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Enhancing Scour Control Downstream Of Stepped Spillways

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Abstract:
The downstream scouring of spillways poses a significant risk to dam stability. Therefore, it is crucial to determine the depth of scour downstream of spillways, as the formation of scour holes near and around spillway foundations can endanger dam stability, potentially leading to catastrophic failure. This paper aims to investigate the scour downstream of stepped spillways. In the experimental setup, a flume with dimensions of 16.2 meters in length, 66 centimeters in width, and a depth of 65 centimeters was utilized. End sills over spillway steps that provided with opening holes were used to minimize local scour depth downstream of the stepped spillway. Various configurations of these opening holes were examined. Additionally, the divergent angles of the spillway outlet were varied within the range of 30° to 180°. The present study outcomes revealed that the optimal configuration, including rectangular opening holes through end sills, reduced scour depth by nearly 56%. Furthermore, our findings indicated that a spillway outlet with a divergent angle of 30° proved to be the most effective in minimizing local scour depth, resulting in a reduction of 68%. In conclusion, these results offer valuable insights into effectively mitigating scour downstream of stepped spillways, thereby enhancing dam safety and reducing associated risks.

Key words*: Spillway, Local scour, Sill, Hydraulic structure.*

1. INTRODUCTION

A stepped spillway is an important hydraulic structure used in various civil engineering projects to safely control and manage the flow of water. It plays a crucial role in preventing erosion and scour downstream by dissipating the energy of flowing water in a controlled manner. In this review, we will discuss the effectiveness of stepped spillways in mitigating scour downstream, with reference to relevant studies and research findings. Stepped spillways are designed to reduce the velocity of water flowing down a slope by breaking it into smaller, manageable steps. This controlled energy dissipation is crucial in preventing scour downstream of the spillway. When water flows over a traditional smooth spillway without steps, it can create high-velocity jets that erode the riverbed downstream, leading to sediment transport and potential infrastructure damage. One of the key mechanisms through which stepped spillways prevent scour is the hydraulic jump phenomenon. As water flows over the steps, it undergoes a sudden change in velocity and depth, causing the formation of a hydraulic jump. This jump acts as an energy dissipator, reducing the erosive potential of the flow and minimizing scour downstream. Numerous studies have investigated the effectiveness of stepped spillways in reducing scour downstream. Research by Chanson 1995 and Chanson et al. 2015 has demonstrated that stepped spillways can significantly reduce scour compared to traditional smooth spillways. Proper hydraulic modeling and analysis are essential to tailor the design to the specific site conditions. It's worth noting that while stepped spillways are effective in scour prevention, they can have environmental impacts, especially if the project is located in a sensitive ecosystem, Hager and Pfister 2013. In 1991, Bormann and Julien conducted a comprehensive review of experimental studies that examined scour phenomena downstream of hydraulic structures positioned beneath both free-flowing and submerged jets. In 1998, Balachandar and Kells revealed that the characteristics of local scour are closely tied to the depth of the tailwater. Dargahi, in 2003, conducted an experimental investigation aimed at establishing the similarity of scour profiles and scour geometry. In 2004, Marion et al. conducted a series of experiments to investigate the effects of bed sill spacing and sediment grading on the potential for erosion caused by jets flowing over these sills. In 2006, Adduce and Sciortino conducted both experimental and numerical investigations to examine the occurrence of local scour downstream of a sill followed by a rigid apron. Their comprehensive study culminated in the creation and validation of a one-dimensional numerical model, which adeptly replicated the progressive formation of scour holes. The experimental study found that the equilibrium scour depth is influenced by the densimetric Froude number, sediment size, and tailwater depth. The time scale of scour depth also decreases with increase in densimetric Froude number, Dey and Raikar2007. In a series of experiments, Hamidifar et al. 2011 investigated the erosion behaviors of non-cohesive sediments downstream of both smooth and rough aprons. They found that rough aprons significantly reduce the dimensions of scour holes compared to smooth aprons. In 2013, Oliveto delved into the temporal and spatial evolution of local scour that occurs downstream of low head spillways featuring horizontal aprons. Fadaei-Kerman and Barani, 2014. conducted a numerical simulation to analyze the flow behavior over a chute spillway, employing the Computational Fluid Dynamics method. The maximum disparity observed between the calculated values and the experimental findings amounted to 5.47% for average velocity and 7.97% for piezometric pressure. Zhang and Gong 2016, investigated the effectiveness of the stepped spillway as a commonly utilized flood energy dissipator, particularly in its capacity to significantly mitigate kinetic or hydraulic energy through air-entrainment in skimming flow over the steps. They show that accurate numerical modeling is essential for understanding the dynamics of air entrainment over stepped spillways. Different experimental conditions were used by Machado et al. 2020 to investigate the influence of various factors on the configuration of scour holes in loose beds, including tailwater depth, flow rate, and ski jump bucket exit angle. The results of this study showed the tailwater depth was the most important factor, followed by the flow rate and the ski jump bucket exit angle. The effect of stilling basin slope on bed scour downstream of Javeh dam was investigated by Eghlidi et al. 2020 in this study. The results showed that the stilling basin slope has a significant influence on the maximum scour depth. The maximum scour depth increased by 47% when the stilling basin slope was 0.02, and decreased by 52.2% when the stilling basin slope was -0.02. The distance of the maximum scour depth to the sill also increased with increasing stilling basin slope and decreased with decreasing stilling basin slope. A study of scour downstream of free hydraulic jump in stilling basin of stepped spillways was carried out by Nasralla 2022. The effect of the contraction ratio of the stepped spillway was highlighted. Different downstream divergent angles were studied to minimize the scour depth. Results showed that the relative scour depth was reduced by 23% for a divergent angle of 170°. Different shapes of buffer in the stilling basin were also studied to reduce the scour depth, and one of the considered buffers decreased the relative scour depth up to 84%. Wang et al. 2023 developed two machine learning models for accurate prediction of scour depth downstream of ski-jump spillways: the support vector regression (SVR) model and the SVR ensemble with the innovative gunner (SVR-AIG) model. The statistical plots showed that the SVR-AIG model predictions were more accurate than the SVR model predictions. The objective of the current research is to concentrate on assessing the extent of local scour downstream of a stepped spillway considering varying downstream outlet angles. Additionally, the study explores the impact of utilizing different configurations of end sills at the end of spillway-steppes, each with a distinct number of openings and shapes.

2. EXPERIMENTAL WORK

Experimental work was conducted in a flume that was 16.2 m long, 65 cm deep, and 66 cm wide, as illustrated in figure 1. The flow from the flume was transferred to a drain in a lower channel that was equipped with a rectangular weir to measure the discharge. The collected experimental data can be found in Table 1. A wooden model of a spillway was built and placed at the mid-length of the flume with a contraction ratio of 20%. The proposed spillway is 32 cm high, 54 cm wide, and has 8 cm high steps. The downstream face of the spillway is inclined at a 30-degree angle. A 120cm stilling basin was used to confine the free hydraulic jump that formed over it. Beyond the stilling basin, there extended a 3.5-meter-long mobile bed composed of a stone layer with a thickness of 20 centimeters. The median size of the fine gravel sample (d_{50}) was determined to be 3.1 millimeters, while the uniformity coefficient (d_{60}/d_{10} <4) was calculated to be 1.68, indicating that the soil can be classified as uniformly graded.

To determine the time required for each run, used 2 hours per experiment was used based on preliminary experiments as shown in Fig. 1 using flow rate of 35l/s (Fo=0.077), which showed that this was sufficient to achieve more than 90% of the maximum equilibrium scour depth. In addition, all experiments were conducted under clear-water conditions. The free hydraulic jump was controlled by a tailgate just downstream of the stepped spillway for all experimental runs.

To precisely gauge the scour depth downstream of stilling basins with an accuracy of ±0.1 mm, a 2 cm by 2 cm mesh is utilized. At each grid point, the scour was measured exclusively using a point gauge, maintaining a high level of accuracy within ±0.1 mm. Furthermore, this same point gauge is also utilized for measuring water depths, both upstream and downstream of the spillway. Various arrangements, including different configurations of the end sill (constant thickness and height, 2cm, and 6.4cm, respectively) fixed at the spillway steps and outlet divergence angles, are detailed in Table 1, Figs. 2, 3 and 4.

3. DIMENSIONAL ANALYSIS

Dimensional analysis, applying Buckingham's π-theorem to the experimental data, reveals a significant relationship. This correlation links the scour depth ratio (Dsmax/yc) to various independent variables, including the Inlet Froude number (Fo), ratio of opening area in sills over spillway steps β= (a_o/a_{sill} where, a_o is the area of opening in sill, and a_{sill} is the plate area (sill) at the end of spillway steps), and the outlet divergence angles of the spillway model (α), resulting in the following equation:

$$\frac{Dsmax}{yc} = f\left(\alpha, \beta, n, F_o\right) \quad (1)$$

In this equation, Dsmax represents the maximum scour depth, yc denotes the critical water depth of the spillway, this relationship allows to better understand the interplay between these variables in the context of the experimental data, see Fig. 4.

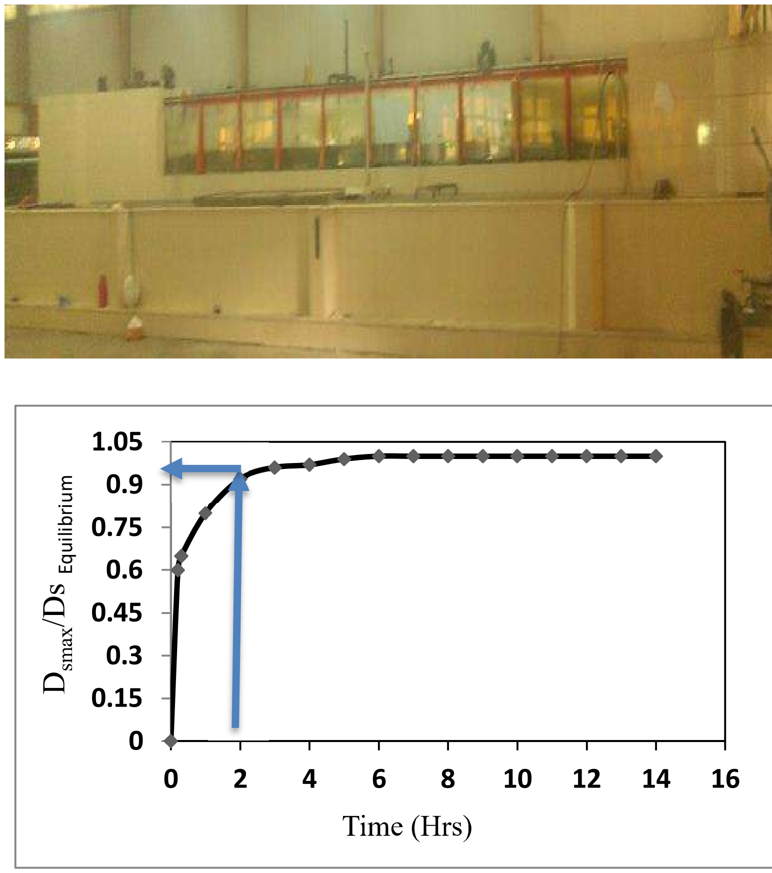

Figure 1. Overview of the laboratory flume (top) and the relationship between local Scour depth and time (bottom, Q= 35l/s with Fo=0.077, runs 1-14, Table 1).

Figure 2. End sills provided with opening area at each side (n=6, with rectangular opening shape).

Figure 3. Outlet divergence (α = 30^o, run no. 63 Table. 1).

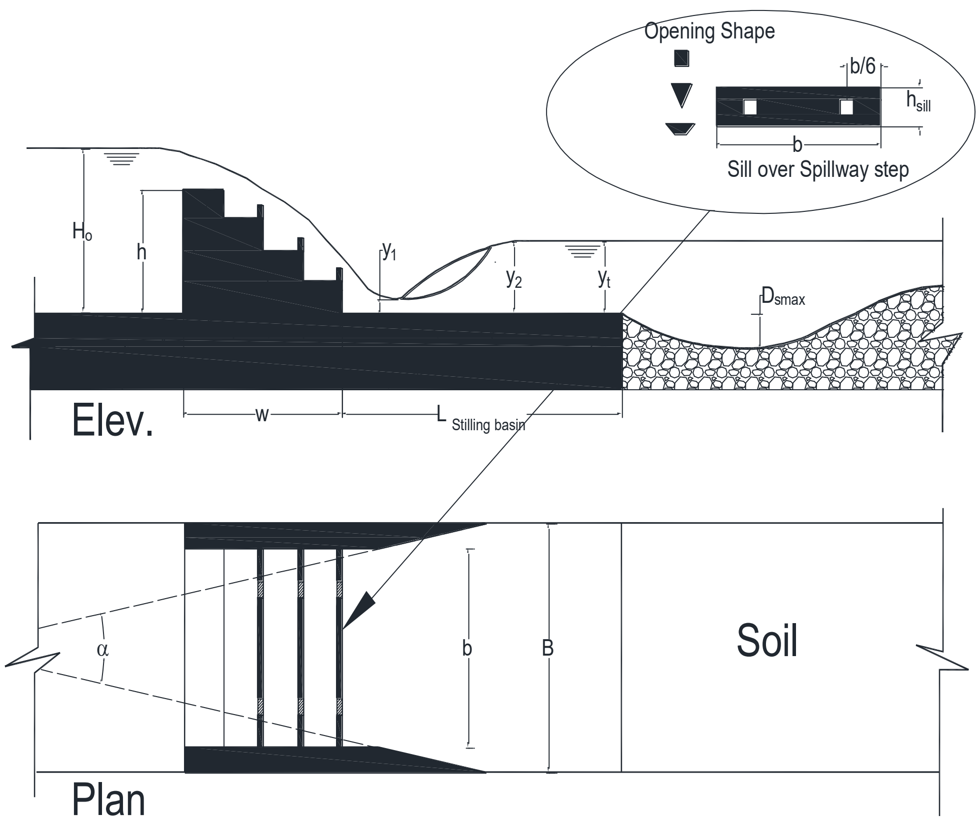

Figure 4. Stepped spillway experimental model.

Table 1. Details of experimental work.

Run #	Q l/s	Inlet Froude number Fo	Inlet Reynolds number	Sill opening shape	No. of opening	Divergence angle (α)	Remarks
1-14	35	0.077	29680	No sill		180°	16 runs (covers time from 20 minutes to 14hours)
15	15	0.016	17265				Time for each run 2hours
16	20	0.029	20408				
17	25	0.043	23584				
18	30	0.060	26737				
19	35	0.077	29680				
20	15	0.016	17265		2		Time for each run 2hours Sill height= 6.4cm Sill thickness= 2cm Percentages of sill opening area ($\beta=a_o/a_{sill}=10\%$)
21	20	0.029	20408				
22	25	0.043	23584				
23	30	0.060	26737				
24	35	0.077	29680				
25	15	0.016	17265		2		
26	20	0.029	20408				
27	25	0.043	23584				
28	30	0.060	26737				
29	35	0.077	29680				
30	15	0.016	17265		2		
31	20	0.029	20408				
32	25	0.043	23584				
33	30	0.060	26737				
34	35	0.077	29680				
35	15	0.016	17265		4		
36	20	0.029	20408				
37	25	0.043	23584				
38	30	0.060	26737				
39	35	0.077	29680				
40	15	0.016	17265		6		
41	20	0.029	20408				
42	25	0.043	23584				
43	30	0.060	26737				
44	35	0.077	29680				
45	15	0.016	17265		8		
46	20	0.029	20408				
47	25	0.043	23584				
48	30	0.060	26737				
49	35	0.077	29680				

Table 2. Details of experimental work (Continue)

Run#	Q l/s	Inlet Froude number Fo	Inlet Rynolds number	Sill opening shape	No. of opening	Divergence angle (α)	Remarks
50	15	0.016	17265		4	90°	Time for each run 2hours Sill height= 6.4cm Sill thickness= 2cm Percentages of sill opening area ($\beta=a_o/a_{sill}=$ 10%)
51	20	0.029	20408				
52	25	0.043	23584				
53	30	0.060	26737				
54	35	0.077	29680				
55	15	0.016	17265		4	60°	Time for each run 2hours Sill height= 6.4cm Sill thickness= 2cm Percentages of sill opening area ($\beta=a_o/a_{sill}=$ 10%)
56	20	0.029	20408				
57	25	0.043	23584				
58	30	0.060	26737				
59	35	0.077	29680				
60	15	0.016	17265		4	30°	
61	20	0.029	20408				
62	25	0.043	23584				
63	30	0.060	26737				
64	35	0.077	29680				

4. RESULTS AND DISCUSSION

In order to mitigate riverbed erosion, it's essential to address the potential consequences of water flowing over a spillway. This flow has the potential to generate a powerful current capable of eroding the riverbed. Such erosion can result in the development of deep cavities known as scour holes, posing risks to both the integrity of the spillway and the surrounding structures. In the present study, sill over spillway steps and outlet divergence angle can be an effective way to dissipate the energy of water flowing over a spillway and control erosion.

4.1. Effect of sills over spillway steps

4.1.1. Shape of opening area in sill

Spillway sills that span the entire width of the spillway are installed at the end of the spillway steps. These sills have openings on each side that account for 10% of the face sill area. The openings through the sills can have different shapes, such as rectangular, triangular, and trapezoidal. Figure 5 shows the relationship between the relative scour depth and the inlet Froude number for different open area shapes through a sill. It was found that the scour depth is reduced for all different open area shapes through a sill compared to the case without a sill.

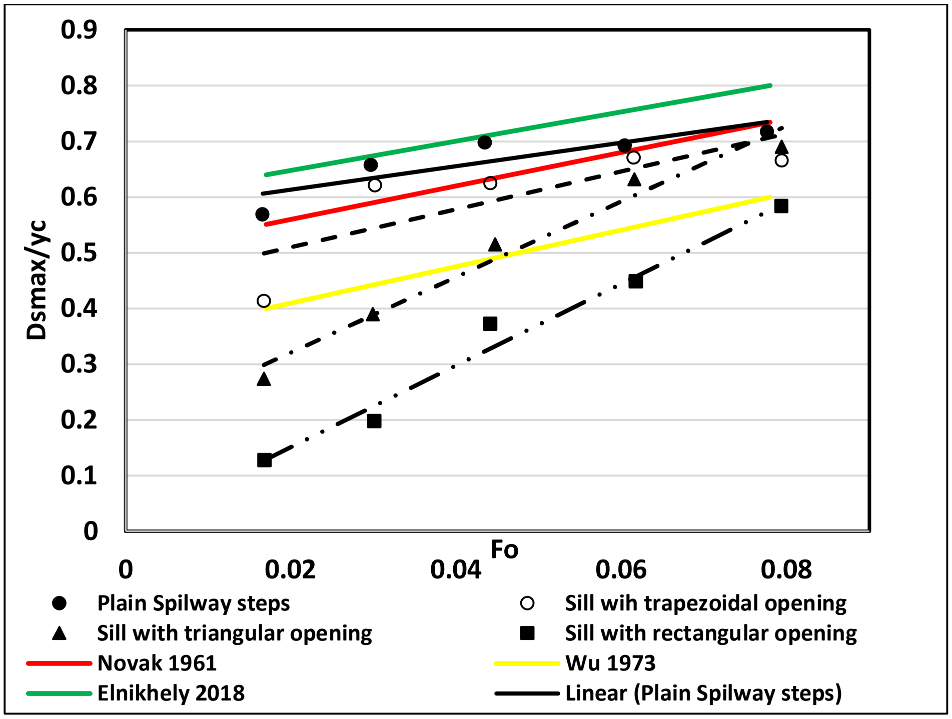

Figure 5. Effect of open area shape on relative scour depth and inlet Froude number.

The use of trapezoidal, triangular, and rectangular opening shapes in sills reduced the scour depth by 11%, 26%, and 47%, respectively. Various researchers have proposed scour equations for use downstream of hydraulic structures. These researchers include Novak (1961), Wu (1973), and Elnikhely (2018). To facilitate comparison, some of these equations were employed to compute the maximum scour depths downstream of hydraulic structures (see Fig. 5). Figure 3 presents a comparative analysis of the experimental outcomes for the plain stepped spillway in this study, contrasted with the results derived from the equations of Novak (1961), Wu (1973), and Elnikhely (2018). Notably, Novak and Elnikhely's empirical equations closely approximate the scour depth observed in our present study. In contrast, the Wu equation yields lower values for relative scour depth, possibly due to variations in particle size in the experimental material. In sum, our findings for the plain stepped spillway align favorably with the results generated by the equations sourced from existing literature. The use of trapezoidal, triangular, and rectangular opening shapes in sills reduced the scour depth by 11%, 26%, and 47%, respectively. The contour maps for scour depth downstream of the stilling basin show that the rectangular opening case produces the minimum scour holes, comparable to the other opening shapes and the no sill case as shown in Figure 6. The openings within the sills permit a fraction of the flow to divert, leading to the convergence of the upper flow with the lateral flow originating from the sill openings. This interaction culminates in heightened energy dissipation within the downstream flow as it traverses the stilling basin. Consequently, these energy dissipators prove to be an effective means for managing and controlling the scour depth. In the context of spillway variations, which encompass both flat plains and configurations featuring sills with associated openings, the plain steppes spillway distinguishes itself by boasting the most substantial scour hole volume, measuring a noteworthy 8602 cm³. Additionally, it produces the longest maximum scour length, extending over 40 cm, (Figure 6). When employing sills with rectangular openings (n=2), there is a substantial reduction in the scour hole volume, surpassing 50%.

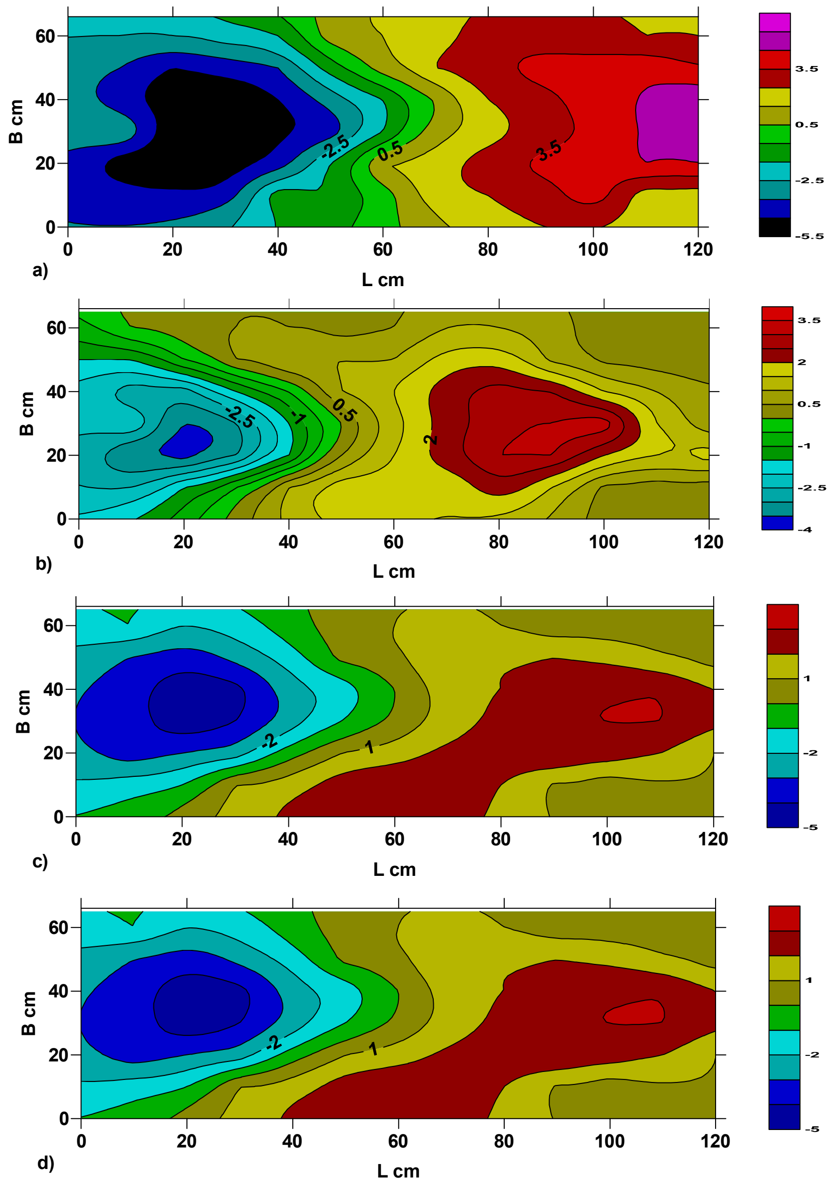

Figure 6. Scour contour maps at flow rate of 35 L/s for, a) plain steps, run no. 19, and cases of sills over steps with n =2 for following shapes, rectangle, run no. 24 (b), triangle , run no. 29(c), and trapezoidal, run no. 34, Table 1(d).

4.1.2. Number of opening areas in sills

An inquiry into the impact of varying the number of rectangular openings in sills positioned over spillway steps on local scour depth was conducted. In alignment with the previous scenario, we maintained a consistent area ratio. This investigation involved the manipulation of the number of openings, ranging from 2 to 8, with a distribution spanning both sides of the sill. In Figure 7, the correlation between the maximum relative scour depth and the upstream Froude number is illustrated across various quantities of openings in the sills. The findings indicate a direct correlation between the maximum relative scour depth and the ascending Froude number, demonstrating an increase as the Froude number rises. Notably, the optimal number of openings appears to be four. This choice is driven by the observation that four openings yield the highest degree of energy dissipation, primarily attributed to the dynamic interaction between the upper flow and the lateral flow emanating from these opening areas. The reduction in scour depth downstream of the stilling basin demonstrated varying degrees of mitigation, with respective percentage reductions of 46%, 56%, 34%, and 14% corresponding to n values of 2, 4, 6, and 8. The scour contour maps downstream of the stilling basin show that sills with four rectangular openings (n = 4) produce the smallest scour holes. As the number of openings increase, the local scour depth increases, as shown in Figure 8. For n = 4, the scour hole volume is 1300 cm^3, which is more than 80% less than for n = 8, which has a scour hole volume of 8600 cm^3. Additionally, the maximum scour depth for n = 4 is 2.4 cm, which is less than half of the maximum scour depth for n = 8, which is 4.7 cm.

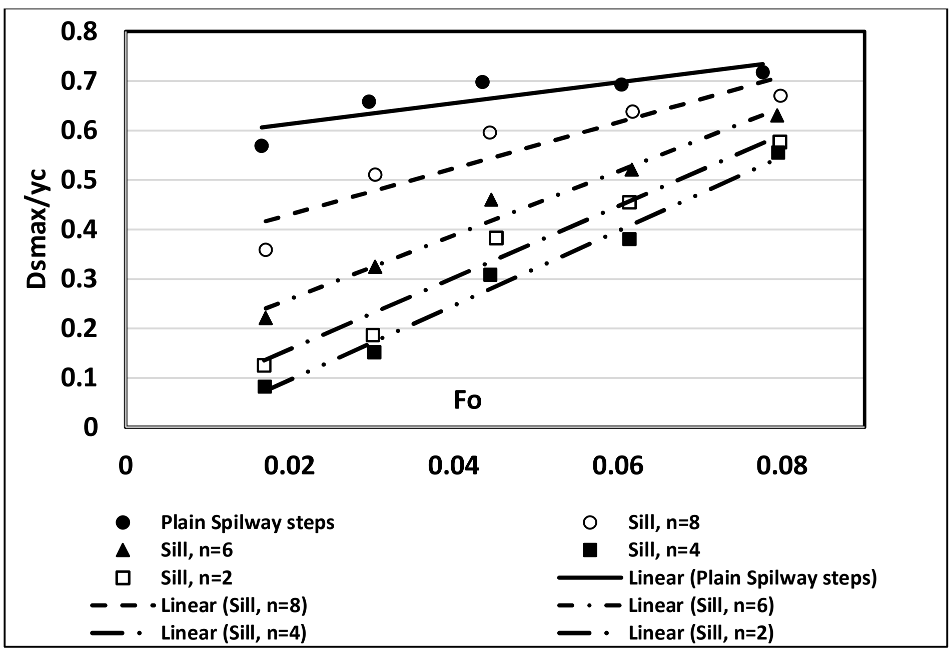

Figure 7. Effect of the number of sill openings on relative scour depth and inlet Froude number (sills have square opening shape)

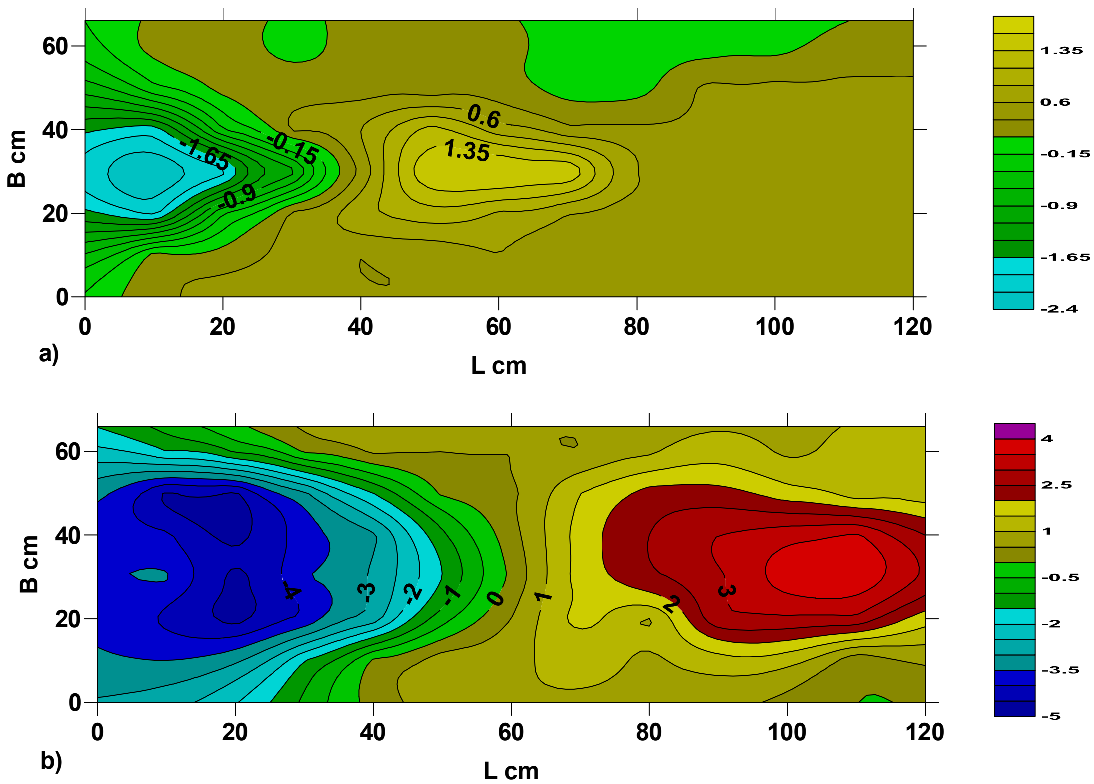

Figure 8. Scour contour maps for different numbers of openings in sills with square openings shape, a) n= 4, run no. 39, and b) n=8, run no. 49, Table 1, at a flow rate of 35 L/s.

4.2. Effect outlet divergence angle

An examination of the influence of the outlet divergence angle on local scour depth was conducted. The study encompassed a range of angles, specifically $\alpha = 180°$, 90°, 60°, and 30°. Figure 9 presents the correlation between the maximum relative scour depth (Dsmax/yc) and the inlet Froude number (Fo). Experimental results showed that as the outlet divergence angle decreased, the local scour depth downstream of the stilling basin also decreased. The relative scour depth decreased by 56%, 64%, 66%, and 68% for outlet divergence angles of 180°, 90°, 60°, and 30°, respectively. Figure 10 shows typical scour contour maps for outlet divergence angles of 60° and 30°. These findings can be explained by the fact that decreasing the divergence angle leads to a more uniform distribution of streamlines downstream of the stilling basin (as evident from the contour map in Figure 8a), which results in smaller scour holes. The scour hole volume for a divergence angle of 30 degrees is less than 75% of the volume for a divergence angle of 60 degrees. In addition, the maximum scour depth for these two typical cases is 2.9 cm and 3.55 cm, respectively.

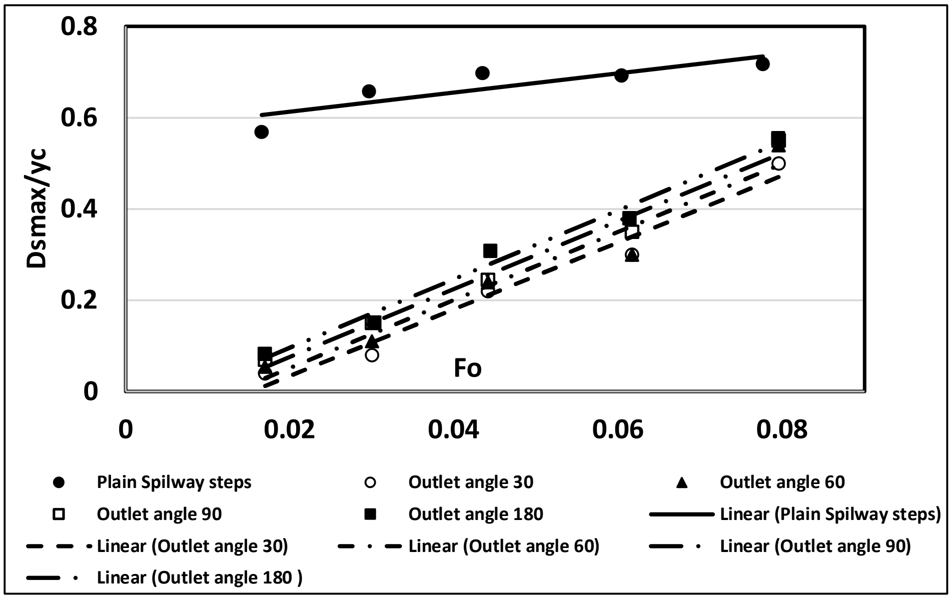

Figure 9. Effect of divergence outlet angle on relative scour depth and inlet Froude number (sills have square openings shape with n=4).

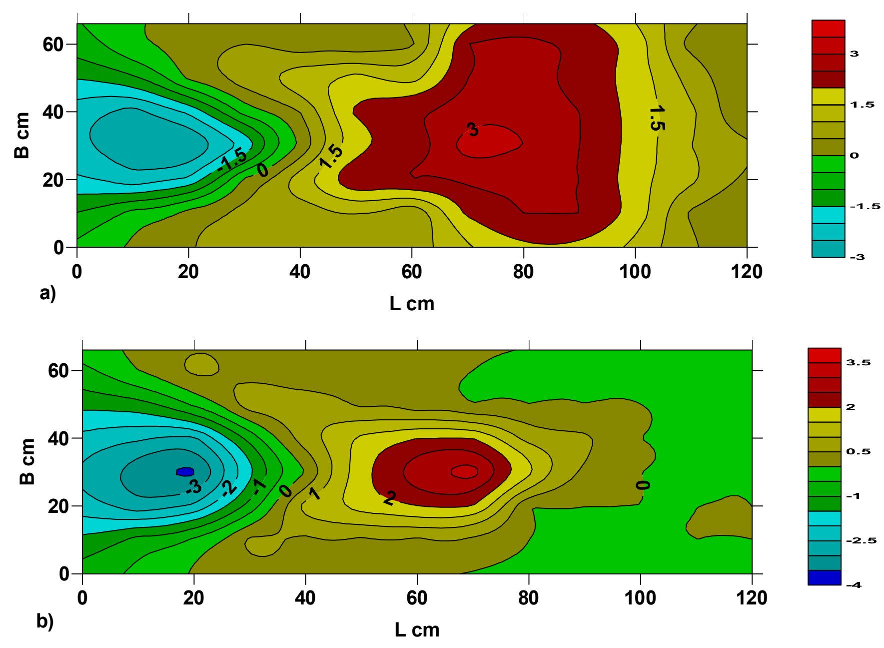

Figure 10. Scour contour maps for different outlet divergence angles, a) α = 30, run no. 63 and b) α=60, run no. 58, Table 1, at a flow rate of 30 L/s (sills have square openings shape with n=4).

5. CONCLUSIONS AND FUTURE OUTLOOK

In conclusion, the study on the control of scour downstream of a stepped spillway has provided valuable insights into mitigating one of the most critical challenges in hydraulic engineering. The research has demonstrated that stepped spillways with sills that have opening areas and adjusted outlet divergence angles can effectively reduce scour and erosion downstream of the stilling basin, making them a promising solution for enhancing the stability and longevity of water infrastructure projects. The following conclusions can be summarized as follows:

1- Local scour depth increases as the inlet Froude number increases
2- The incorporation of a rectangular opening area on the steps of a spillway sill, amounting to 10% of the total sill area, in a rectangular configuration, results in a notable reduction of 56% in the depth of local scour.
3- The number of opening areas through a sill has a significant effect on controlling local scour depth downstream of a stilling basin.
4- Setting the outlet divergence angle downstream of the spillway to 30 degrees, in addition to the presence of an open sill spanning the spillway steps, can lead to a reduction in scour depth of approximately 70%.

This article presents the development of an appurtenance as a sill with opening area over spillway steps to minimize and control local scour depth downstream of hydraulic structures. This is very important in hydraulic design to avoid the harmful effects of scour. Numerical simulation of such hydraulic phenomena is very important to have a good understanding of the evolution of scour.

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