (2016).

[2] A. Hasanalipour, M. Azhdarimoghadam, M. Kavianpour, Experimental investigation of the effect of stepped spill slope on flow regime and field hydraulic parameters (Case study: Siahbishe Dams Spillways), Iranian Journal of Water Research, 33 (2019) 139-149. (in persian)

[3] H. Chanson, Comparision of Energy Dissipation between Nappe and Skimming Flow Regimes on Stepped chutes, Journal of Hydraulic Research, 32(2) (1994) 213-218.

[4] U. Fratino, F. Piccini, Dissipation efficiency of stepped spillways, Proc. International workshop on Hydraulics of Stepped Spillways, in: H.E. Minor, W. Hager (Eds.) International workshop on Hydraulics of Stepped Spillways, Zurich, Switzerland, 2000, pp. 103-110.

[5] F. Salmasi, M. Bina, H. Mousavi, Experimental investigation of current head loss over stepped spillways, in: the 6th international conference of civil Engineering, industrial university of Isfahan, civil college, 2004. (in persian).

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