

Effect of Blocks on Tunnel Structures on Local Scour Downstream of Piano Key Weirs

Wadi Mohammed Wadi¹, Ali Khoshfetrat^{1*}, Musa Habib Jasim², Niloofar Salemi¹

¹ Department of Civil Engineering, Isf.C., Islamic Azad University, Isfahan, Iran.

² Department of Civil Engineering, Faculty of Engineering, University of Karbala, Karbala, Iraq.

ABSTRACT

The piano key weirs are a novel type of non-linear, labyrinth weir. The high discharge efficiency of these structures, however, necessitates an investigation of the resulting local scour and the development of effective countermeasures. In the present study, blocks with different geometries were installed in the tunneled outlet keys of a type B rectangular piano key weir. The weir model was 0.20 m high and consisted of three cycles (three outlet keys, two inlet keys, and two inlet half-keys). Blocks with rectangular, trapezoidal, and cylindrical cross-sections were placed in each outlet key of the weir, specifically on the tunnel structure. This tunnel structure prevented the mixing of flows exiting the inlet and outlet keys. The blocks redirected the flow and shifted the location of maximum scour depth further from the weir toe; they also acted as a barrier, reducing the velocity of the outflow from the keys. Positioning the maximum scour depth farther from the weir toe reduces the risk of weir overturning. Among the configurations tested, the rectangular blocks resulted in the greatest reduction in maximum scour depth and placed the scour hole farthest from the weir toe. Additionally, the maximum scour depth was found to increase with higher particle Froude numbers, higher flow rates, and lower downstream depths. In the present study, the densimetric Froude number ranged from 0.43 to 0.55. Finally, dimensional analysis was employed to develop an empirical relationship for predicting the maximum scour depth.

KEYWORDS

Output keys, Scour index, Rectangular, Type B, Different block geometry.

1. Introduction

Piano key weirs (PKWs) are a novel type of non-linear weir that offers a higher flow capacity than conventional weir designs. Consequently, numerous studies have investigated the factors influencing local scour downstream of these structures. Research has primarily focused on three areas: the effects of hydraulic parameters (such as flow rate), the characteristics of the bed material (specifically particle diameter), and the geometric configuration of the weir itself. More recently, investigations have explored the use of additional structural elements to mitigate scour. For instance, Rdhaiwi et al. (2023), Fathi et al. (2024), Abdi-Chooplou et al. (2024), Mshali et al. (2024), and

Fathi et al. (2025) examined the effectiveness of aprons, steps, baffles, flow splitters, and hydraulic jumps in type A and C piano key weirs [1-5]. Their findings indicate that aprons effectively reduce the maximum scour depth by dissipating the energy of the jets issuing from the weir's inlet and outlet keys. Similarly, incorporating steps or fixed-geometry baffles within the outlet keys was found to decrease flow velocity and weaken vortex formation, thereby reducing scour. The inclusion of a hydraulic jump in the outlet keys serves a different purpose: it projects the falling jet further downstream, shifting the point of maximum scour away from the weir toe and reducing the risk of structural undermining. Finally, the use of flow splitters, while reducing the effective crest length, also directs the flow further

* Responsible author: ali.khoshfetrat@iau.ac.ir

downstream, resulting in a shallower scour hole located at a safer distance from the weir. The present study introduces, for the first time, the use of various block geometries—specifically rectangular, trapezoidal, and cylindrical cubes—installed on the tunnel structure within the outlet keys of a type B rectangular piano key weir. The experimental investigation was conducted under varying hydraulic conditions, including three flow rates and three tailwater depths, using a gravel bed. The tunnel structure geometry remained constant throughout the experiments to isolate the effect of the block shapes on scour dynamics.

2. Dimensional analysis

Equation (1) presents the parameters influencing local scour downstream of a type B rectangular piano key weir equipped with various block geometries on the tunnel structure within its outlet keys. In Eq. (1), Z_s represents the maximum scour depth, X_s denotes the distance of the maximum scour depth from the weir toe, E_1 is the specific energy of the upstream flow, Er is the relative energy, Fr_d is the densimetric Froude number, and "Type" refers to the configuration of the weir: simple weir, tunnel weir, or weirs with blocks on the tunnel structure.

$$\left(\frac{Z_s}{E_1}, \frac{X_s}{E_1}\right) = f(Er, Fr_d, Type) \quad (1)$$

3. Materials and methods

The experiments were conducted in a rectangular flume measuring 10 m long, 0.8 m wide, and 1.0 m high, with a zero slope. Three flow rates were tested: 0.030, 0.035, and 0.040 m³/s. Three ultrasonic sensors, connected to the PLC, measured the water depths: the first sensor was located upstream at a distance of $4P$ from the weir centerline, the second sensor was downstream at a distance of $10P$ from the weir centerline, and the third sensor measured the flow depth directly on the weir crest. Three tailwater depths of 0.05, 0.10, and 0.15 m were established using an adjustable end valve. Additionally, the combination of maximum discharge and minimum tailwater depth was chosen to prevent scour from reaching the flume bottom. A natural gravel bed material was used for all experiments. The material had a mean particle diameter (d_{50}) of 0.0075 m and a uniformity coefficient of 1.19. To determine the time required to reach equilibrium scour conditions, a preliminary 16-hour test was conducted under the most erosive conditions (maximum discharge, minimum tailwater depth, and without any blocks or tunnel structures).

It was observed that changes in the scour hole after 9000 seconds (2.5 hours) were less than 0.001 m; therefore, this duration was considered sufficient for reaching equilibrium in subsequent tests. A type B rectangular piano key weir with a height (P) of 0.20 m was used in this study. The weir had a thickness of 0.01 m. The key dimensions were as follows: inlet and outlet key widths (W_i and W_o) of 0.145 m, wall length (B^*) of 0.40 m, and upstream overhang length (B_i) of 0.13 m. The total crest length (L) was 27.3 m. A tunnel structure was installed within the outlet keys. This consisted of a rectangular sheet, 0.30 m long and 0.145 m wide, placed parallel to the weir floor at a distance of 0.04 m from the bottom of the outlet keys. The distance from the beginning of the outlet keys to the leading edge of the tunnel structure (a) was 0.15 m. The position of the tunnel was optimized through trial and error to prevent flow reversal toward the upstream side. Blocks (baffles) of various geometries were installed on the tunnel structure within the outlet keys. Three block shapes were tested: rectangular, trapezoidal, and cylindrical. After each test, once equilibrium was reached, the pump was turned off and the flume was drained. The resulting scour hole topography was then measured using a laser meter on a 0.03 m × 0.03 m grid. These measurements were used to determine the maximum scour depth (Z_s) and its corresponding distance from the weir toe (X_s). A total of 45 experiments were conducted. This included 18 tests for control configurations (simple weirs and weirs with the tunnel structure but no blocks) and 27 tests for weirs with blocks installed on the tunnel structure.

4. Results and discussion

Flow from the weir inlet keys is transferred downstream as a free jet, while flow exiting the outlet keys descends as an inclined jet. These flows converge at the entrance to the outlet keys, where a local submerged zone with a higher flow depth is created. This zone generates a powerful vortex that propagates downstream and impinges on the bed. Due to its high velocity, this vortex readily entrains and transports bed material. To mitigate this, a tunnel structure was installed within the outlet keys. Its primary purpose was to prevent the mixing of the outflow from the outlet keys with the flow entering from the inlet keys. By preventing this mixing, lateral surface vortices are eliminated, resulting in reduced sediment transport downstream. Consequently, the outflow from the outlet keys and the flow exiting the tunnel structure are conveyed downstream separately. Importantly, the outflow from the tunnel structure discharges further from the weir toe, thereby reducing the risk of weir

overturning. The results indicate that both the maximum scour depth and its distance from the weir toe increase with an increasing densimetric Froude number. As the unit discharge increases, the velocity of the falling and inclined jets downstream of the weir also increases, intensifying flow turbulence. Conversely, increasing the tailwater depth reduces scour. As downstream depth increases, the flow downstream of the weir mixes with the outflow, reducing its velocity. This decrease in flow velocity lowers the shear stress on the bed, and scour development continues only until a critical equilibrium is reached. Furthermore, with greater tailwater depth, the propagation length of the jets impinging on the bed increases. As this propagation length increases and the eddies and jets become shallower, the maximum scour depth decreases, the scour hole becomes more elongated, and the hydraulic jump weakens, eventually becoming submerged. Consequently, the volume of the scour hole decreases, and its location shifts further from the weir toe. The inclusion of the tunnel structure and blocks within the outlet keys consistently reduced the maximum scour depth and resulted in a shallower longitudinal bed profile. This occurs because these features reduce the outflow velocity over the tunnel structure, thereby diminishing the strength of turbulence and eddies downstream of the weir. Additionally, by preventing flow mixing, the downstream jets become shallower, increasing their propagation length and producing a longer, shallower scour hole. The blocks themselves also generate a hydraulic jump on the tunnel structure, which projects the falling jets further downstream while reducing their erosive power. Compared to a simple weir (N), the average reduction in maximum scour depth was 10% for the tunnel weir (NT), 14.8% for the weir with rectangular blocks (R), 13.2% for the weir with trapezoidal blocks (T), and 11.8% for the weir with cylindrical blocks (C). The superior performance of the rectangular blocks is attributed to the formation of additional vortices and hydraulic jumps immediately behind these blocks, which further dissipate flow energy. Eq. (2) is proposed for estimating the maximum scour depth. The equation yields a correlation coefficient of 98.8% and was developed using 75% of the experimental data, with the remaining 25% reserved for calibration. In this equation, the coefficients K_1 , K_2 , and K_3 are dimensionless parameters that depend on the weir type; their values are presented in Table 1.

$$\frac{Z_s}{E_1} = K_1 (Fr_d^{K_2} Er^{(K_3 Fr_d)}) \quad (2)$$

Table 1 The K coefficient values for calculating maximum scour depth

Row	Type	K_1	K_2	K_3
1	N	1/18	1/0.7	0/0.1
2	NT	1/14	1/1.8	0/0.1
3	R	1/57	1/6.5	0/0.2
4	C	1/62	1/6.9	0/0.2
5	T	1/61	1/7.7	0/0.2

5. Conclusion

The tunnel structure alone reduced the maximum scour depth by approximately 10% compared to a simple weir. However, due to the absence of a downstream overhang in the Type B weir, the outflow from the inlet keys remained close to the weir toe, exacerbating scour in this region. The inclusion of blocks on the tunnel structure elongated the scour hole and shifted the location of maximum scour depth further downstream, thereby reducing the risk of structural undermining. Among the geometries tested, rectangular blocks were the most effective, producing the greatest reduction in scour depth and the greatest shift in its location. Overall, the combination of the tunnel structure and rectangular blocks yielded the lowest scour depths, indicating superior hydraulic performance in mitigating local scour downstream of the weir.

6. References

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