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Jet flow in hydraulic-jump-stepped spillways: experimental study

Yu Zhou [a], Jianhua Wu [b,*], Fei Ma [b], Jianyong Hu [c] and Jianfen Zhou [d]

[a] Key Laboratory for Technology in Rural Water Management of Zhejiang Province, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China
[b] College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China
[c] Zhejiang Institute of Water Resources and Ocean Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China
[d] College of Water Conservancy and Environmental Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China
*Corresponding author. E-mail: jhwu@hhu.edu.cn

YZ, 0000-0002-5082-4345; JW, 0000-0003-1346-9046

ABSTRACT

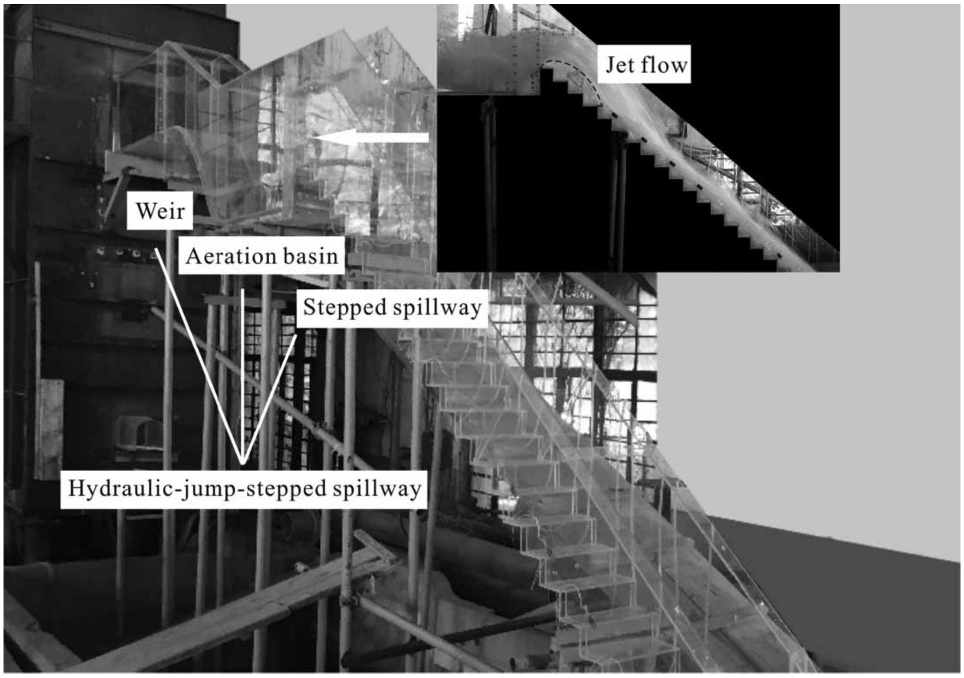
A hydraulic-stepped spillway was designed using an aeration basin to provide aerated flow to the stepped spillway utilizing a hydraulic jump. However, the flow through the entrance of the stepped spillway might separate from the first step top and impact the downstream steps at a large unit discharge, causing a so-called jet flow. A new experimental study was conducted to better understand the jet flow in the hydraulic-jump-stepped spillway with comparisons with conventional stepped spillways. The results showed that the critical condition required for the formation of the jet flow was close to the geometric parameters of the upstream aeration basin. Among these parameters, the height of the reverse step had a more significant effect on the local flow pattern, thus lowering the risk of jet flow. The relationships between the critical condition and the geometry of the aeration basin suggested that the Froude number at the entrance of the stepped spillway was the key parameter forming the jet flow. Compared with conventional stepped spillways, the hydraulic-jump-stepped spillway could effectively extend the practical application for large unit discharges by providing a better understanding of jet flow conditions.

Key words: aeration basin, critical condition, entrance of the stepped spillway, hydraulic-jump-stepped spillway, jet flow

HIGHLIGHTS

- A jet flow for large unit discharges in a hydraulic-jump-stepped spillway.
- Investigation of the critical condition of the jet flow as compared with conventional stepped spillways.
- The critical condition affected by the geometry of the aeration basin.
- An effective element to smooth the surface profile.
- A linear relation between the critical condition and the Froude number at the brink of the first step.

GRAPHICAL ABSTRACT



INTRODUCTION

Stepped spillways have become increasingly popular flood-release structures that can dissipate the energy of high-velocity flow (Boes & Hager 2003a, 2003b; Stojnic *et al.* 2021). With the increase in the unit discharge, the flow conditions in stepped spillways are classified as three typical flow patterns, i.e., nappe flow, transition flow, and skimming flow (Chamani & Rajaratnam 1999; Renna & Fratino 2010; Biethman *et al.* 2021). In nappe flow, the water bounces from one step to another, with the steps acting as a succession of free-falling nappes. In skimming flow, the water flows down the spillway as a coherent stream, skimming over the step edges and being cushioned by the recirculating vortices trapped between the mainstream and the steps. The disappearance of the cavity beneath the free-falling nappes indicates the onset of the skimming flow. In addition to the three typical flow patterns, there are some special flow patterns (e.g., water fins, spray flow, shooting flow, and water droplets) observed locally due to the step geometry of stepped spillways (Han *et al.* 2006; Pfister *et al.* 2006b; Zare & Doering 2012; Hunt & Kadavy 2017). The resultant cavity (i.e., cavity flow, a separation bubble or roller) may induce improper flow behavior, resulting in cavitation damage, structure erosion, flow instability, and the reduction of overflow discharge (Yu *et al.* 2008; Wang & Chen 2009; Amromin 2018; Wehrmeister & Ota 2021). In addition, stepped spillways are now used in newly built dams with a combination of upstream apparatuses, such as flaring gate piers, a labyrinth weir, a piano key weir, a deflector, a step aerator, and a ski jump aeration basin (Pfister *et al.* 2006a; Silvestri *et al.* 2013; Qian *et al.* 2016; Dong *et al.* 2019; Tullis *et al.* 2021; Terrier *et al.* 2022). For these new types of stepped spillways, the resultant jet flow and cavity will occur locally for some circumstances compared with conventional stepped spillways with ogee-crested weirs and flat steps.

Given that the inception point of the air entrainment moves downstream with increasing unit discharge, a backwater reach for large unit discharges is prone to cavitation damage, and the maximum unit discharge of a conventional stepped spillway is restricted to 50–60 m^2/s at a prototype-scale (Chanson 2015). We have proposed a hydraulic-jump-stepped spillway (HJSS) that increased the unit discharge by 100 m^2/s in prototype (Wu *et al.* 2018; Zhou *et al.* 2020, 2021). Figure 1 shows a definition sketch of the HJSS, which consisted of a weir, an aeration basin, and a stepped spillway. The aeration basin used in this study supplied the aerated flow to the stepped spillway utilizing a hydraulic jump. However, with the increasing unit discharge, the flow through the entrance of the stepped spillway might separate from the first step top and impact the downstream steps with a large unit discharge, causing a jet flow.

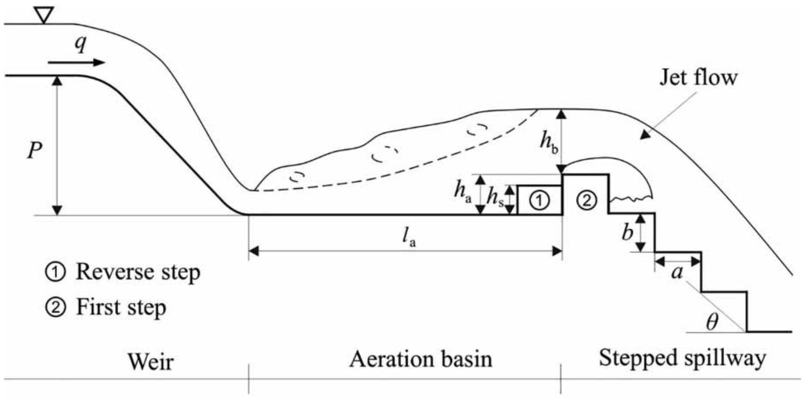


Figure 1 | Definition sketch of the hydraulic-jump-stepped spillway (HJSS).

Therefore, the main objective of the study was to experimentally investigate the jet flow in a hydraulic-jump-stepped spillway (HJSS) as compared with a conventional stepped spillway. Our intent was to analyze the critical condition for the onset of the jet flow. In this analysis, the hydraulic parameters and geometric parameters of the aeration basin were used to propose an empirical equation based on the experimental data.

EXPERIMENTAL SETUP AND METHODOLOGY

Experimental setup

All of the experiments were conducted at the High Speed Flow Laboratory in Hohai University. The experimental setup consisted of a pump, an approach conduit, a large feeding basin, a test model, and a flow return system. The test model included an approach flow channel, a weir, an aeration basin, a stepped spillway, and a tailwater channel, and their widths B were all 0.275 m (Figure 2). The physical model, made of Perspex, was designed at a scale of 1:40 according to an existing stepped spillway project based on the Froude similarity criterion.

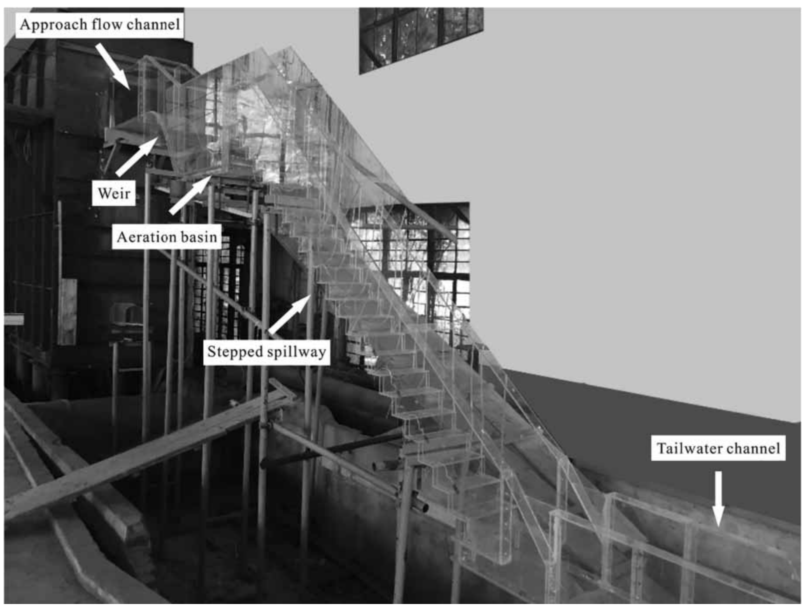


Figure 2 | Experimental setup.

The approach flow channel was 1.0 m long. The weir was a standard Waterways Experiment Station (WES) weir with the profile of $y = 1.1255x^{1.85}$. The height from the crest of the weir to the bottom of the aeration basin P was 0.63 m; the slope of the overflow surface was 1V:0.75H, and the toe of the weir was connected to the bottom of the aeration basin by an ogee curve with a radius of 0.275 m. The aeration basin upstream of the stepped spillway was added to provide the aerated flow for the stepped spillway, with l_a and h_a being the length and the height of the aeration basin, respectively. The stepped spillway was made up of 24 steps. The single step length a was 0.11 m, the single step height b was 0.09 m, and the stepped spillway slope θ was 39.3°. To stabilize the flow in the aeration basin, a reverse step was added with the same length and width as the downstream single step, with h_s being the height of the reverse step.

Experimental methodology

The discharges were measured by a V-notch weir downstream of the test model with a relative error below 2%. The flow depth h_b upstream of the first step brink was measured by a point gauge, resulting in the Froude number Fr_b at the brink $Fr_b = Q/(Bh_b^{3/2}g^{1/2})$, with g being the acceleration of gravity. The visual observation of flow patterns and the hydraulic data measurements were carried out for a wide range of unit discharges, $0.036 \leq q \leq 0.403$ m^2/s (i.e., the relative critical flow depths of $0.56 \leq h_c/b \leq 2.83$, corresponding to a Reynolds number $Re > 2 \times 10^4$ and a Weber number $We > 100$. Therefore, the scale effects associated with the flow behaviors should be negligible, according to Boes & Hager (2003a). In this study, we focused on the flow through the entrance of the stepped spillway, with particular emphasis on the effect of the aeration basin. The detailed geometric parameters of these experimental cases are listed in Table 1. The critical condition for the onset of the jet flow (h_c/b, Fr_b), along with the relevant Fr and We, is also listed in Table 1.

Table 1 | Experimental cases and geometric parameters of the aeration basin and the critical condition for the onset of the jet flow

Cases	l_a (10^{-2} m)	h_a (10^{-2} m)	h_s (10^{-2} m)	$(h_c/b)_{cri}$	$(Fr_b)_{cri}$	Re (10^4)	We (10^2)
M111	87.5	18.0	0	1.24	0.41	11.60	9.32
M112	87.5	18.0	4.5	1.46	0.51	14.76	14.80
M113	87.5	18.0	9.0	1.84	0.77	20.95	30.96
M114	87.5	18.0	13.5	2.34	0.82	30.12	52.65
M121	87.5	27.0	0	0.96	0.20	7.91	3.43
M122	87.5	27.0	4.5	1.14	0.26	10.18	5.75
M123	87.5	27.0	9.0	1.30	0.36	12.38	9.21
M124	87.5	27.0	13.5	1.50	0.49	15.46	15.28
M211	105.0	18.0	0	1.34	0.38	13.00	10.32
M212	105.0	18.0	4.5	1.70	0.49	18.67	19.81
M213	105.0	18.0	9.0	2.11	0.67	25.69	37.07
M214	105.0	18.0	13.5	2.41	0.65	31.44	47.80
M221	105.0	27.0	0	1.02	0.43	8.71	6.52
M222	105.0	27.0	4.5	1.20	0.42	11.05	8.81
M223	105.0	27.0	9.0	1.39	0.34	13.75	10.32
M224	105.0	27.0	13.5	1.67	0.42	18.13	17.01
M311	122.5	18.0	0	1.69	0.59	18.40	21.92
M312	122.5	18.0	4.5	1.96	0.68	23.08	32.55
M313	122.5	18.0	9.0	2.43	0.74	31.82	52.63
M314	122.5	18.0	13.5	2.83	0.87	40.05	80.08
M321	122.5	27.0	0	1.20	0.41	11.05	8.67
M322	122.5	27.0	4.5	1.36	0.41	13.31	11.07
M323	122.5	27.0	9.0	1.63	0.69	17.46	22.60
M324	122.5	27.0	13.5	2.07	0.57	25.02	32.06

RESULTS AND DISCUSSION

Flow patterns

For the conventional stepped spillway, the hydraulic condition for the formation of each flow pattern was expressed by the ratio of the critical flow depth (h_c) to the step height b. The onset of skimming flow can be predicted by Boes & Hager (2003b):

$$\frac{h_c}{b} = 0.91 - 0.14 \tan\theta \tag{1}$$

Substituting $\theta = 39.3°$ (the same as the stepped spillway slope of the HJSS) into Equation (1), the critical h_c/b for the onset of skimming flow in the conventional stepped spillway was equal to 0.80. A skimming flow was always observed in the conventional stepped spillway when $h_c/b > 0.8$ according to the variation of the flow patterns.

Figure 3 shows the flow patterns over the stepped spillway of the HJSS at different dimensionless unit discharges for case M211. At $h_c/b = 0.76$ and 1.17, a nappe flow and skimming flow were observed along the stepped spillway, as shown in Figure 3(a) and 3(b), respectively. From that moment, the flow pattern over the stepped spillway was similar to the conventional stepped spillway. At $h_c/b = 1.37$, the aeration basin upstream acted as a deflector. The flow separated from the top of the first step and entered the downstream steps in the form of a jet, as seen in Figure 3(c). With the further increase in the unit discharge, the cavity expanded, as shown in Figure 3(d). The separated jet directly bypassed the several steps and impacted the foregoing steps. Moreover, the jet flow resulted in significant air entrainment and impacted the downstream steps. Some instabilities, water level rises, and erosion on the steps were observed in the jet impact region, although the flow quickly regained stability and skimmed over the steps along the pseudo-bottom (i.e., skimming flow). Furthermore, compared with the conventional stepped spillway, a local jet flow was also observed at large unit discharges in other cases of the HJSS. From a practical point of view, this local jet flow should be avoided.

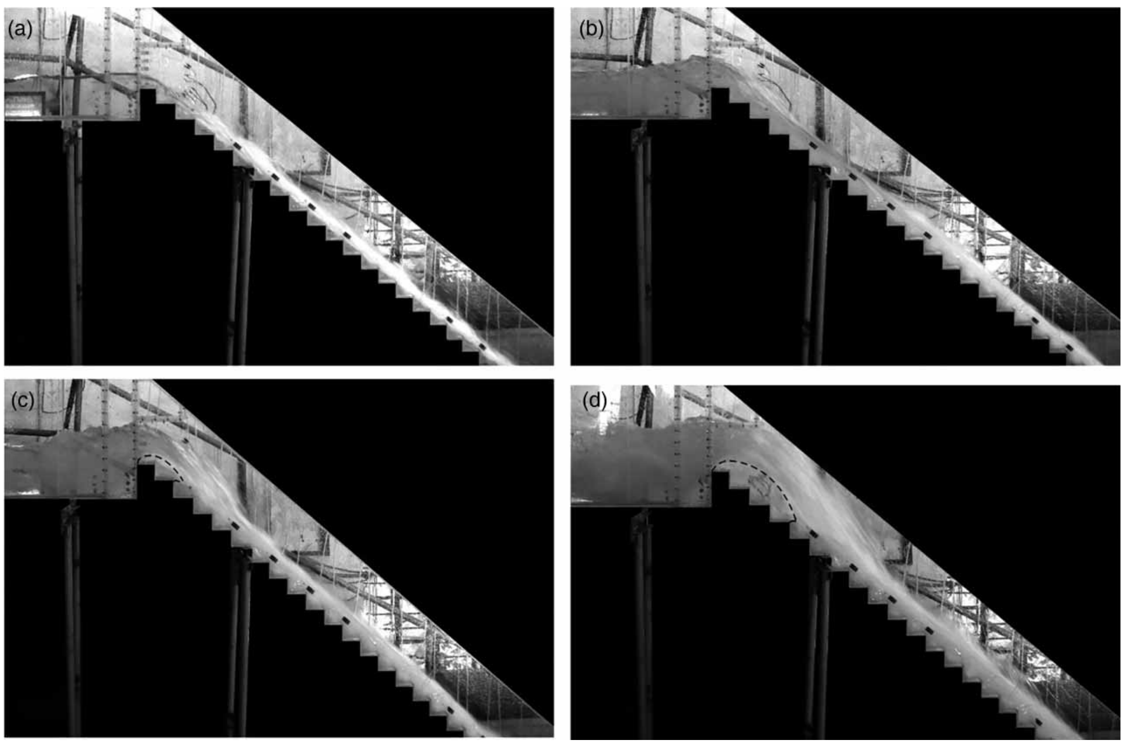


Figure 3 | Flow patterns over the stepped spillway of the HJSS at different h_c/b for case M211: (a) $h_c/b = 0.76$; (b) $h_c/b = 1.17$; (c) $h_c/b = 1.37$; (d) $h_c/b = 1.60$.

Reverse step effect

For the HJSS, the reverse step added in the aeration basin affected the flow patterns over the stepped spillway. Figure 4 shows the flow patterns with a reverse step at different h_c/b for case M213, which merely added a reverse step as compared with case M211 in Figure 3.

It was observed that, for any h_c/b, the local flow pattern on the stepped spillway with a reverse step in the aeration basin always adhered to the top of the first step, and the jet flow appeared to be nonexistent. Compared with the flow pattern for case M211, for an identical inflow condition of $h_c/b = 0.76$ and 1.17, the flow patterns with and without a reverse step were similar. However, when h_c/b increased to 1.37 and 1.60, the flow through the first step without a reverse step exhibited a local jet flow.

Furthermore, the height of the reverse step also had a significant effect on the flow pattern, as shown in Figure 5. For case M213, the flow began to detach from the top of the first step when h_c/b equaled 2.13 (Figure 5(a)), whereas the water surface profile for case M214 seemed to be smooth for the conditions of the higher reverse step height (Figure 5(b)). The reverse step, as an effective method to smooth the water surface profile, changed the angle of the streamline at the entrance section with a horizontal flat step (Tajabadi *et al.* 2018). The commonly used method of smoothing the water surface profile involves adding an inserted apparatus, e.g., the step edge arrangements in the stepped spillway proposed by Pfister *et al.* (2006b) as shown in Figure 6. Obviously, the flow through the first step had to separate in the HJSS. There was a critical condition for the onset of the jet flow when h_c/b increased to some extent, regardless of the geometry of the aeration basin.

Critical conditions of jet flow

As mentioned above, if the unit discharge increased to some extent, the flow through the first step of the HJSS would exhibit a local jet flow. There was a critical hydraulic condition $(h_c/b)_{cri}$ required for the formation of the jet flow, and the jet flow occurred once $(h_c/b) > (h_c/b)_{cri}$. Figure 7 shows the critical condition $(h_c/b)_{cri}$ with different reverse step heights in the aeration basin.

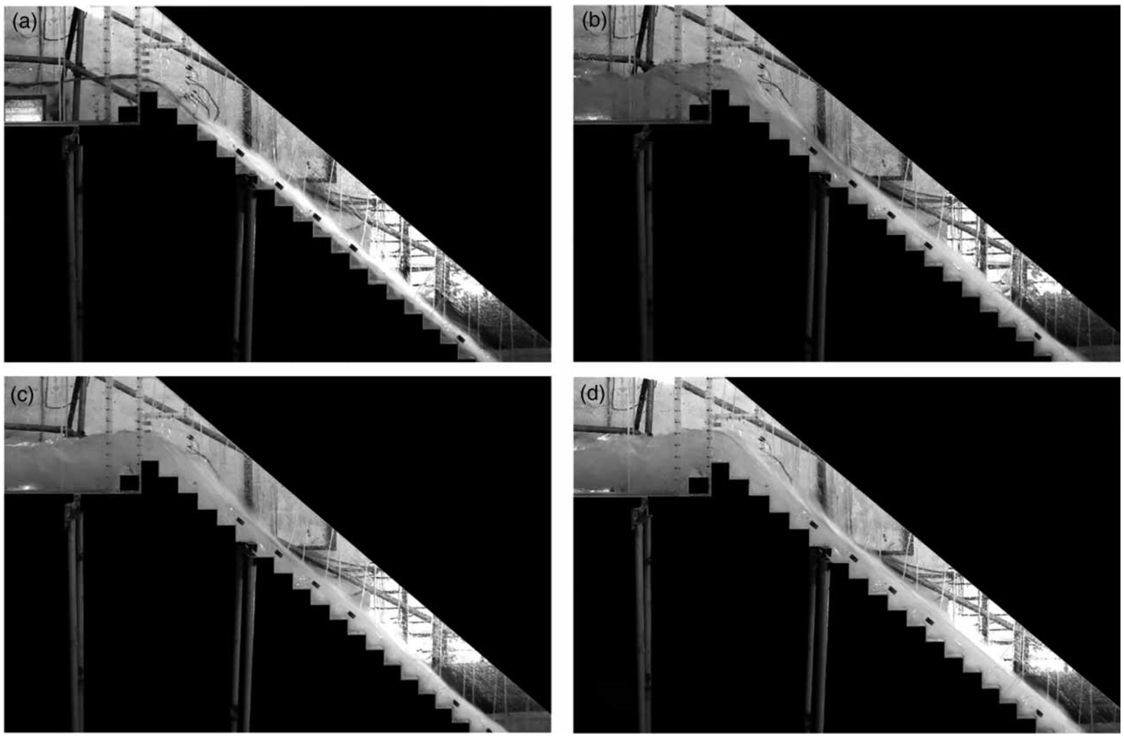


Figure 4 | Flow through the first step with a reverse step in the aeration basin at different h_c/b for case M213: (a) $h_c/b = 0.76$; (b) $h_c/b = 1.17$; (c) $h_c/b = 1.37$; (d) $h_c/b = 1.60$.

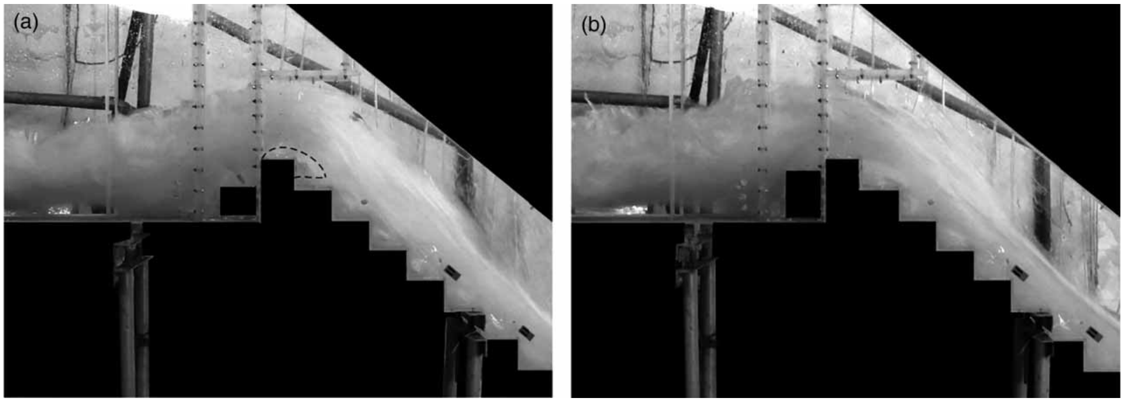


Figure 5 | Flow through the first step with different heights of reverse steps at $h_c/b = 2.13$: (a) case M213; (b) case M214.

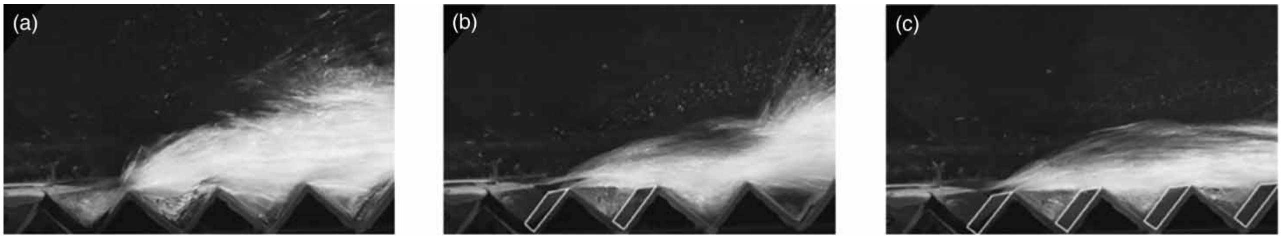


Figure 6 | Local flow patterns over stepped spillways with different step edge arrangements in foregoing steps for $n =$ (a) 0, (b) 2, (c) 5 and $h_c/b = 0.59$ (Pfister *et al.* 2006b).

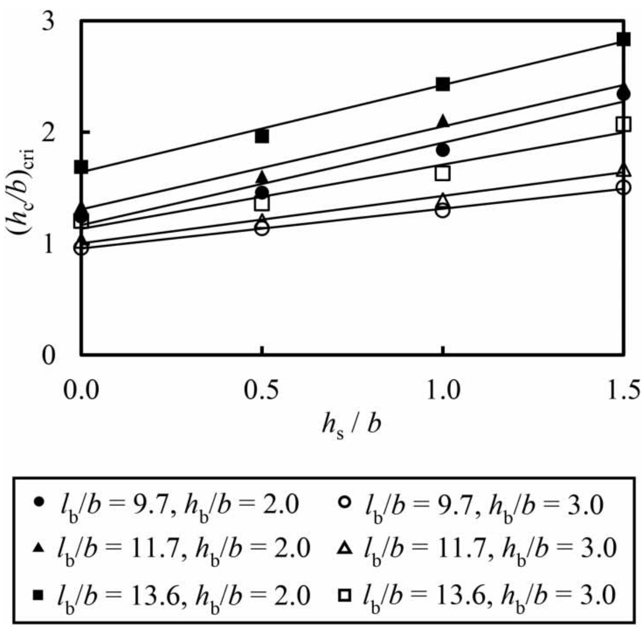


Figure 7 | Critical conditions of the HJSS with different reverse step heights in the aeration basin.

Clearly, all critical conditions $(h_c/b)_{cri}$ for the jet flow formation increased with the relative height of the reverse step (h_s/b) in the aeration basin regardless of the relative length (l_a/b) or relative height (h_a/b) of the aeration basin, and their trend had a roughly similar growth rate. As shown in this figure, the value of $(h_c/b)_{cri}$ increased with increasing l_a/b and decreasing h_a/b.

Utilizing the multiple linear regression method and based on the experimental data, we can obtain Equation (2) by considering the geometric parameters of the aeration basin, as shown in Figure 8.

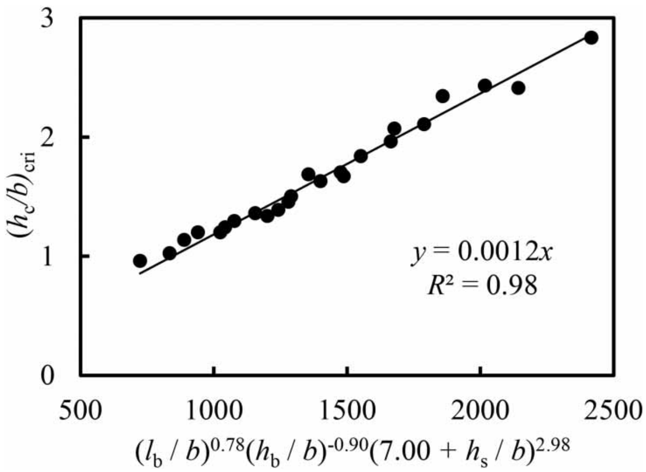


Figure 8 | Variation of $(h_c/b)_{cri}$ with $(l_a/b)^{0.78}(h_a/b)-^{0.90}(7.00+h_s/b)^{2.98}$.

$$(h_c/b)_{cri} = 0.0012\left(\frac{l_b}{b}\right)^{0.78}\left(\frac{h_b}{b}\right)^{-0.90}\left(7.00+\frac{h_s}{b}\right)^{2.98},\ R^2 = 0.98 \tag{2}$$

where $9.7 \le l_a/b \le 13.6$, $2.0 \le h_a/b \le 3.0$ and $0 \le h_s/b \le 1.5$. Equation (2) reflects not only the relationship between the critical conditions and geometric parameters of the aeration basin (i.e., $(h_c/b)_{cri}$ increased with increasing l_a/b and h_s/b, but decreased with increasing h_a/b), but also the magnitude of the effect of these parameters. The relative reverse step height h_s/b had a greater effect on the critical conditions $(h_c/b)_{cri}$ than the other geometric parameters of the aeration basin. The reverse step proved useful for smoothing the water surface profile.

To integrate the influence of the geometric parameters of the aeration basin into the inflow of the stepped spillways, Figure 9 summarizes the experimental results regarding the onset of the jet flow as a function of the Froude number at the brink of the first step (Fr_b). The critical condition $(h_c/b)_{cri}$ can be expressed as:

$$(h_c/b)_{cri} = 2.45Fr_b + 0.37,\ \text{for } 0.1 \le Fr_b \le 0.9,\ R^2 = 0.78 \tag{3}$$

As seen in Figure 9, for the HJSS, with the increasing Fr_b, $(h_c/b)_{cri}$ increased, and the relationship appeared to be linear. For the conventional stepped spillway, the hydraulic conditions required for the formation of the jet flow were defined as follows (Chanson 1996):

$$(h_c/b)_{cri} = \frac{Fr_b^{2/3}\sqrt{1+\dfrac{1}{Fr_b^2}}}{\sqrt{1+2\cdot Fr_b^2\cdot\left(1+\dfrac{1}{Fr_b^2}\right)^{3/2}\left(1-\dfrac{\cos\theta_b}{\sqrt{1+\dfrac{1}{Fr_b^2}}}\right)}} \tag{4}$$

where θ_b is the initial angle of the streamlines in the horizontal direction, and the jet flow occurred for $h_c/b < (h_c/b)_{cri}$. Because the stepped spillway of the HJSS was similar to the conventional stepped spillway for the flat crest, by substituting $\theta_b = 0$ into Equation (4), a linear form between $(h_c/b)_{cri}$ and (Fr_b) can be obtained in Equation (5) as follows (Figure 9):

$$(h_c/b)_{cri} = 0.38Fr_b + 0.49,\ \text{for } 0.1 \le Fr_b \le 0.9,\ R^2 = 0.99 \tag{5}$$

The data for this study and those of Chanson (1996) both had the linear relation. This indicated that the risk of flow deflection at the first step for the HJSS could be reduced by increasing the step height, contrary to the conventional stepped spillway

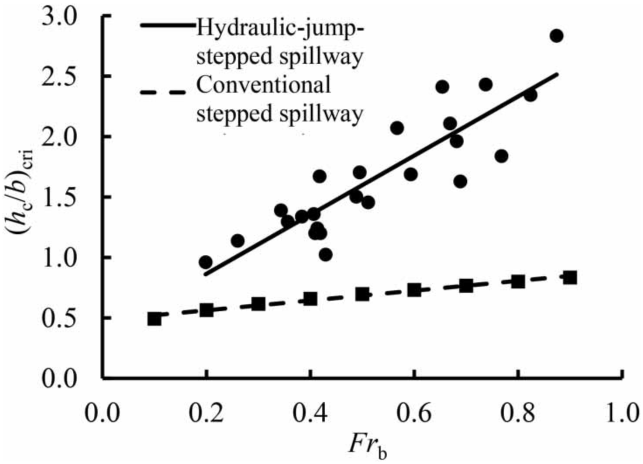


Figure 9 | Variation of $(h_c/b)_{cri}$ with Fr_b.

at a given unit discharge. The difference between the two curves was larger as Fr_b increased, which further reveals the appearance of the jet flow at larger unit discharge in the HJSS, whereas for small unit discharges in the conventional stepped spillway, both Equations (3) and (5) reveal that the jet flow could be attributed to the Froude number *Fr* at the entrance of the stepped spillway.

Although the aeration basin upstream of the stepped spillway increased the risk of flow deflection for large unit discharges, the resultant aerated flow might reduce the risk of cavitation damage of the non-aerated flow region of the stepped spillway (Wu *et al.* 2018; Zhou *et al.* 2021). In future research on the HJSS, it will be important to focus on the air concentration, velocity profiles, and other hydraulic performances by numerical simulations.

CONCLUSION

For the hydraulic-jump-stepped spillway we proposed, the jet flow near the entrance of the stepped spillway with a large unit discharge was experimentally investigated. The critical condition for the formation of the jet flow increased with the increase in the length of the aeration basin and the height of the reverse step in the aeration basin, but the critical condition decreased with the increase in the height of the aeration basin. The height of the reverse step height was more effective in lowering the risk of jet flow. By integrating the influence of the geometric parameters of the aeration basin into the inflow condition of the stepped spillway, a linear relationship could be obtained, i.e., the occurrence of jet flow in the hydraulic-jump-stepped spillway could be attributed to the Froude number at the entrance of the stepped spillway. Compared with conventional stepped spillways, the hydraulic-jump-stepped spillway could effectively extend the practical application in large unit discharges with the knowledge of jet flow conditions. Research is ongoing on the hydraulic performance of a hydraulic-jump-stepped spillway with numerical methods.

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DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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