Experimental study of the effect of jump on the Downstream Scouring of type-C trapezoidal piano key weir

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ABSTRACT

Piano key weirs (PKWs) represent an evolved and novel type of labyrinth weirs, offering a higher discharge coefficient when compared to linear weirs. Recent attention has focused on investigating energy loss and downstream scouring associated with piano key weirs, given their high efficiency and potential for reducing financial and life risks. In this research, a type-C trapezoidal piano key weir with a height of 0.2 m was utilized, incorporating two jumps with radii of 0.15 and 0.21 m at the weir outlet keys. After setting the flow rate and the tailwater, scouring was started, and then after the equilibration time, the pump was turned off after complete drainage, and the bed profile was taken by a laser meter. The findings indicated that the presence of a jump contributes to an increase in maximum scour depth. Furthermore, the presence of a jump causes the maximum scouring depth to occur further away from the weir toe. Increasing the radius of the jumps also results in an augmented maximum scour depth. The length of the maximum scour depth, compared to the weir toe, is approximately 12% greater in weirs with a bigger jump radius than those with a smaller radius. On average, the maximum length of the scour depth about the weir toe is 29.4% and 19.5% longer in weirs with jump radii of 0.21 and 0.15 m, respectively, compared to weirs without jumps. Additionally, the presence of a jump diminishes scouring at the weir toe, with toe scour being approximately 42% less pronounced in weirs with a bigger jump height compared to weirs without jumps. The average scour index in weirs with jump radii of 0.21 and 0.15 m is approximately 2.77% and 0.52% lower, respectively, compared to weirs without jumps. Moreover, an increase in jump radius correlates with a decrease in the discharge coefficient.

KEYWORDS

Piano key weir (PKW), local scour, jump effect, Experimental investigation, discharge coefficient.

1. Introduction

Due to the light foundation and high discharge coefficient in piano key weirs, it is very important to investigate the local scour downstream of these hydraulic structures and find a solution to reduce it. Piano key weirs have triangular, rectangular, and

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trapezoidal shapes in plan and have four types A, B, C, and D. Type A has overhangs upstream and downstream of the weir, and types B and C have overhangs upstream and downstream of the weir, and type D has no overhangs. Many studies have been done on the influence of geometric and hydraulic parameters on the discharge coefficient of these weirs, fewer study have investigated their scouring. In recent years, Fathi et al. (2024) reduced scour downstream of the weir by creating steps in the outlet keys of the A-type trapezoidal PKW [1]. Also, Abdi et al. (2024) reduced the scour downstream of the weir by creating a baffle in the weir outlet keys of the type A trapezoidal PKW [2]. Due to the high efficiency of piano key weirs compared to linear weirs, it is very important to study scouring in their case. Also, according to the above information and the research conducted on the scouring of piano key weirs, no study has been done on the presence of a jump and its function in reducing or increasing scouring. Moving away the maximum scour depth from the weir toe and reducing scour in the weir toe are also of great importance; Because they reduce the risk of overturning the weir. In this study, it was tried a trapezoidal piano key weir with a height of 0.2 m and two jumps with heights and radii of 0.14, 0.075, 0.21, and 0.15 m to reduce the amount of scour in their toe and, the distance of the maximum scour depth to the lower toe should be specified. Also, three tailwater depths, three flow rate depths, and gravel materials were used in the downstream bed of the weir.

2. Dimensional analysis

By using Buckingham's π theory and considering the three repeated variables of discharge per unit width (q), water density, and flow depth plus the equivalent height of kinetic energy upstream of the weir (H_u), the following dimensionless relations are obtained. In this relation, h is the height of the jumps, R is the radius of the jumps, $\mathrm{Fr_d}$ is the landing number of particles, $\emptyset$ is the maximum scour depth (Z_s), its distance from the weir toe (X_s), and the scour of the weir toe (Z_t).

$$\frac{\phi}{H_u} = f\,(\mathrm{Fr_d}, \frac{R}{h}) \qquad (1)$$

3. Materials and methods

The experiments were carried out in a laboratory flume with a length of 10 m, a width of 0.6 m, and a height of 0.8 m. The flow enters the tank with flow stabilizers through two surface tanks and then enters the laboratory flume and reaches the weir after 5.5 m. The weir has a width of W=0.6 m, height of P=0.2 m, width of inlet keys W_i=0.215 m, width of outlet keys W_o=0.075 m, length of overhang downstream of weir B_o=13 m, The length of the side walls is B=0.5 m, the crest lengths is L=6.2 m, and the thickness of the crest is Ts=0.01 m. Three flow rates of 0.03, 0.035, and 0.04 m^3/s were used. The flow rate was adjusted by a valve and a monitor (to show its value) with an error of ±0.01%. Also, by the valve at the end of the laboratory channel, the three tailwater depths were set equal to 0.05, 0.1, and 0.15 m. Before turning on the pump, a galvanized sheet was used on the bed, and after adjusting the flow rate and tailwater depth, this metal bed was slowly removed from the bed to prevent initial scouring. The used gravel material has uniform granulation, the average diameter of particles is equal to 0.0075 m and the specific density is equal to 2650 kg/m^3. The jumps used at the end of the outlet keys weir have a radius of 0.21, 0.15 m, and a height of 0.14 and 0.075 m, respectively. After 150 (minutes), the pump was turned off and after drainage, the bed was removed by a laser meter. The scouring changes in 150 (minutes) for gravel is less than 1 mm and this time was considered as the equilibrium time. Also, the depth upstream of the weir was measured by a point gauge with an error of ±1 mm.

4. Results and discussion

The flow passing over the C-type trapezoidal piano key weir flows as an inclined jet from the outlet keys and as a free-falling jet from the input keys to the downstream. In the type C piano key weir, due to the absence of an overhang upstream of the weir, the slope of the outlet keys is higher and the length of the submerged area or the local protrusion of the current in the outlet keys is very small. The lack of overhangs upstream of the weir has caused the indentation of the flow at the entrance of the outlet keys. Also, due to the greater slope in the outlet keys, scouring has been created near the weir toe, and due to the overhang downstream of the weir, the flow falls into the bed in the form of a jet and causes flow disturbance in this place. This disturbance of the flow causes the material to return to the side of the weir and the slope of the scour downstream of the weir becomes more inclined and at the place of the flow falling from the overhang of the inlet key to the bed, the gravel materials are slightly raised. The existence of the jump and its height increases the depth of the flow in the outlet keys, water backs up to the upstream side of the weir, and finally reduces the discharge coefficient. However, the presence of the jump causes the flow to be thrown downstream. After the flow hits the materials, it causes local scour at a distance away from the weir toe. Also, a weak hydraulic jump was observed downstream of the weir without a jump. In weirs with jumps and especially in weirs with larger radii, the hydraulic jump becomes stronger and creates eddies downstream and at the place where it meets the depth of the abutment. The existence of these eddies causes the materials to be washed and their rotation. After rotating the materials and separating them from the surface of the bed, they are transported downstream along with the flow. This collision and disturbance of the flow causes the scour to rise more. Also, by increasing the radius of the jumps, hydraulic jumps are formed at a further distance from the weir toe. The impact of the current in the jumps becomes more inclined to the bed and acts like an inclined jet. After the flow hits the material, it creates a pit and returns the material to the weir toe. The flow rate and the tailwater depth have an effect on the amount of erosion. As the flow rate increases, the flow velocity increases, and the scour increases. Increasing the speed causes stronger eddies and more disturbance of the flow. Increasing the flow rate also increases the volume and length of the scour hole. As the tailwater depth decreases, the maximum scour depth also increases. The presence of a greater tailwater depth reduces the velocity of the flow downstream and prevents further scouring. As the flow rate increases, the flow depth upstream of the weir increases and the discharge coefficient decreases. Also, with the increase in flow rate in the jump weirs, the depth of flow upstream of the weir increases and the discharge coefficient of the weir decreases. On average, the value of the discharge coefficient in the weir without a jump, the weir with A smaller jump, and the weir has a bigger jump to 2.76, 2.65, and 2.46, respectively. Equations 2, 3, and 4 are provided to calculate the maximum scour depth, its distance from the weir toe, and the scour depth in the weir toe, respectively, and *K* coefficients 1 to 4 can be seen in Table 1.

$$\frac{Z_s}{H_u} = K_1(\mathrm{Fr_d})^2 + K_2\,\mathrm{Fr_d} \tag{2}$$

$$\frac{X_s}{H_u} = 1.5719\,\frac{Z_s}{H_u} \tag{3}$$

$$\frac{Z_t}{H_u} = K_3\left(\frac{Z_s}{H_u}\right)^2 + K_4\,\frac{Z_s}{H_u} \tag{4}$$

Table 1 Calculation of *K* values to calculate the maximum scour depth and scour depth in the weir toe

Row	*R/h*	K_1	K_2	K_3	K_4
1	0	-16.616	27.290	0.0964	0.1514
2	1.5	-52.473	38.565	0.1484	-0.396
3	2	-50.644	36.632	0.1594	-0.325

5. Conclusion

The presence of jumps in the weir outlet keys of the C-type trapezoidal piano key weirs has increased the maximum amount of scouring depth, but it causes the maximum scouring depth to move away from the weir toe and reduces the scouring of the weir toe. In the jump weir with a larger jump radius, the distance of the maximum scour depth is far away from the weir toe and the amount of weir scour is less. The average value of the maximum scour depth in weirs with a jump radius of 0.21 and 0.15 m is 27 and 19% higher than the weir without a jump. Also, the average value of the maximum scour depth compared to the weir toe in weirs with jumps with a jump radius of 0.21 and 0.15 m compared to the weir without a jump is 29.4 and 19.5% less, respectively, and the average amount of scour to the weir in them, respectively, it is about 42 and 25.6% less. Jump increases scouring index. Also, the presence of a jump with a higher edge height and radius reduces the discharge coefficient.

6. References

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