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The Inception Point of Flow Aeration on a Rough Stepped Spillway

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Abstract

Stepped spillways are used in hydraulic engineering projects such as small and large dams. The inception point of aeration on such hydraulic structures is essential in determining the zones of single and two-phase flow. In this study, the effect of the surface roughness of steps on the location of IFPA on a stepped spillway is studied. For this purpose, a laboratory model of Ogee-stepped spillway was designed based on the maximum energy dissipation guidelines and its steps were roughened with gravel (with a specific grain size). The experiments were conducted in a channel with a longitudinal slope of 0.001, length of 12m, width of 0.5m, and depth of 0.8m on a stepped spillway with a height of 0.6m that has 9 steps. The flow discharge ranged between 6 (l/s) and 16(l/s). It was concluded that flow aeration starts at a distance of about 12 times the critical depth from the crest and by doubling the critical depth, its distance from the crest increased up to 50 percent. Notably, roughing the step surface reduces the length of the non-aeration area by about 15%.

Keywords: Rough Steps, Flow Aeration, Effective Roughness. Critical Depth.

1. Introduction

Spillways are an essential part of dam projects. Each spillway usually consists of a pair of guide walls, an approach channel, a crest, a chute, and a stilling basin. The performance of each spillway depends on the performance of its components. The guide walls will help the smooth transfer of flow from the reservoir to the approach channel. Proper design of guide walls leads to the removal of transverse waves (Chen, 2015; Wang and Chen, 2010; Wang and Chen, 2009). The crest is the most crucial part of the spillway in determining the discharge capacity and its geometrical shape is very effective on the discharge coefficient factor (Parsaie and Haghiabi, 2021; Shamsi et al., 2022). The chute of spillways is the central part of transferring the flow from the reservoir to the stilling basin and downstream river (Chen, 2015).
According to Bernoulli's law, the increase in velocity is accompanied by a decrease in pressure; hence, the risk of cavitation increases. Two solutions, including dissipation of energy of flow along the chute and flow aeration, have been proposed to remove cavitation. Stepped spillways have the potential for both energy dissipation and flow aeration (Chanson 1993). Based on the reports, stepped spillways can dissipate the energy of flow between 40 and 95 percent (Parsaie and Haghiabi, 2021; Parsaie and Haghiabi, 2019).
Chanson (1996) declared that 4 to 8% of the air concentration near the surface of the chute could prevent cavitation damage. The positive effects of steps are moving the start of aeration upstream and reducing the risk zone against cavitation. Natural aeration on the smooth chute begins after fully developing the boundary layer and reaching the surface of the flow (water). The point of entry of air into the flow usually is recorded by observation, so the specifications and coordinates provided for this point by various researchers are different (Boes and Hager, 2003). However, classically, this point corresponds to the step where the water flow becomes white or milky. That is where the air bubbles will remain constant inside the flow jet. Of course, flow aeration with the help of various hydraulic structures is very common, and different types of research have been conducted in this field (Baylar et al., 2001; Baylar et al., 2011; Kumar et al., 2021; Kumar et al., 2022). Determining the inception point of flow aeration is essential in determining the area at risk of cavitation (Baylar et al., 2006).
Reviewing the literature shows that most studies on stepped spillways have focused on the mechanism of energy dissipation and ways to improve its performance. For example, roughing the steps to increase the energy dissipation of flow over the stepped spillways and applying the nonuniform steps can be mentioned (Roushangar et al., 2022).
Due to the complex mechanism of flow aeration and its inception point, especially on stepped spillways, many studies have been conducted to determine its inception point. Parsaie and Haghiabi (2019) analyzed the effect of crest geometry on the inception point of flow aeration on the quarter-circular crested stepped spillway. Table 1 presents a list of studies conducted during the last decade on determining the inception point of flow aeration (IPFA) on stepped spillways.

Table 1. The list of recent studies on the inception point of flow aeration on stepped spillways

Authors	Equations
Chanson and Toombes (2002)	$L_i = 9.719\left(h_s \cos\theta\right)\left(\sin\theta\right)^{0.0796} F_r^{*0.713}$ $F_r^* = \dfrac{q}{\sqrt{g.\sin\theta\ .(h_s.cos\ \ \theta)^3}}$
Chamani and Rajaratnam (1999)	$L_i = 26.19 f^{\ 0.267}\ \left(h_s \cos\theta\right)^{1.0995}\left(\sin\theta\right)^{0.0995} F_r^{0*.33}$
Boes and Hager (2003)	$L_i = 9.72\left(h_s \cos\theta\right)\left(\cos\theta\right)^{1.29} F_r^{*0.86}$
Boes et al. (2000)	$L_i = 6.289\left(h_s \cos\theta\right) F_r^{*0.734}$
Wood (1991)	$L_i = 13.6\left(h_s \cos\theta\right)\left(\sin\theta\right)^{0.0796} F_r^{*0.713}$

where F_r*: the step Froude number, h_s: the step height, g: the acceleration due to gravity, θ: the longitudinal slope of the stepped chute, L_i: distance of *IPFA* from the crest, and q: discharge per width of the channel.

Reviewing Table 1 shows that the previous scholars considered the flow rate and geometric size of steps on the location *IPFA*. Further examination of this table indicates that previous researchers did not feel surface roughness. Hence, In this study, the effect of the surface roughness of the steps on the *IPFA* is considered. Because of the importance of the subject, a series of experiments were planned and tried to focus on the effect of the roughness of the step's surface. For this purpose, a laboratory model of a stepped spillway was designed and built based on the maximum energy dissipation. The horizontal parts of the steps were covered with gravel having specific granulation.

2. Materials and methods

A sketch of flow over the stepped spillway is shown in Fig. 1 to visualize the *IPFA*. In this figure, the *P* is the height of the stepped spillway, y_{up} are the depth of flow over the crest, y_1 and y_2 are the conjugated depths of the hydraulic jump.

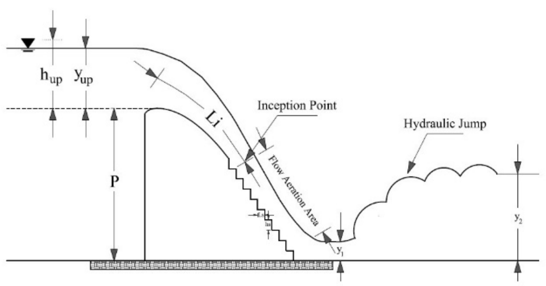

Fig. 1 The sketch of the stepped spillway and inception point of flow aeration

This study analyzes the effect of roughing the surface of steps on the *IPFA*. For this purpose, the involved parameters in the *IPFA* are summarized in Eq. (1).

$$\Psi\left(\rho_w, g, V, \tan\theta, h_s, n_s, k_s, L_s, h_{up}, L_i, \mu, \sigma\right) = 0 \quad (1)$$

where, h_s and L_s are the height and length of steps, h_{up} is the head of flow, L_i denotes the length of the non-aerated area or distance of *IPFA* from the crest, ρ_w is water density, and V is the flow velocity at the location of *IPFA*. n_s is the roughness of the surface of steps, k_s is the effective roughness resulting from the size of steps and is equal to $k_s=h_s cos(\theta)$. $S=tan(\theta)$ indicates the slope of the stepped chute. μ is the dynamic viscosity. $\boldsymbol{\sigma}$ is surface tansion of waterter. By choosing the ρ_w, V and k_s as repeated parameters, and with the aid of the Buckingham Π theorem, the dimensionless parameters involved in the *IPFA* are derived and given in Eq. (2).

$$\frac{L_i}{k_s} = \phi\left(\tan(\theta), \frac{n_s}{y_c}, \frac{y_c}{k_s}, \frac{n_s}{k_s}, F_r^*, \mathrm{Re}, We\right) \quad (2)$$

2.1. Experimental setups

A laboratory model of a stepped spillway was constructed to study the effect of the roughness of the step's surface on the location of IPFA. The surfaces of the steps were covered with gravel with specified granulation (d_{50} =7.1mm, 10.1mm, 14.2mm). The design of the stepped spillway structure is based on the criterion of maximum energy dissipation. The height of the steps was equal to 3.5 cm, and their length was equal to 2.45 cm. The slope of the stepped chute was considered 1.0:0.7 (vertical: horizontal). Details of geometric and flow discharge are given in Table (2). The laboratory model was installed in a flume with a longitudinal slope of 0.001 and a depth of 80cm, a width of 50 cm, and a length of 12 m. All expeirments were performed in Mashhad Agricultural Jihad Hydraulic Laboratory. The flow discharge varied between 6 and 16 (*l/s*). The location of IPFA on rough stepped spillways was compared with a smoothly stepped spillway as the baseline model. The flow depth was measured by a point gauge with a ±0.1 mm precision upstream and downstream of the model. A V-notch was used to measure the flow rate. Fig. 2 shows the inception point of flow aeration on a rough stepped spillway.

Table 1. The details of geometric of stepped spillway and flow discharge

P (cm)	h_s (cm)	L_s (cm)	N (-)	d_{50} (mm)	h_{up} (cm)	Q (l/s)
				7.1		
52.18	3.5	2.45	9	10.1	2.5-5.4	6-16
				14.2		

3. Results and Discussion

This study focuses on the effect of roughness on the IPFA. Hence, the effect of other parameters, such as the slope of the stepped chute and the size of the steps, on the location of *IPFA* has not been considered. Noteworthy that previous scholars have studied the effect of such parameters on the *IPFA*. Laboratory experiments

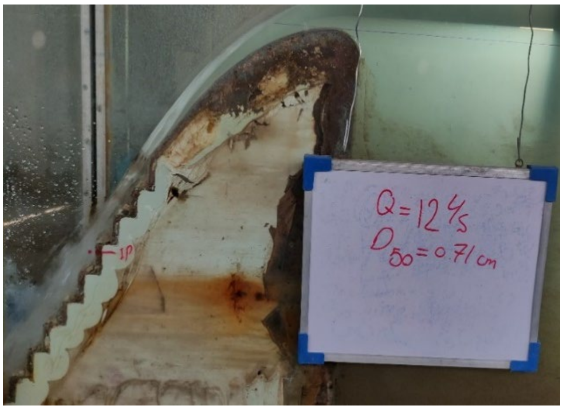

Fig. 2 Experimental test of inception points of flow aeration on rough stepped spillways models

experiments began on the baseline model with a flow rate of 9.5 (l/s). After the flow stabilization, the location of *IPFA* was recorded. The flow rate was increased up to 16 (l/s) in six steps, and at each step of the increase (after the flow stabilization), the *IPFA* was re-recorded. Notably, the skimming flow regime over the stepped chute was observed in all experiments. This was validated by the proposed criteria for recognition of flow regime on stepped spillway that were summarized by Boes et al. (2000). It should be noted that in these tests, the longitudinal slope of the stepped chute (h_s/L_s) is 1.4 and the range of the relative critical depth (y_c/h_s) is between 1.05 and 1.5. As presented in the materials and methods, the *IPFA* on stepped spillways is a function of stepped chute slope (S), effective roughness (k_s), relative critical depth (representing flow rate: y_c/k_s), and step Froude number (Fr^*).

According to calculations, the minimum Reynolds number in the experiments, which corresponds to the lowest flow rate, is 95,000. Hence, flow is fully turbulent and the effect of flow viscosity is negilible. Also, all the data related to the flow head (were used in results) are more than 3 cm (Novak et al., 2017; Salmasi and Abraham, 2022), threrefore, the effect of surface tension is also insignificant.

Fig. 3 shows the dimensionless form of the location of *IPFA* versus the relative critical depth (y_c/h_s). As shown in this figure, the length of the non-aerated zone increases by increasing the y_c/h_s. In other words, with the increase in y_c/h_s, the location of *IPFA* is moved downstream.

Fig. 3 shows that flow selfaeration starts from about 12 times the critical depth and by doubling the critical depth, the critical point increases up to 50 percent. It is notable that the size of steps was designed according to maximum energy dissipation of flow (Chanson and Toombes, 2002). In this case, the $h_s \cong 0.3 y_c$. At low value of flow rates (y_c/h_s<1), by increasing roughness (n_s/k_s), the location of *IPFA* does not change significantly and its effect is negligible. As the flow rate increases, the impact of roughness on the *IPFA* transmission becomes clearer. This is due to increased flow turbulence and earlier touching of the boundary layer with the water surface. In this case, the share and role of the roughness of step surface compared to the effective roughness (caused by the geometry size of steps (k_s)) is increased. For y_c/h_s>1, The effect of n_s/k_s =0.248 for all flow discharge on *IPFA* location is negilible. However, the effect of other values of n_s/k_s (n_s/k_s=0.378 and 0.495) on the reduction of the length of *IPFA* is the same and is by about 15% and. However, their effects on the *IPFA* are different from the previous one.

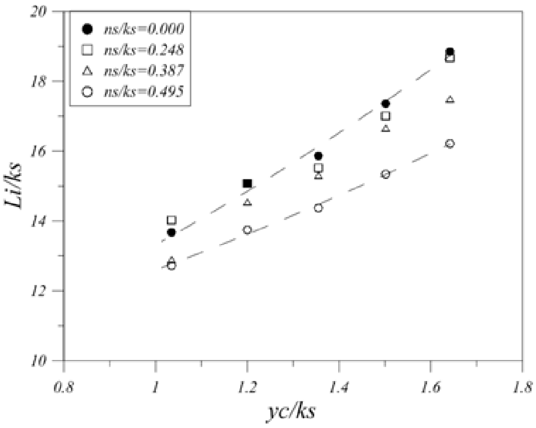

Fig. 3 Variation of the location of *IPFA* versus the relative critical depth

As mentioned, naturally on smooth chute, the flow starts to selfaerate when the of the boundary layer reaches the flow (water) surface. By increasing the roughness of the chute in the form of stepping the chute, the turbulence intensity is much higher and the boundary layer touches the water surface sooner and the flow starts to selfaerate at a smaller distance from the flow crest. Increasing the surface roughness of the steps also strengthens the disruption and turbulence of the flow. Therefore, by roughening the surface of the steps, the flow starts to aerate itself at a shorter distance from the crest in compare to the smooth stepped spillway. With the increase of flow rate due to increase of flow energy, the starting point of aeration is moved downstream. In this case, the

boundary layer reaches the water surface at a greater distance from the crest.
In the following, the values of L_i/k_s were plotted versus the step Froude number (F_r*) and shown in Fig. 4. Since the dimensions of the steps and longitudinal slope of the chute (*S*) are constant; therefore, Fig. 4 is similar to Fig. 3. The values of F_r* changes between 1.0 and 2.4. As the number of step Froude number descends, the distance of the aeration point from the crest (*IPFA*) increases, and its location moves downstream.

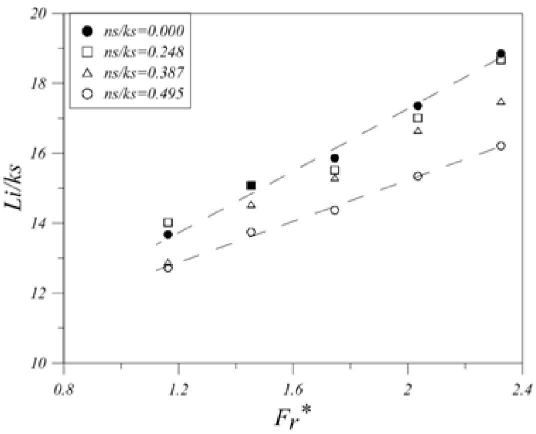

Fig. 4 variation of the location of *IPFA* versus step's Froude number

Fig. 5 shows the effect of size of surface roughness of in a given discharge (n_s/y_c) on the location of *IPFA*. As shown in this figure, at a given roughness, with the increasing flow rate (thus increasing the critical depth), the effect of the roughness on the *IPFA* location increased rapidly. As the critical depth increases, the role of roughness in creating and increasing flow turbulence increases. Of course, after a certain amount of flow, the intensity of its impact decreases.

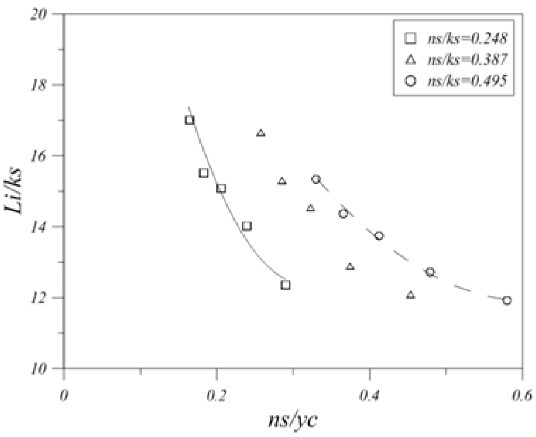

Fig. 5 the effect of roughness on the place of IP of flow aeration

The following accuracy of the proposed equations is given in Table 1. The error indices, including the coefficient of determination (R^2) and root mean square of errors (RMSE) are used. The results of the evaluation of the proposed equations are given in Table 3. As presented in this Table, Boes and Hager (2003) formula is more accurate than the others.

Table 3. The accuracy of the proposed equations

Equations	R^2	RMSE
Chanson and Toombes (2002)	0.886	23.879
Chamani and Rajaratnam (1999)	0.878	36.200
Boes and Hager (2003)	0.889	6.352
Boes et al. (2000)	0.887	10.942
Wood (1991)	0.886	39.388

4. Conclusion

In this study, the effect of the surface roughness of steps on the location of *IFPA* was studied experimentally. To this end, some laboratory tests were programmed. To examine the objective of this study, a stepped spillway in which the horizontal part of the steps was covered by gravel with a given grain size. The results declared that three factors, including the flow rate, the roughness caused by steps size (k_s), and the roughness of steps surface (n_s), are influential in the location of *IPFA*. There is a direct exponential relationship between the discharge and the *IPFA* (length of the non-aerated area on the stepped spillway). As the flow rate increases, this point's location moves exponentially downstream. By increasing the flow rate, the role of roughness in *IPFA* location became more apparent, and its reason is its role in creating and rising flow turbulence. On average, surface roughness can be about 15% effective in reducing the location of *IPFA*.

5. Notation

IPFA	Inception Point of Flow Aeration
h_s	step height
h_{up}	head of flow
F_r*	Froude number
L_i	length of the non-aerated area
L_s	step length
R^2	coefficient of determination
k_s	effective roughness caused by the step's geometry
n_s	roughness of the surface of steps
y_1, y_2	the conjugated depths of the hydraulic jump
y_c	critical depth
y_{up}	depth of flow
ρ_w	water density

D_{50}	Mean diameter of gravel
g	acceleration due to gravity
P	height of the stepped spillway
RMSE	root mean square of errors
V	flow velocity
θ	longitudinal slope of the stepped chute
μ	dynamic viscosity
σ	Surface tension of water

6. Acknowledgments

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