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Study The Effect Of The Number Of Steps On Energy Dissipation Of Stepped Spillways In Non-Nappe Or Skimming Flow

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ABSTRACT: One goal to use stepped spillway is to increase the intensity of energy dissipation along the weir, and thus reduce the size and number of stilling basin. The flow mechanism over these structures is complex, and many studies are ongoing to understand it around the world. In this study, we examined the effect of number of steps on energy dissipation. The results showed that increasing the number of steps in stepped spillway leads to increased relative energy dissipation up to a certain level. Then, it shows a declining trend. However, work in this area is dynamic, and changes in the future design criteria can be expected.

***Keywords*:** Number of steps, Flow energy dissipation, Skimming, Stepped spillway, Flow mechanism.

INTRODUCTION

Stepped spillways are among the structures that are used to improve the hydraulic conditions of flow and energy dissipation. By construction of this type of spillway, the size of stilling basin and thus the costs will reduce, and in some circumstances, it may result in the removal of the stilling basin. In stepped spillways, the steps act like large and resistant roughs against the flow, and therefore significantly increase the flow energy dissipation. In general, three types of flow can be seen on the stepped spillways. The first type is Nappe flow that occurs at low flow rates and big steps height. Each step acts as a waterfall or in a separate vertical up, and the flow continues to the spillway downstream as sequential colliding jets to the bottom of the steps. The second type is Skimming flow that occurs in spillways with higher flow rates and steps with lower height. Due to the high flow rate, the steps are completely submerged below the water level (Ohtsu et al., 2004). The third type, Transition flow, has an intermediate state and is associated with high dispersion of water droplets in the air. Many dynamic forces are imposed the spillway structure, and therefore, it is not recommended to design on this basis (Chanson and Gonzalez, 2006).

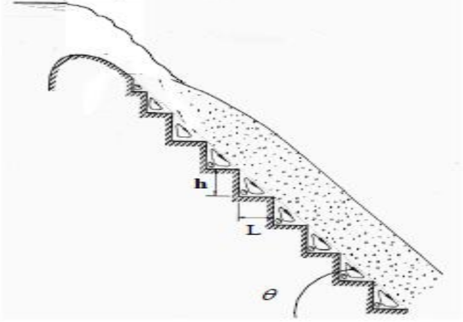

Figure 1. Flow on the stepped spillway

MATERIALS AND METHODS

In this study, according to relations and conducted research, we first made some analyses about the impact of steps number on reducing energy dissipation. Then, the stepwise design of the stepped spillways was evaluated. Based on the results, some charts were presented to determine the optimal number of steps. These charts would help to better understanding of complex relationships. The first criterion to describe the start of skimming flow was provided by Rajaratnam (1990). He presented the beginning of skimming flow as $\frac{dc}{h}\rangle 0/8$, where d_c is the critical depth and h is the height of each step. This criterion was provided based on experiments in the range of slopes $\frac{h}{l}=$ 0.4 to 0.9 (l is the horizontal length of each step). Chanson (1994) showed that for the incidence of slimming flow, the flow rate should become higher than a certain critical value. This certain flow for the start of skimming regime $[(d_c)onset]$ was provided as equation (1).

$$\frac{(d_c)_{onset}}{h} = 1.057 - 0.465\frac{h}{L} \qquad (1)$$

Where: d_c: Critical depth, h: Height of each step, L: Horizontal length of each step. In spillways with mild to moderate slopes, Chanson and Gonzalez (2006) separated skimming regimes into two SK1 and SK2 sub-sections. SK2 is for gentle slopes less than 19 degrees and SK1is for moderate slopes more than 19 degrees. In Figure 2, the way this division is presented (In spillways, the slopes greater than 25 degrees are called steep slopes, while 15 to 25 degrees slopes are called moderate and less than 15 degrees are called gentle or mild).

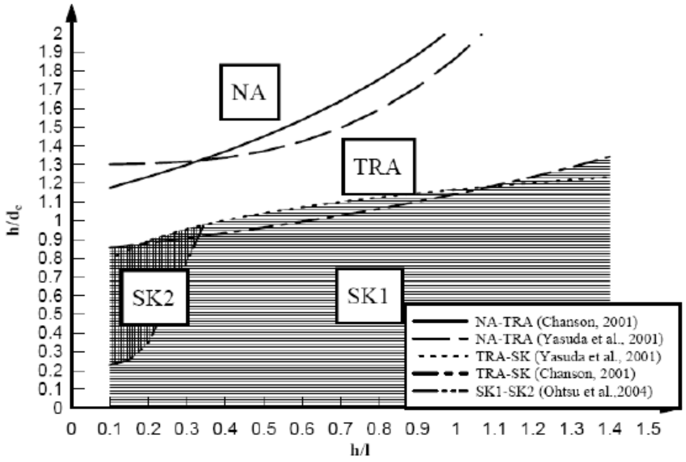

Figure 2. Determining the flow regime on the stepped spillway

Note: NA-TRA: Border of Nappe to Transition; TRA-SK: Transition to Skimming
Ohtsu et al. (2004) defined the occurrence limit of skimming flow with equation (2).

$$\left(\frac{h}{d_c}\right)_S = \frac{7}{6}(\tan\alpha)^{1/6} \quad for \quad 5.7^\circ < \alpha \le 55^\circ \qquad (2)$$

Rajaratnam (1990) provided equation (3) for the stepped spillway with constant slope of $S_\circ = \sin\alpha$.

$$\tau = d.\gamma.\sin\alpha \qquad (3)$$

Where
D: Net air-free depth
γ : Water density
τ : Reynolds average shear stress between skimming flow and swirling flow
If we have in equation (4):

$$\tau = \frac{f}{4}\left(\frac{P.V^2}{2}\right) \tag{4}$$

Where: V: Constant average speed, f: Darcy–Weisbach Friction Factor, ρ : Fluid specific gravity. Combining equations (3) and (4), we will have:

$$f = \frac{8g.d.\sin\alpha}{V^2} = \frac{8g.d^3\sin\alpha}{q^2} \tag{5}$$

Where: ,g: Acceleration of gravity, q: Flow rate per spillway width unit. For non-uniform flows, the friction factor is expressed by the energy equation (6):

$$f = \frac{8g.d^3}{q^2}.S_f \tag{6}$$

Where, S_f: Friction slope. Gonzalez et al (2008) showed that the results the relation with hyperbolic tangent function can be used for distribution of air bubbles content.

$$C = 1 - \tanh^2\left(k' - \frac{y/y90}{2D_0} + \frac{\left(y/y90 - 1/3\right)^3}{3D_0}\right) \tag{7}$$

Where, K 'and D0 are obtained from relation (8):

$$K' = 0.327 + \frac{1}{2D_0} - \frac{8}{81D_0}$$

$$C'_{mean} = 0.762\left(1.043 - \exp(-3.61D_0)\right)$$

$$C_{mean} = \frac{1}{y_{90}}\int_{y=0}^{y90} C.\,dy \tag{8}$$

Where: C: Concentration of air bubbles, y90: The depth that form 90% of air, D0: A parameter dependent to the average concentration of air bubbles (C_{mean}). Ohtsu et al. (2004) provided the following regression equation for the design:

$$C_{mean} = D - 0.3\exp\left(-5\left(\frac{h}{dc}\right)^2 - 4\left(\frac{h}{dc}\right)\right)$$

$$D = 0.3 \quad for \;\; 5.7^\circ < \alpha < 19^\circ$$

$$D = -0.00024\alpha^2 + 0.0214 - 0.0357$$

$$for \;\; 19^\circ \le \alpha \le 55^\circ \tag{9}$$

Ohtsu et al. (2004) provided the Friction Factor by Equation (10):

$$f = f_{\max} - A\left(0.5 - \frac{h}{d_c}\right)^2$$

$$for\ 0.1 \le \frac{h}{d_c} \le 0.5$$

$$f = f_{\max} \quad for\ 0.5 \le \frac{h}{d_c} \le \left(\frac{h}{d_c}\right)_s$$

$$A = -1.7*10^{-3}\alpha^2 + 6.4*10^{-2}\alpha - 1.5*10^{-1}$$

$$f_{\max} = -4.2*10^{-4}\alpha^2 + 1.6*10^{-2}\alpha + 3.2*10^{-2}$$

$$for\ 5.7° \le \alpha \le 19°$$

$$A = 0.452$$

$$f_{\max} = 2.32*10^{-5}\alpha^2 - 2.75*10^{-3}\alpha + 2.31*10^{-1}$$

$$for\ 19° \le \alpha \le 55°$$

(10)

Chanson et al. (1995) provided the air entry point (aeration start) from the spillway crest and the depth of the water at that point by relation (11):

$$\frac{L_I}{h.\cos\alpha} = 9.719 \sin\alpha^{0.0796} *$$

$$\left(\frac{q}{\sqrt{g.\sin\alpha(h\cos\alpha)^3}}\right)^{0.713}$$

$$\frac{d_I}{h.\cos\alpha} = \frac{0.4034}{(\sin\alpha)^{0.04}} *$$

$$\left(\frac{q}{\sqrt{g.\sin\alpha(h\cos\alpha)^3}}\right)^{0.592}$$

(11)

In designing, it should be controlled that the length of the spillway is larger than the L_I. Ohtsu et al. (2004) provided equation (12) for the occurrence of the quasi-steady flow:

$$\frac{H_e}{d_c} = \left(\begin{matrix} -1.21*10^{-5}\alpha^3 + 1.60* \\ 10^{-3}\alpha^2 - 7.13*10^{-2}\alpha + 1.30 \end{matrix}\right)^{-1} *$$

$$\left(5.7 + 6.7\exp\left(-6.5\frac{h}{d_c}\right)\right)$$

$$for\ \ 5.7° \le \alpha \le 55°$$

(12)

That should have:

$$\frac{H_{dam}}{d_c} \ge \frac{H_e}{d_c}$$

In equation (13), the energy remaining over the spillway with the quasi-steady flow is calculated as follows:

$$E_{res} = d.\cos\alpha + \frac{V^2}{2g} =$$

$$d.\cos\alpha + \frac{d_c^3}{2d^2} \Rightarrow$$

$$\left(\frac{E_{res}}{d_c}\right)_U = \frac{d}{d_c}\cos\alpha + \frac{1}{2}\left(\frac{d_c}{d}\right)^2 =$$

$$\left(\frac{f}{8\sin\alpha}\right)^{1/3}\cos\alpha + \frac{1}{2}\left(\frac{f}{8\sin\alpha}\right)^{-2/3} \tag{13}$$

In equation (14), the energy remaining over the spillway with the non-steady flow is calculated as follows:

$$\frac{E_{res}}{d_c} = 1.5 + \left(\left(\frac{E_{res}}{d_c}\right)_U - 1.5\right) *$$

$$\left(1 - \left(1 - \frac{H_{dam}}{H_e}\right)^m\right)$$

$$m = -\frac{\alpha}{25} + 4 \tag{14}$$

The relative energy dissipation can be determined by equation (15).

$$\frac{\Delta E}{E_{\max}} = \frac{E_{\max} - E_{res}}{E_{\max}} = 1 - \frac{E_{res}}{H_{dam} + 1.5 d_c} \tag{15}$$

To evaluate the effect of number of steps on the stepped spillway, first, the spillway height (H_{dam}) and the spillway slope (α) were obtained from topographic maps and locating the head body and its overflow. The design flow rate (Q) is estimated based on flood with a specific return period. A basic assumptive width (W) is selected for the spillway. The critical depth is calculated from relation (16):

$$d_c = \sqrt[3]{\frac{q^2}{g}} \tag{16}$$

The dimensionless parameter is determined by equation (17).

$$\frac{H_{dam}}{dc} \tag{17}$$

The height of steps for occurrence of skimming flow is selected in such a way that $0.25 \le \frac{h}{dc} \le \left(\frac{h}{dc}\right)_s$

Where, $\left(\frac{h}{dc}\right)_s$ is obtained from equation (18).

$$\left(\frac{h}{d_c}\right)_s = \frac{7}{6}(\tan\alpha)^{\frac{1}{6}} \quad for\ 5.7° < \alpha \le 55° \tag{18}$$

According to Chanson and Gonzalez (2006), in most of steeped spillways in the structure of Gabion and concrete roller dams, the height of steps is in the range of 0.2 to 0.9 meters, which can be considered as another criterion in the selection of appropriate height for steps by the designer. The value of $\left(\frac{h}{d_c}\right)$ is determined. The value of $\frac{H_e}{d_c}$ is calculated by relation (19):

$$\frac{H_e}{d_c} = \left(\begin{matrix} -1.21*10^{-5}\alpha^3 + 1.60* \\ 10^{-3}\alpha^2 - 7.13*10^{-2}\alpha + 1.30 \end{matrix}\right)^{-1} * \left(5.7 + 6.7\exp\left(-6.5\frac{h}{d_c}\right)\right)$$

$$for\ \ 5.7° \leq \alpha \leq 55° \qquad (19)$$

If the condition of $\frac{H_{dam}}{d_c} \geq \frac{H_e}{d_c}$ is true, the flow of even network is created, and the friction factor is calculated from equation (20):

$$f = f_{\max} - A\left(0.5 - \frac{h}{d_c}\right)^2$$

$$for\ \ 0.1 \leq \frac{h}{d_c} \leq 0.5$$

$$f = f_{\max} \quad for\ 0.5 \leq \frac{h}{d_c} \leq \left(\frac{h}{d_c}\right)_s$$

$$A = -1.7*10^{-3}\alpha^2 + 6.4*10^{-2}\alpha - 1.5*10^{-1}$$

$$f_{\max} = -4.2*10^{-4}\alpha^2 + 1.6*10^{-2}\alpha + 3.2*10^{-2}$$

$$for\ \ 5.7° \leq \alpha \leq 19°$$

$$A = 0.452$$

$$f_{\max} = 2.32*10^{-5}\alpha^2 - 2.75*10^{-3}\alpha + 2.31*10^{-1}$$

$$for\ \ 19° \leq \alpha \leq 55° \qquad (20)$$

The flow depth is calculated from relation (21):

$$d = d_c\left(\frac{f}{8\sin\alpha}\right)^{\frac{1}{3}} \qquad (21)$$

The flow rate is achieved as $v = \frac{q}{d}$:

The relation (22) calculates the average concentration of air bubbles:

$$C_{mean} = D - 0.3\exp\left(-5\left(\frac{h}{dc}\right)^2 - 4\left(\frac{h}{dc}\right)\right)$$

$$D = 0.3\ \ for\ \ 5.7° < \alpha < 19°$$

$$D = -0.00024\alpha^2 + 0.0214 - 0.0357$$

$$for\ \ 19° \leq \alpha \leq 55° \qquad (22)$$

Equation (23) calculates y_{90}:

$$d = \int_{y=0}^{y90}(1-C)dy = (1-C_{mean})y_{90} \qquad (23)$$

The height of the protective side walls of the spillway is obtained from relation (24):

$$H_w = 1.4y_{90} \qquad (24)$$

The remaining energy with quasi-uniform or non-uniform flow regimes is determined by relations (25):

$$E_{res} = d.\cos\alpha + \frac{V^2}{2g} =$$

$$d.\cos\alpha + \frac{d_c^3}{2d^2} \Rightarrow$$

$$\left(\frac{E_{res}}{d_c}\right)_U = \frac{d}{d_c}\cos\alpha + \frac{1}{2}\left(\frac{d_c}{d}\right)^2 =$$

$$\left(\frac{f}{8\sin\alpha}\right)^{1/3}\cos\alpha + \frac{1}{2}\left(\frac{f}{8\sin\alpha}\right)^{-2/3} \qquad (25)$$

$$\frac{E_{res}}{d_c} = 1.5 + \left(\left(\frac{E_{res}}{d_c}\right)_U - 1.5\right)*$$

$$\left(1-\left(1-\frac{H_{dam}}{H_e}\right)^m\right)$$

$$m = -\frac{\alpha}{25}+4$$

Relative energy dissipation is determined by relation (26):

$$\frac{\Delta E}{E_{\max}} = \frac{E_{\max} - E_{res}}{E_{\max}} = 1 - \frac{E_{res}}{H_{dam} + 1.5 d_c} \qquad (26)$$

With regard to the procedures mentioned for designing stepped spillway, the above steps were formulated in the Excel spreadsheet. The goal was to determine the effect of steps number on energy dissipation. By increasing the rate of energy dissipation, the administrative costs of energy dissipation facilities in the spillway downstream such as stilling basin would decline.

RESULTS AND DISCUSSION

In Figure 2, the changes curve of relative depreciation in energy flow in the vertical axis was provided than to the number of steps in the horizontal axis. In the figure, the spillway slope was considered as the constant value of 22 degrees, and the discharge per width unit and the height of the spillway were assumed variable. This means, the dimensionless ratio of $\frac{H_{dam}}{d_c}$ was selected variable from 59.71 to 124.2. According to Figure (2), increasing the number of steps leads to increased relative energy dissipation process to a certain extent, and then reduces relative energy dissipation. According to Figure, by reducing the flow rate of the design or increasing the height of the spillway, the optimal number of steps would enhance as well.

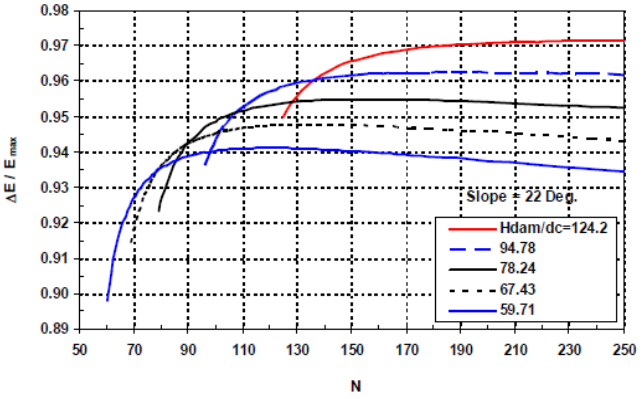

Figure 3. Effect of number of steps on increasing energy dissipation

This indicates that although the flow was assumed a skimming type, but with flow rate decrease and the flow tendency to Nappe flow, the number of optimal steps would increase. In contrast, in high flow rates that the flow regime is quite skimming and all steps are submerged under the water, the number of optimal steps will reduce. According to Figure 2, the exact number of optimal steps for different flow rates is presented in Table 1.

Table 1. The optimal number of steps for different flow rates over the spillway and its energy dissipation

Flow rate in width unit ($\frac{m^2}{s}$)	Spillway height to critical depth ratio	Number of optimal steps	Relative energy dissipation
q	H_{dam}/d_c	N	$\Delta E/E_{max}$
0.8	125	198	0.981
1.4	94.50	180	0.970
2.2	68.33	120	0.954
2.3	60.11	101.4	0.921
4.1	50.222	86.98	0.885

In Table 1, the flow rate per unit width was considered variable from 0.8 to 3.2 square meters per second. It can be easily increased in Excel spreadsheet to higher values of flow rate, in correspondence, the rate of relative energy dissipation and other parameters can be calculated.

CONCLUSION

In this study, the effect of the number of steps on energy dissipation in stepped spillways in skimming flow was evaluated. For a fixed ratio of $\frac{H_{dam}}{d_c}$, increasing the number of steps in the stepped spillway leads to increased relative energy dissipation to a certain limit, and then, reduces the relative energy dissipation. By reducing the design flow rate or increasing the height of the spillway, the number of optimal steps would also enhance. This shows that although the flow regime was assumed skimming, but with lowered flow rate and the flow tendency to Nappe regime, the optimal number of steps will increase, and vice versa, in high flow rates where the flow regime is fully skimming, the number of optimal steps shows reduction.

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