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Effects of Channel Bed Slope on Energy Dissipation of Different Types of Piano Key Weir

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Abstract**—**The present investigation aims to study the effect of channel bed slopes on energy dissipation across the different types of Piano Key Weir (PK weir or PKW) under the free-flow conditions in rigid rectangular channels. To this end, three different types (type-A, type-B, and type-C) of PKW models were tested and examined. To document and quantify this experimental investigation, a total of 270 tests were performed, including detailed observations of the flow field. The results show that the energy dissipation of all PKW models increases with the bed slopes and decreases with increasing the discharge over the weirs. In addition, the energy dissipation over the PKW varies significantly with the geometry of the weir. The type-A PKW has shown the highest energy dissipation than the other PKWs. As the bottom slope changed from S_b = 0% to 1.25%, the energy dissipation increased by about 8.5%, 9.1%, and 10.55% for type-A, type-B, and type-C, respectively.

Keywords**—**Piano key weir, bed slope, energy dissipation across PKW, free overfalls**.**

I. INTRODUCTION

In recent years, drop structures and stepped spillways have been the most common hydraulic structures used in irrigation channel systems, water distribution networks, and waste collection networks. They function as grade control structures required to control channel degradation [1]. According to [2], stepped spillways are increasingly being used to handle flood releases from large dams associated with hydropower plants. The free overfall is crucial in hydraulic engineering because it serves as the starting point for computations of the water surface in a gradually varied flow (such as discharge spills into a reservoir at the downstream end). It is also vital to study free overfall because it can be used as a simple discharge measuring device. Numerous theoretical and experimental studies on the channel free overfall have been conducted to establish a relationship between the brink depth and the upstream flow depth [1], [3]-[5]. Moreover, [3] investigated the prediction of energy dissipation of flow over stepped spillways using data-driven models and depicted that drop number, the ratio of critical depth to the height of steps, and Froude number are the most influential parameters to consider the energy dissipation. Recently, [4] examined the effects of weir geometry on scouring development downstream of PKW. The energy dissipation on stepped spillway with PKW was performed by [5]. They found that the energy dissipation enhances with steps. In the last decade many studies related to the PKW efficiency and the downstream component were presented by researchers [6]**-**[9]. Furthermore, the weir structure aids in forming the hydraulic jump, its location (including its length, which is determined by the slope of the downstream apron), and energy dissipation downstream of the weir [10]. The effect of channel bed slope on flow energy dissipation for single-step Broad–Crested weir was studied experimentally under free-flow conditions. Five weir models were manufactured and tested [11]. The uniform rough stepped spillways are more efficient than the discrete rough stepped spillways in energy dissipation [12]. The fluctuating pressure field on the steps is essential and must be assessed. Reference [13] presented the energy dissipation of flow over the triangular and trapezoidal labyrinth weirs with one and two key cycles of labyrinth weirs. The hydraulic performance of the weirs depends on the nappe geometry and aeration conditions [14], [15]. For PKW, the flow over the sideways and downstream inlet key crests forms a continuous curtain with a contained air pocket, i.e., a nappe. The energy over the PKW is mainly affected by the air pocket contained over the crest [16], [17].

Many researchers have examined the channel bed slope effects on the energy dissipation over the broad crested weir [18], [11], [19]. They all noticed that higher channel bed slopes result in more energy dissipation. Thus, the effect of the channel slope plays a significant role in the discharge carrying capacity and energy dissipation across the hydraulic structures. At higher channel bed slopes, the probability of the critical section at the outlet crest increases in order to reduce heads. This is unfavorable, so avoid it at all costs. No significant changes were observed during the investigation at higher heads or lower bottom slopes. The channel slope is critical in determining the relationship between the end depth and the discharge over the weir. It also clearly shows the consistent nappe appearances downstream of the weir.

This study presents the effects of channel bed slope on energy dissipation over the different types (type-A, type-B, and type-C) of PKWs (see Fig. 1). In order to perform the energy dissipation across the PKW, three different types of PKW were examined and assessed. The test of the present study was conducted in the rectangular channel flume, so this study is primarily applicable in the flow regulating and channel flow approaches.

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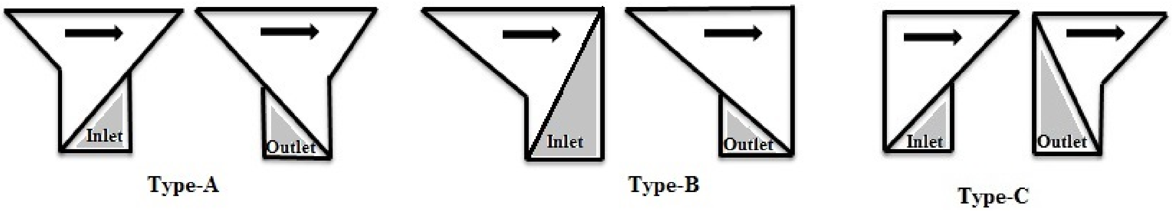


Fig. 1 PK weir Types [type-A, type-B and type-C] (Adapted from [20])

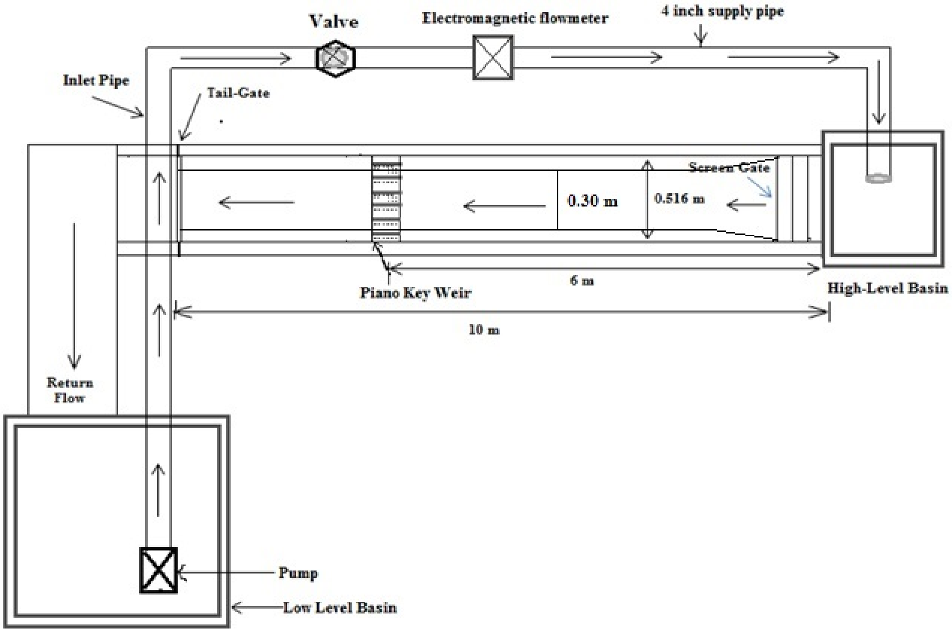


Fig. 2 Schematic plan view of the experimental setup

II. Experimental Setup

The experiments of this study were performed in tilting flume dimensions (10 m x 0.516 m x 0.6 m) in the "Fluid Mechanics and Hydraulics Research Laboratory" at Delhi Technological University, Delhi. During the investigation, the testing section was reduced to 0.30 m. The water was supplied by a 20 Horse Power (HP) pump connected to a series of 4-inch supply pipes, has a flow regulating valve to control the discharge, delivers predictive discharges of up to 50 L/s, and was calibrated using an orifice meter on the flume supply line (0.25% uncertainty). In order to reduce surface disturbance and cross currents, three honeycomb grid walls, a series of flow straighteners, and a wave suppressor were installed upstream of the flume, and water enters the flume via the head tank. The Plexiglas plate sheet has furnished both sidewalls of the flume up to 6.5 m for an incredible assessment of flow patterns throughout the entire channel height. In order to the head measurement, a 4-20 mA ultrasonic level sensor (accuracy ± 0.2%) and a pointer gauge of most minor count (± 0.1 mm) is furnished for measuring the head. The discharge was measured using 4-20 mA electromagnetic flowmeters (accuracy ± 0.2%) (see Fig. 2). The mean flow velocities were measured using an ADV (Acoustic Doppler Velocimeter).

III. Methodology and Model Fabrication

The effect of channel bed slope on energy dissipation downstream of PK weirs was studied by considering the six-channel bed slopes under free-flow conditions. The energy over the PKW is calculated under free-flow conditions, as follows;

$$E_i = P_i + h_{ti}\cos\theta + \frac{{V_{ti}}^2}{2g} \tag{1}$$

where E represents the specific energy at section i, P represents the height of the weir (m) (for downstream of the weir the P = 0 m), h_t represents the head at section i, V_t is the velocity at section i, and i represents the section (i.e., i = 1, 2.). Sections 1 and 2 were considered upstream and downstream sides of the PKW, respectively, as shown in Fig. 3.

The values of E_1 and E_2 were used to compute the relative energy loss ($\Delta E/E_1$) based on (2):

$$\frac{\Delta E}{E_1} = \frac{(E_1 - E_2)}{E_1} \times 100 = \left(1 - \frac{E_2}{E_1}\right) \times 100 \tag{2}$$

In the case of the present study, all the models were fabricated using an 8 mm thick transparent acrylic sheet and affixed with the help of chloroform. The models' configurations are as follows: the relative width ratio (W_i/W_o) is 1.28. The L/W ratio is 6, the height of all models (P) is 0.185 m. The inlet-outlet key slopes are 45^0 ($S_i = S_o = 1$) for Type-A, $S_i = 1$, & $S_o = 0.37$ for Type-B, and $S_i = 1$, & $S_o = 3.2$ for Type-C. The two overhang portions are such that $B_i = B_o$, are alike for Type-A, whereas $B_i = 0$, $B_o = 2/3\ B_b$, for Type-B, and $B_i = 2/3\ B_b$, $B_o = 0$, for Type-C (see Table I). The testing discharges over the model were varied between $0.005\ \text{m}^3/\text{s} \le Q \le 0.050\ \text{m}^3/\text{s}$. The other relative parametric variations associated with the testing are $0.097 \le H_t/P \le 0.94$, $0.018\ \text{m} \le H_t \le 0.174\ \text{m}$. and $0.28 \le \{B_i/P = B_o/P\} \le 1.6$.

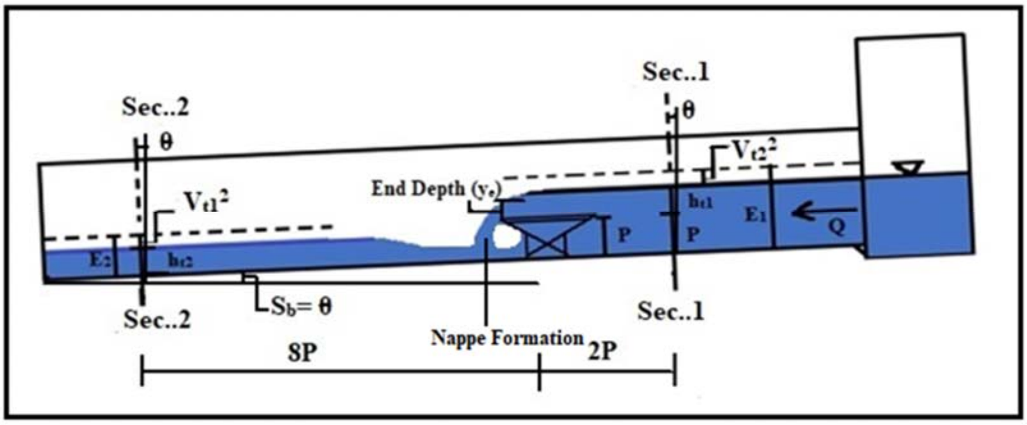


Fig. 3 Schematic plot for specific energy measurement

TABLE I
RANGES OF DATA COLLECTED IN THE PRESENT STUDY

Model No.	Range of Q (m³/s)	Range of H_t (m)	$\frac{W_i}{W_o}$	W_i (m)	W_o (m)	P (m)	$\frac{L}{W}$	B (m)	B_i (m)	B_o (m)	Range of $\left(\frac{\Delta E}{E_1}\right)$	N (No. of cycles)	No. of runs
PKW-A	0.005-0.50	0.0180-0.169	1.28	0.088	0.069	0.185	6	0.427	0.142	0.142	0.855-0.1745	3	90 (15 run @ per bed slope)
PKW-B	0.005-0.50	0.0181-0.167	1.28	0.088	0.069	0.185	6	0.427	0	0.284	0.825-0.1366	3	90(15 run @ per bed slope)
PKW-C	0.005-0.50	0.0183-0.174	1.28	0.088	0.069	0.185	6	0.322	0.214	0.139	0.8056-0.1414	3	90(15 run @ per bed slope)

IV.RESULTS AND DISCUSSIONS

The flow behavior over the PKW is highly ventilated and three-dimensional, with splash and spray regions within the outlet keys and at the structure's base [20]. The spray and splash region only marginally increased proportionally to H_t and planar jet trajectory departing from the downstream-most extents of the weir crest (see Fig. 4). The geometry of the PKW has influenced the flow behavior of the weir. However, the aeration region significantly increased with H_t due to increased local velocity resulting in higher vorticity levels and turbulent mixing [9]. The present investigation aims to study the effect of bed slopes on energy dissipation across the PKWs under the free-flow conditions in rectangular horizontal channels. To this end, three different types of PKW models were built, tested, and analyzed.

In order to compute and document the practical analysis of the channel bed slope, the 90 tests comprising each model and a total of 270 tests have been conducted on three different types of PKW models along with six different bed slopes (S_b = 0%, 0.25%, 0.5%, 0.75%, 1.0%, and 1.25%). The results demonstrated that the energy dissipation across the various PKWs increased with increasing channel bed slope; however, it decreased as the discharge over the weir increased.

As literature said, the energy dissipation across the hydraulic structures depends on the fluid and geometrical parameters. The geometry of the PKW configurations highly influenced the energy dissipation over the weir [21]. In the present study, it was seen that the geometry and discharge/head over the weir significantly affect the dissipation efficiency of the weir. The L/W proportion is the most significant factor influencing PKW discharge capacity. With certain H_t/P ratios, the W_i of the inlet key width can become more vital than the L/W when normalizing the hydraulic head (H_t) with the PKW height (P). It reveals that the PKW's vertical and horizontal shapes (P/W_i) ratio is also an essential key design parameter. In general, hydraulic efficiency increases with an increasing L/W ratio. So it is vital to know the effects of the L/W ratio on energy dissipation.

The results demonstrated that more energy dissipation corresponds to the low flow depths for all the bed slopes, and for higher flow depths, the PKW is less effective in dissipating energy corresponding to all the bed slopes. A slight change in H_t/P results in a comparatively notable difference in relative energy loss when H_t/P is less than 0.25. The relative energy dissipation [$\Delta E/E_1$] rate decreases steadily as H_t/P increases. Fig. 5 shows that the relative energy dissipation [$\Delta E/E_1$] has a nonlinear trend and is inversely proportional to H_t/P. From these results, it is clear that, as the slope of the channel bed increases, the energy dissipation over the weir increases (see Fig. 5).

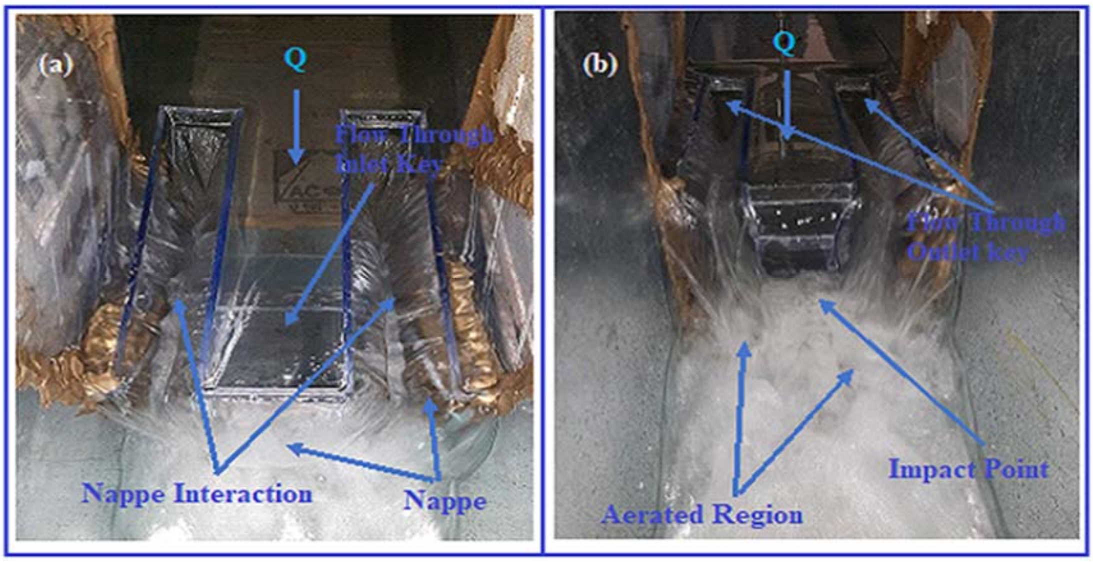
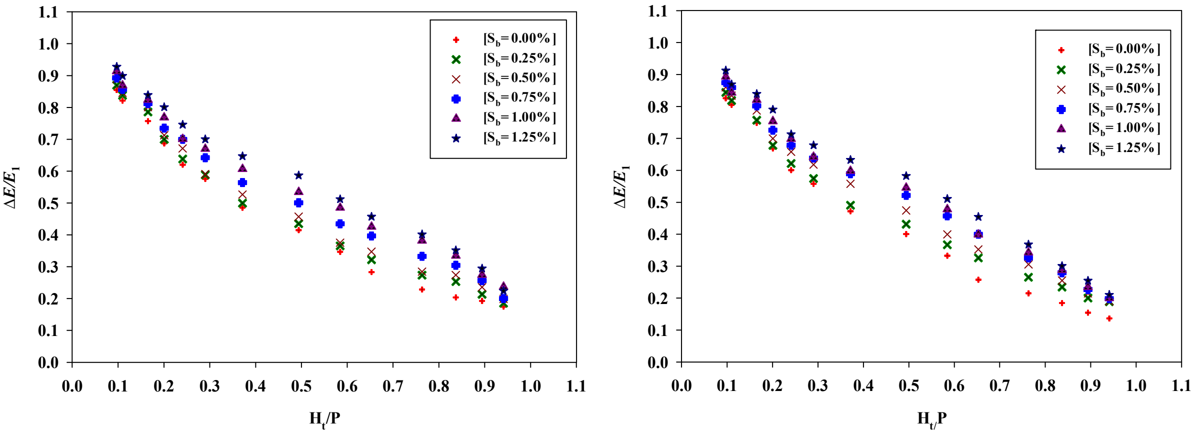
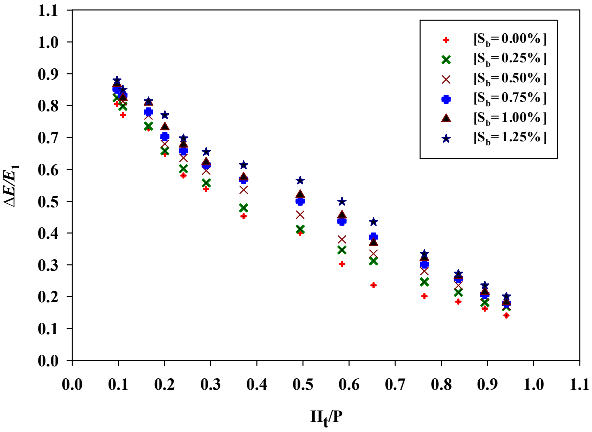


Fig. 4 Flow pattern over PKW



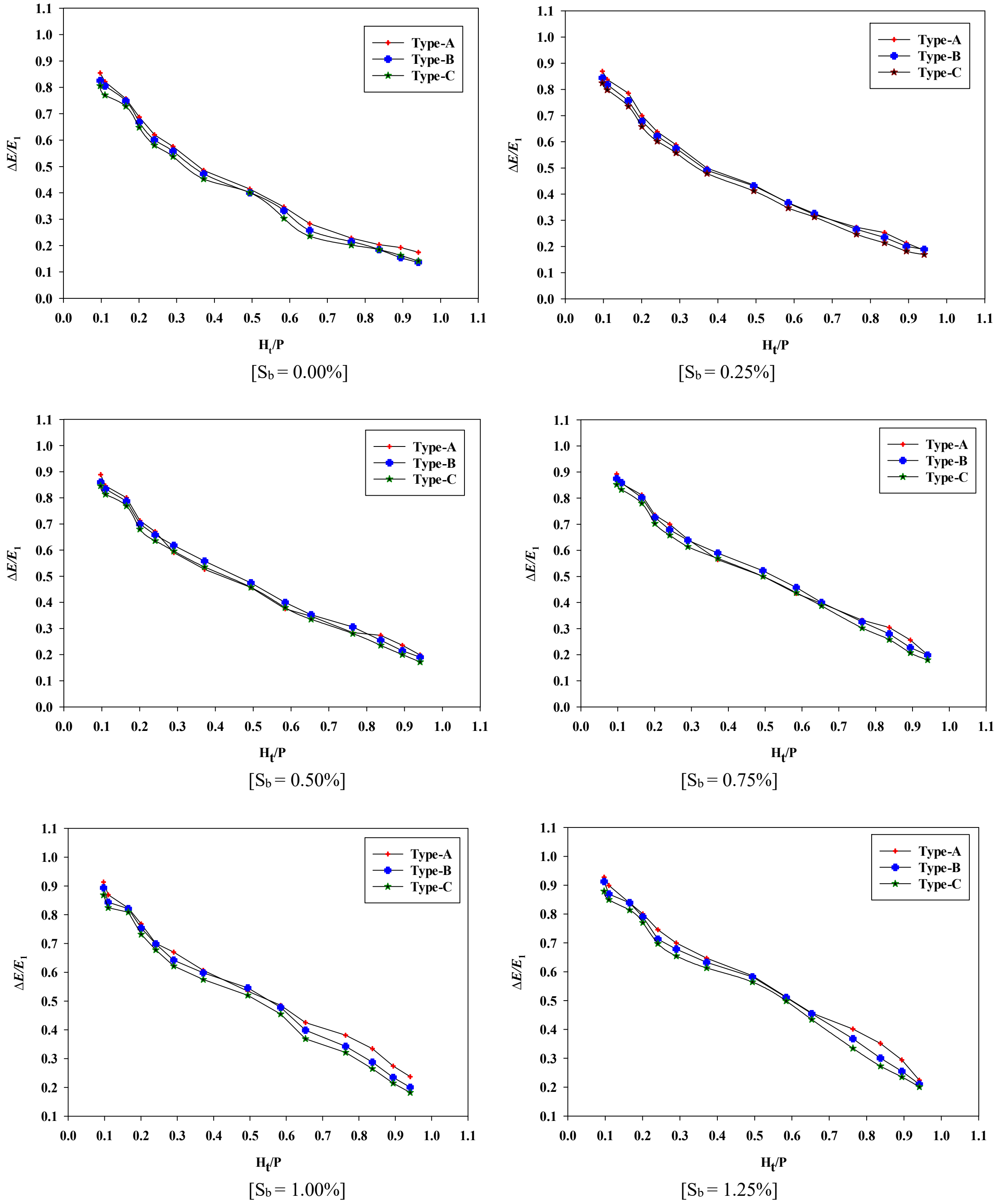
(a) Type-A

(b) Type-B



(c) Type-C

Fig. 5 Variation of the relative energy dissipation ($\Delta E/E_1$) with head to weir height (H_t/P) ratio: (a) Type-A (b) Type-B, and (c) Type-C PKWs



[S_b = 0.00%] [S_b = 0.25%]

[S_b = 0.50%] [S_b = 0.75%]

[S_b = 1.00%] [S_b = 1.25%]

Fig. 6 Comparison of the energy dissipation curves of various PKWs models with different channel bed slopes

Fig. 6 shows that the maximum energy dissipation was observed at approximately 85%, 82%, and 80.5% for type-A, type-B & type-C, respectively, at the horizontal bed (S_b = 0.0). And for the maximum bed slope S_b = 1.25%, the energy dissipation has increased (approximately) 92%, 91%, and 87%, respectively. That is enhanced by about 8.5%, 9.1%, and 10.55% for type-A, type-B, and type-C, respectively. So, it can be concluded that as the slope of the channel bed increases, the relative energy dissipation increases, which may help in the design of energy-dissipative structures, and to reduce the downstream scour, the length of hydraulic jump and apron length for the weir, etc. [22]. Therefore, accurately predicting the relative or residual energy downstream of a PKW is crucial in designing energy-dissipative structures.

Fig. 6 concludes that the overall energy dissipation performance of the type-C PKW is lesser than the type-B. Type-

A has 3.6% more energy dissipation than type-B and 5.6% more than type-C for almost all the discharges at horizontal or zero bed slopes. The type-A PKW has shown an approximately similar energy dissipation to type-B but 5.77% higher than the type-C at maximum channel bed slope. The type-A and type-B PKW models have upstream overhang portions that reduce the formation of the free jet. As a result, free jet falls on the downstream or outlet inclined key bottoms that reduce the velocity of the flowing fluid.

V. CONCLUSIONS

Within the limits of the experimental data of the current study, the following main conclusions can be made:

1. The channel slope affected the energy dissipation across the PKW significantly. As the channel bed slope increases, the energy dissipation over the PKW increases for all the model's cases.
2. A marginal change in H_t/P results in a relatively significant difference in relative energy dissipation when H_t/P is less than 0.18. The rate of $[\Delta E/E_1]$ relative energy dissipation steadily decreases as H_t/P increases. There were about 8.5%, 9.1%, and 10.55% gain in energy dissipation for type-A, type-B, and type-C, respectively, as the bottom slope changed from $S_b = 0\,\%$ to $S_b = 1.25\%$.
3. During the investigation, it was noticed that the geometry of the PKW significantly influenced the energy dissipation across the PKW. With certain H_t/P ratios, the W_i of the inlet key width can become more vital than the L/W when normalizing the hydraulic head (H_t) with the PKW height (P).

NOTATIONS

B	Length of side weir $(B_i + B_b + B_o)$
B_b	Base length
B_i	Length of overhang portions at the inlet side
B_o	Length of overhang portions at the outlet side
E	Specific energy at section' i'
ΔE	Relative energy dissipation
g	Acceleration of gravity
H_t	Total energy head
h_t,	Piezometric head
i	Section
L	Total developed crest length
N	Number of cycles
P	PKW height
Q	Discharge over the PKW
S_i	Inlet key slope
S_o	Outlet key slope
V_t	Mean flow velocity
$V_t^2/2g$	Approach velocity head
W	Channel width/width of PKW
W_i	Inlet key width
W_o	Outlet key width

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