



Effect of canal bed slope on the working efficiency of water energy dissipaters downstream control structures

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Abstract

The design of open irrigation channels typically includes a bed slope to achieve the desired hydraulic performance, governing key parameters such as velocity, water depth, and discharge. Diversion head structures, often constructed across these channels, raise upstream water levels, generating potential energy that converts into high-velocity kinetic energy downstream. Previous research has studied the type and configuration of water energy dissipaters, considering most hydraulic parameters affecting their performance, except for canal bed slope. The current work aims to explore the extent to which canal bed slope affects the performance efficiency of water energy dissipaters behind head structures, ensuring their safety. The experiments utilized a tilting flume under controlled conditions at six different bed slopes (0.05% to 0.30%) in addition to a zero bed slope, with five discharge values ranging from 9.76 to 17.14 L/s. Through 150 experimental runs, all hydraulic parameters affecting the performance efficiency of the water energy dissipater (relative energy loss, hydraulic jump, sequent depth ratio, and jump length) are measured and recorded. The results clearly show that increasing the canal bed slope to 0.20% enhances the water energy dissipater's performance efficiency by 31.9%, reduces the jump length by 20% and lowers the sequent depth ratio ($\frac{y_2}{y_1}$) by 20%. The recommended relative dissipater location ($\frac{L_b}{b}$) of 5.83 is accurate for canals with slopes up to 0.20% but for steeper slopes, this ratio must be checked.

Keywords Water energy dissipation · Open channel · Bed slope · Head structures · Solid apron

1 Introduction

Diversion head structures are critical in open irrigation canal water management. These structures control flow direction, velocity, water levels, and volumes under different canal elevations, which are basic performance indicators of irrigation systems. These elements of diversion head structures should be protected from hydraulic risks that could undermine their safe operation. Hydraulic hazards are usually the greatest source of danger even with adequate structure.

Kinetic energy is produced due to the high-velocity water flow as it transitions from upstream to downstream sections of the diversion head structure. If the kinetic energy is not mitigated, it can lead to erosion and failure of the structure. Therefore, their sufficient energy dissipation is extremely important for the structure's longevity and safe operation Zabaleta et al. (2022a, b; Meshkati et al. (2025).

To mitigate this issue, designers typically add a solid apron behind the head structure and energy dissipaters to create turbulent flow and dissipate flow energy. Hydraulic jumps, natural formations that occur when supercritical flow becomes subcritical, can dissipate up to 60% of flow energy. Engineers use design enhancements to dissipate additional energy by including structural institutions that roughen the bed surface and incite additional turbulence (Shearin-Feimster 2016; Babaali et al. 2019). The most significant parameters that can influence the performance of an energy dissipater is the canal bed slope. Flow velocity can be affected by bed slope and turbulence intensity which can affect the energy dissipation capability of devices (Abdel-Mageed 2015). Thus, an understanding of the relationship

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between bed slope and energy dissipation mechanisms is important in the design of viable and efficient canals. Laboratory studies and numerical simulations can help better understand the relationship and contribute to enhanced designs of hydraulic structures (Chanson 2009).

The aim of the present research is to experimentally investigate the influence of canal bed slope on the working efficiency of water energy dissipaters behind head structures. This study attempts to determine the optimum location for bed sills in the sloping channel, as well as the relationship between the efficiency of these dissipaters and the degree of slope of the canal bed.

The possible asked questions concerning the working efficiency of energy dissipater downstream control structures may be as follows: Does the canal bed slope have any impact on the working efficiency of the used water energy dissipater downstream control structures? And which canal bed slope gives the maximum possible impact on the dissipater performance efficiency? In the current study, these questions will be addressed.

The flowchart below in Fig. 1 illustrates the research process for evaluating the influence of bed slopes on the hydraulic performance of energy dissipater D.S. head structures in open canals. This flowchart represents a systematic experimental research methodology, emphasizing hydraulic efficiency as affected by structural and flow conditions. The methodology begins with data collection and an inspection, followed by a review of previous studies

to identify research gaps. Thereafter, two main questions are addressed: the impact of the canal bed slope and the dissipater location effect on performance efficiency. These ways form the basis for the experimental study and result in identifying these research gaps, which contribute to the experimental design and help determine the necessary parameters and the design criteria. These factors include the dissipater shape and scale, the slope range, the flow rate range, the gate opening height, and the location of the dissipater. This design stage is linked to the theoretical approach, and consequently, the basis for the experimental methodology is performed. The methodology then involves setting up the experiment by following specific procedural steps:

- Set discharge (Q) as the initial parameter.
- Adjust the bed slope to the desired angle.
- Stabilize flow conditions.
- Measure parameters during steady-state conditions.
- Change discharge and change canal slope for iterative testing.

This experimental loop allows for systematic variation of key parameters while maintaining controlled conditions. The flowchart culminates in results exploration, followed by analysis and discussion phases. Finally, the process leads to covered gaps and conclusions that complete the research cycle.

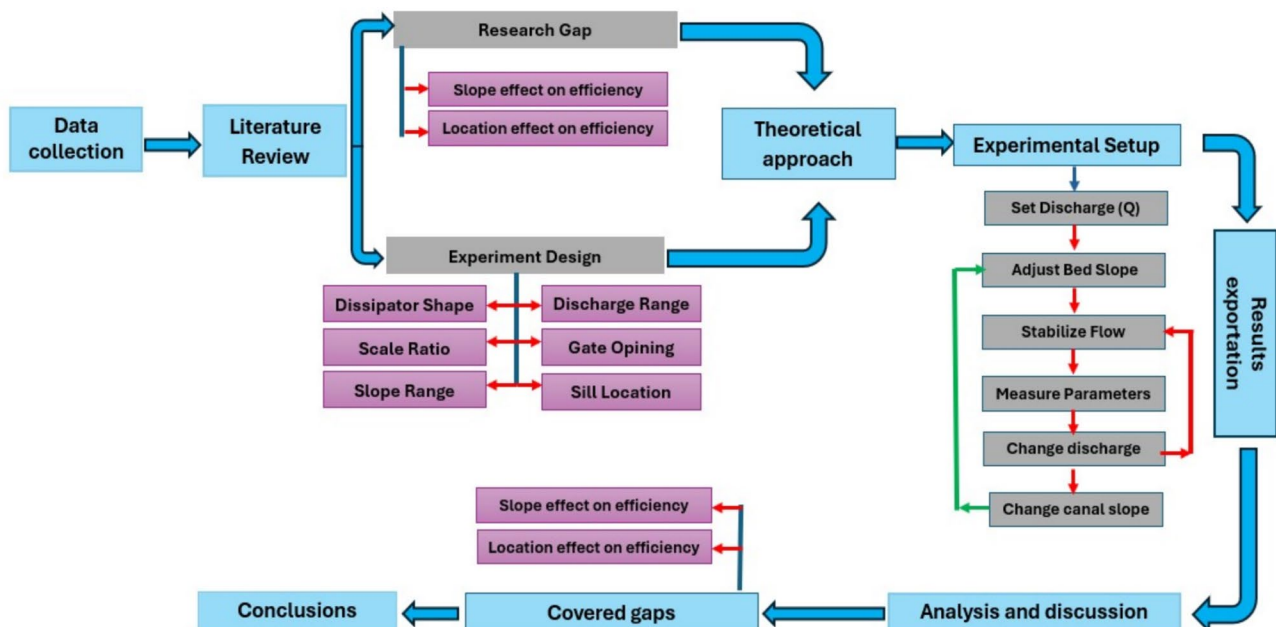


Fig. 1 The research process for testing the effect of canal bed slope on the working efficiency of energy dissipaters downstream of control structures

2 Literature review

The placement of energy dissipaters downstream of control structures increases bed roughness and promotes the rapid formation of hydraulic jumps, enhancing energy loss and protecting the head structure. The choice of dissipater type depends on several key factors: the volume of energy to be dissipated, erosion potential, the upstream Froude number (F_{e1}), available tail-water depth, and the properties of the bed and bank materials. As stated by the federal highway administration, the types of energy dissipaters can be classified into two broad categories: Hydraulic jump-type dissipaters and impact-type dissipaters. Hydraulic jump -type dissipaters dissipate energy by tensioning water over a turbulent roller generated during the jump. Impact-type dissipaters deflect water against an obstruction or plunge pool and create turbulence by redirection of the water. The methods of impact-type dissipaters can include check drops, vertical drops, baffled outlets, and baffled aprons. Impact-type dissipaters are often more economical for smaller hydraulic structures (FHWA 2006; Ashour et al. 2016).

This literature review is divided into two key sections: (1) a comparison of recent research on water energy dissipation in stilling basins, and (2) the effects of sloping channels on hydraulic jump characteristics and energy dissipation efficiency.

2.1 Comparative review of energy dissipater configurations

Numerous studies have examined different dissipater shapes and configurations positioned on the solid apron downstream of control structures. The goal is to determine which arrangements most effectively dissipate the kinetic energy resulting from elevated upstream water levels. Energy dissipation mechanisms include stilling basins fitted with sills, baffle blocks, stepped beds, or radial configurations. Modified Tables 1 and 2 summarize recent studies on the relative energy dissipation efficiency ($\Delta E/E_1$) of these configurations. In Table 1, the curved dissipater used by Ashour et al. (2016), with a curvature angle of 120° facing upstream, achieved the highest energy dissipation (60%). Gül et al. (2024) reported similar success (55%) using a comparable approach. In contrast, the straight dissipater design proposed by Wafaie (2001) showed the least efficiency.

Table 2 highlights that stepped or radial stilling basins can also be highly effective. Meshkati et al. (2012) demonstrated a relative energy dissipation of up to 90% using a positive step design. Kalateh et al. (2024) reported an 86% dissipation rate using pyramid sills arranged in lines.

While these results provide valuable design insights, it is important to note that all these studies are conducted

under horizontal channel conditions, limiting their applicability to real-world scenarios involving sloped canals.

2.2 Influence of sloping channels on hydraulic jump

Channel slope significantly impacts the behavior of hydraulic jumps, influencing parameters such as jump length, sequent depth, and energy dissipation. Mild slopes tend to enhance turbulence and promote effective energy dissipation, whereas steep slopes may reduce jump stability and energy loss. Thus, accounting for slope is critical when designing hydraulic structures to prevent downstream erosion and structural damage.

Recent studies have provided valuable insights into water energy dissipation in sloping channels. Gupta and Dwivedi (2024) found that while the sequent depth ratio (y_2/y_1) increases with slope, it decreases with surface roughness height. They also reported that relative jump length (L_j/y_1) decreases with both slope and roughness height, while energy loss increases. Similarly, Laishram et al. (2022) showed that sloped rough beds dissipate more energy and produce shorter jumps than horizontal ones. These features also improve structural safety and flow control. In a related study, Zabaleta et al. (2022a, b) conducted numerical modeling of stilling basins with apron slopes from 0% to 6.08%. They concluded that slopes around 3.04% offer the best trade-off between energy dissipation and hydraulic performance. Kateb et al. (2017) investigated hydraulic jumps in a sloped rectangular channel, testing five slopes (0%, 0.5%, 1%, 1.5%, and 2%). They discovered that for a consistent Froude number, the sequent depth ratio increases with the channel slope and developed empirical relationships that link the inflow Froude number to the sequent depth ratio and channel slope.

Moreover, Eltoukhy (2016) examined hydraulic jump characteristics in a rectangular open channel with varying bed slopes and a sill. Their study involved five bed slopes (1.75%, 3.49%, 5.24%, 6.99%, and 8.75%) and analyzed the impact of a sill at different heights and distances. Results showed that the sequent depth ratio (y_2/y_1) rises with increasing Froude numbers and channel bed slopes, while the relative jump length (L_j/y_2) increases with initial Froude numbers across all tested slopes. Cherhabil and Debabèche (2016) performed a theoretical and experimental study of hydraulic jumps in a sloped U-shaped channel, focusing on the D-jump configuration. They tested six positive slopes (0%, 1%, 2%, 3%, 4%, and 5%) and found that the final height of the hydraulic jump (y_2) increases with the channel slope for the same inflow Froude number. Abdel-Mageed (2015) further investigated the effects of channel slope on hydraulic jump characteristics, including sequent depth, jump length, and energy dissipation downstream of a sluice gate in rectangular channels with five positive bottom slopes (0.27%, 0.4%, 0.54%, 0.81%, and 1.1%). The results

Table 1 Relative energy dissipation ($\Delta E/E_1$) (case of stilling basins with sills or baffle blocks)

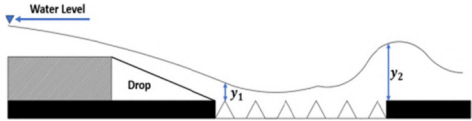
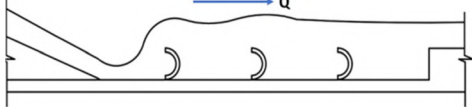
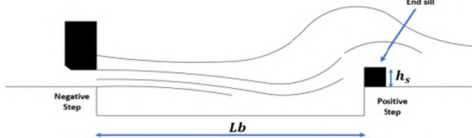
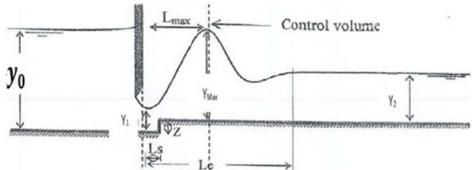
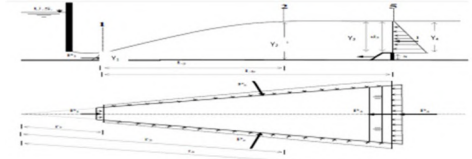
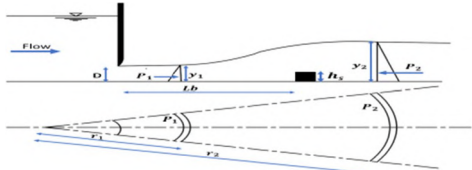
Author	Equation	Definition Sketch	Dissipater Shape	$\left(\frac{\Delta E}{E_1}\right)\%$
Gül et al. (2024)	$\frac{\Delta E}{E_1} = \frac{\left[y_1 + \frac{v_1^2}{2g}\right] - \left[y_2 + \frac{v_2^2}{2g}\right]}{\left[y_1 + \frac{v_1^2}{2g}\right]}$			55
Hamid and Mohammed (2023)	$\frac{\Delta E_2}{\Delta E_1} \% = \frac{22.615\left(\frac{y_2}{y_1}\right)^{-0.594} + 24.076\left(F_{e1}\right)^{-0.735} + 0.565\left(\frac{L_j}{y_1}\right)^{0.037}}{0.008\left(\frac{H_{up}}{y_1}\right)^{0.004} - 11.47\left(\frac{y_2}{y_1}\right)^{-0.742}}$			---
Abdelmonem et al. (2018)	$\frac{\Delta E}{E_1} = \frac{1}{8} \frac{\left(\sqrt{1+8F_{e1}^2}-3\right)^3}{(2+F_{e1}^2)\left(\sqrt{1+8F_{e1}^2}-1\right)}$			53
Ashour et al. (2016)	$\frac{\Delta E}{E_1} = A * \ln(F_{e1}) - B$			60
Kim et al. (2015)	$\frac{\Delta E}{E_1} = \frac{\left(-3 + \sqrt{1+8F_{e1}^2}\right)}{8\left(-1 + \sqrt{1+8F_{e1}^2}\right)\left(2+F_{e1}^2\right)}$			50
AA et al. (2012)	$\frac{\Delta E}{E_1} = 1 - \frac{\left(y_r + \frac{0.5F_{e1}[b/y_1]^2}{[b/y_1]^2 y_r^2 + 0.5[b/y_1]^2 y_r^3 + 0.0625 y_r^4}\right)}{(1+0.5F_{e1})}$			53
Wafaie (2001)	$\frac{\Delta E}{E_1} = (AE * Fe1) + (BE * Fe1) + CE$			39

indicated that relative energy loss, sequent depth ratio, relative jump length, and relative distance of the jump increase with higher bed slopes and approach Froude numbers, while jump length increases as slope decreases.

In a complementary study, Das et al. (2014) experimentally assessed energy dissipation in hydraulic jumps on inclined rectangular chutes with varying contraction degrees. Their experiments involved three chute slopes (10%, 12.5%, and 16.67%) and chute contractions ranging from 0° to 6°. They

concluded that energy dissipation decreases with increasing contraction but increases with slope. Finally, Jan and Chang (2009) studied hydraulic jump characteristics in inclined rectangular chute contractions, examining five different contracting angles of sidewalls (37.93°, 32.99°, 27.45°, 21.29°, and 14.56°) and three bed angles (10.90%, 19.47%, and 28.35%). They noted that inclined chute contractions result in significantly greater hydraulic jump heights and shorter jump lengths compared to horizontal rectangular channels.

Table 2 Relative energy dissipation ($\Delta E/E_1$) (case of stilling basins with steps or radial stilling basin)

Author	Equation	Definition Sketch	Dissipater Shape	$\left(\frac{\Delta E}{E_1}\right)\%$
Kalateh et al. (2024)	$\frac{\Delta E}{\Delta E_1} = 0.8013(F_{e1})^{-2.423} \times 0.801\left(\frac{y_c}{H}\right)^{-0.0325} \times (\theta)^{0.531}$			86
El-Saie et al. (2023)	$\frac{\Delta E}{E_1} = \frac{1}{8} \frac{(\sqrt{1+8F_{e1}^2}-3)^3}{(2+8F_{e1}^2)(\sqrt{1+8F_{e1}^2}-1)}$			63
MeshkatI et al. (2012)	$\frac{\Delta E}{E_1} = \frac{\left[\frac{v_0^2}{2g} + y_3\right] - \left[\frac{v_5^2}{2g} + y_5\right]}{\left[\frac{v_0^2}{2g} + y_3\right]}$			90
Habib (2012)	$\frac{\Delta E}{E_1} = 1 - \left[\frac{y_0^2(Z+y_0)(\beta+2C^{**})^2+0.5\beta F_{e1}^2}{y_0^2(1+0.5\beta F_{e1}^2)(\beta+2C^{**})^2} \right]$			75
Habib et al. (2003)	$\frac{\Delta E}{E_1} = \frac{r_0^2 y_0^2 (2+F_{e1}^2-2y_0)-F_{e1}^2}{r_0^2 y_0^2 (2+F_{e1}^2)}$			62
Rageh (1999)	$\frac{\Delta E}{E_1} = 1 - \left[\frac{F_{e1}+2r_0 y_0}{r_0 y_0 (F_{e1}+2)} \right]$			67

2.3 Synthesis and research gap

In conclusion of the literature review, it is clear that the previous investigations and studies demonstrate that the canal bed slope (S) plays an important role in affecting the hydraulic jump behavior, and accordingly the water energy dissipation. It is evident that an increase in canal bed slope corresponds with larger relative energy loss ($\Delta E/E_1$) and larger distances from jump formation (D_{jf}). But there is a conflict in the case of relative jump length (L_j/y_1), which increases with the canal bed slope (S) increase as recommended by (Abdel-Mageed 2015), while decreasing with the increase of the canal bed

slope (S) as recommended by (Gupta and Dwivedi 2024). Also, there is a conflict in the case of the initial and sequent depth of the hydraulic jump, where the sequent depth ratio (y_2/y_1) increases with the canal bed slope (S) increase as recommended by (Gupta and Dwivedi 2024; Kateb et al. 2017; Eltoukhy 2016; Abdel-Mageed 2015), the height of the jump (y_2-y_1) increases with the canal bed slope (S), as experimented by (Jan and Chang 2009), while (Zabaleta et al. 2022a, b) concluded that with increasing the canal bed slope (S), the sequent depth (y_2) decreases and the initial (y_1) is not very significant in the variation of the slope of the stilling basin. Because of these conflicting results, the present study

will investigate the effect of the bed slope of irrigation canals on the working efficiency of energy dissipaters downstream control structures using curved sill dissipaters.

Based on the literature review, the following main technical points can be concluded:

- There are notable conflicts among the results of various studies.
- There is a significant lack of research on how the hydraulic performance of different types of water energy dissipaters is affected by canal bed slope, as bed slope is a key parameter in designing open canals.
- While all studies confirm the effect of canal bed slope on hydraulic jump characteristics and formation, the influence of water energy dissipaters with different shapes, dimensions, and arrangements downstream of head structures also affects the formation and location of the hydraulic jump. Therefore, there is a great need to study all these parameters together (type of water energy dissipater, hydraulic jump, canal bed slope, and water energy dissipation).
- To address the above-mentioned research gap, the present study is conducted to clarify the extent to which canal bed slope affects the formed hydraulic jump and, consequently, the water energy dissipated.

3 Materials and methods

3.1 Involved technical parameters, and theoretical approach

In fact, numerous technical parameters affect the energy dissipation in downstream (D.S.) head structures. Understanding the theoretical implications of canal bed slope on the efficiency of energy dissipaters involves several key factors, including energy dissipation mechanisms. The primary mechanisms through which flowing water energy is dissipated include the hydraulic jump generated by the velocity influenced by the slope of the canal bed and the turbulence expected with steeper slopes. These factors enhance energy loss through friction and mixing. Additionally, flow velocity dynamics, where steeper slopes increase kinetic energy and alter velocity profiles, play a crucial role.

Other important considerations include erosion risks, as higher scouring and sediment transport can threaten structural integrity, and design considerations, where the geometry, sizing, and spacing of dissipaters, such as stilling basins, must align with slope-induced flow characteristics. Fluid dynamics modeling quantifies energy losses across slopes, enabling the optimization of design parameters. The interplay between slope and efficiency involves hydrodynamic principles, structural engineering, and empirical validation, necessitating a holistic

approach to optimize hydraulic performance and ensure effective energy dissipation in head and control structures (Table 3).

The various affecting parameters can be classified as follows:

1. **Fluid characteristics:** ρ the density of water (kg/m^3); μ the dynamic viscosity (kg/m.s); and g the gravitational acceleration (m/s^2).
2. **Flow characteristics:** y_1 the initial depth of the hydraulic jump (m); y_2 the sequent depth of the hydraulic jump (m); L_j the length jump (m); D_{jf} distance of the jump formation (m); h_j the height of the jump (m); q the discharge per unit width of the channel (m^2/s); and ΔE the dissipation energy in rectangular basin with curved sill dissipaters (m).
3. **Sill dissipater and channel geometry:** S bed slope (%); b_s length of the curved sill dissipater (m); h_s the height of the curved sill dissipater (m); L_b the location of the curved sill dissipater (m); D the gate opening (m); b the width of the channel (m); and hg the height of the tail gate (m).

The following Fig. 2 represents a schematic diagram of the experimental model used in this work.

The general relationship for the variables can be expressed as follows:

$$\Delta E = \varphi(\rho, \mu, g, D, y_1, y_2, D_{jf}, L_j, h_j, L_b, h_s, b, b_s, h_g, S, q) \quad (1)$$

Using Buckingham's π theorem with three repeating variables (ρ , μ , and y_1), Eq. (1) can be rewritten as:

$$\frac{\Delta E}{y_1} = \varphi\left(\frac{y_2}{y_1}, \frac{D}{y_1}, \frac{L_j}{y_1}, \frac{L_b}{y_1}, \frac{b}{y_1}, \frac{h_j}{y_1}, \frac{D_{jf}}{y_1}, \frac{b_s}{y_1}, \frac{h_g}{y_1}, \frac{h_s}{y_1}, S, \frac{v_1}{\sqrt{gy_1}}, \frac{\rho v_1 y_1}{\mu}\right) \quad (2)$$

where $\frac{v_1}{\sqrt{gy_1}} = F_{e1}$ (Froude number at upstream section) and $\frac{\rho v_1 y_1}{\mu} = \text{Re}$ (Reynolds number). In Eq. (2), temperature will be maintained constant during the experimental work, allowing us to neglect the effect of R_e , as viscosity has a negligible impact on hydraulic jump characteristics in this study. Additionally, the $\left(\frac{D}{y_1}, \frac{b}{y_1}, \frac{b_s}{y_1}, \frac{h_g}{y_1}, \frac{h_s}{y_1}\right)$ are constant. Thus, Eq. (2) simplified to the following dimensionless parameters:

Table 3 Independent and Dependent Variables in experimental

Independent Variables	Dependent Variables
$S(\%)$	$y_1(\text{m})$
$b_s(\text{m})$	$y_2(\text{m})$
$h_s(\text{m})$	$L_j(\text{m})$
$L_b(\text{m})$	$D_{jf}(\text{m})$
$D(\text{m})$	$h_j(\text{m})$
$b(\text{m})$	$\Delta E(\text{m})$
$hg(\text{m})$	

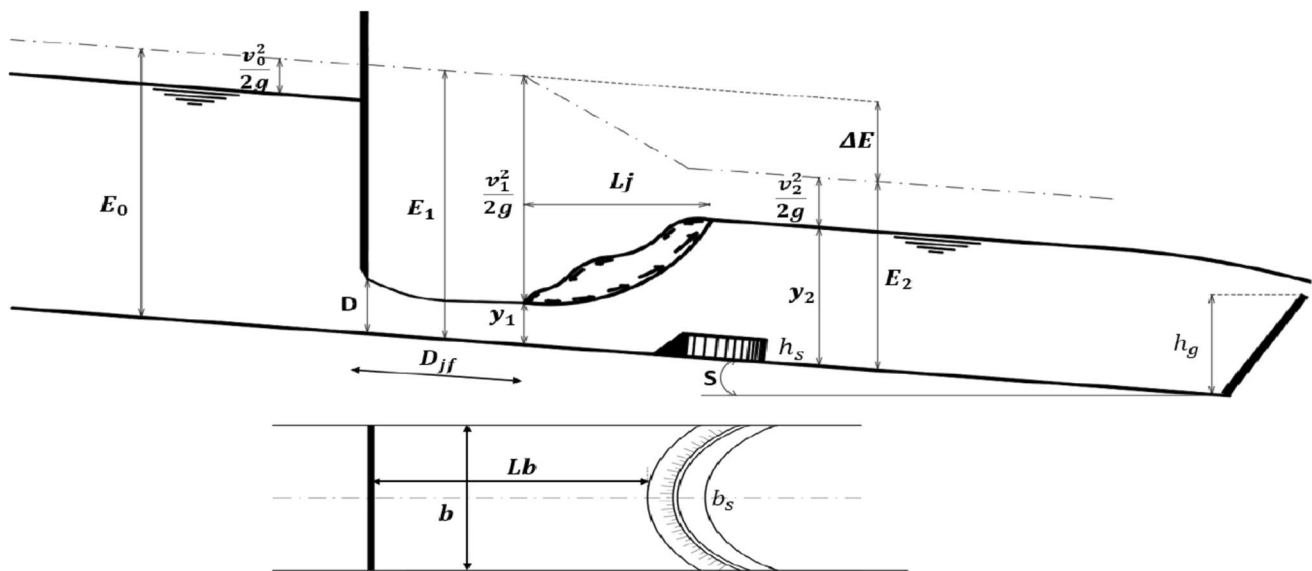


Fig. 2 Definition sketch of the experimental model

$$\frac{\Delta E}{y_1} = \varphi\left(\frac{y_2}{y_1}, \frac{L_j}{y_1}, \frac{L_b}{y_1}, \frac{h_j}{y_1}, \frac{D_{jf}}{y_1}, S, F_{e1}\right) \quad (3)$$

where: $\frac{\Delta E}{y_1}$: Relative energy loss, $\frac{y_2}{y_1}$: Relative depth of hydraulic jump, $\frac{L_j}{y_1}$: Relative length of hydraulic jump, $\frac{L_b}{y_1}$: Relative sill location, $\frac{h_j}{y_1}$: Relative height of the jump, $\frac{D_{jf}}{y_1}$: Relative jump location, S : Bed slope, and F_{e1} : Froude number.

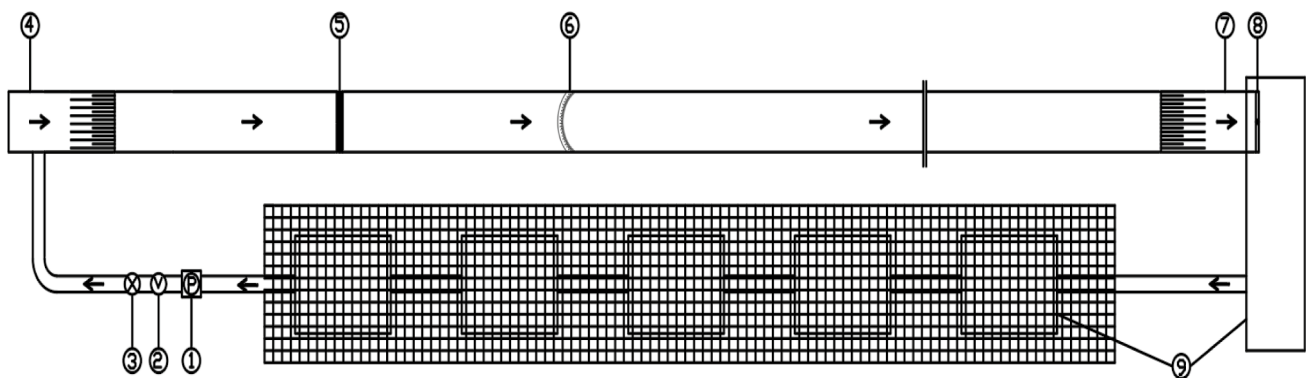
3.2 Apparatus and experimental procedure

3.2.1 Experimental flume setup

All experiments are conducted in a tilting flume located in the Hydraulics Laboratory of the Civil Engineering Department at Assiut University. The flume has a rectangular

cross-section with a height of 0.5 m, a width of 0.3 m, and a length of 20 m, featuring a smooth, painted bed. The flume accommodates discharges ranging from 6.9 L/s to 24.7 L/s. The channel used is demonstrated in Fig. 3.

A geometric and dynamic similarity between the model and the prototype is ensured by adopting Froude scaling, which governs free surface flow conditions. Since the dominant forces in open channel flow are inertial and gravitational, Froude number similarity ($F_e = \frac{v}{\sqrt{gy}}$) is maintained throughout the experiments to ensure accurate representation of the prototype behavior. A geometric scale ratio of 1:10 (model: prototype) is selected to balance laboratory feasibility and measurement accuracy. The experimental flume is constructed with a bed width of 30 cm and a channel height of 50 cm, which corresponds to a prototype channel that is 3.0 m wide and 5.0 m deep. Water depths during



1-Pump, 2-Valve, 3-Orifice meter, 4-Approach basin, 5-Sluice gate, 6-End sill, 7-Downstream ramp, 8-Tail gate, 9-Collecting tanks

Fig. 3 Experimental set-up. 1-Pump, 2-Valve, 3-Orifice meter, 4-Approach basin, 5-Sluice gate, 6-End sill, 7-Downstream ramp, 8-Tail gate, 9-Collecting tanks

Table 4 Range values of the experimental parameter

Parameter	Symbol	Values	Range		Unites
			From	To	
Discharge	Q	$3.986 \sqrt{H_m}$	9.76	17.14	L/s
Jump initial depth	y_1	Varied	1.90	2.18	Cm
Jump sequent depth	y_2	Varied	2.35	16	Cm
Gate opening	D	3	—	—	Cm
Jump length	L_j	Varied	52	97	Cm
Jump location	D_{jf}	Varied	5	319	Cm
Froude number	F_{e1}	$q/y_1 \sqrt{g v_1}$	3.46	6.5	—
Canal Bed slope	S	0.05, 0.10, 0.15, 0.20, 0.25, 0.30	0.05	0.30	%

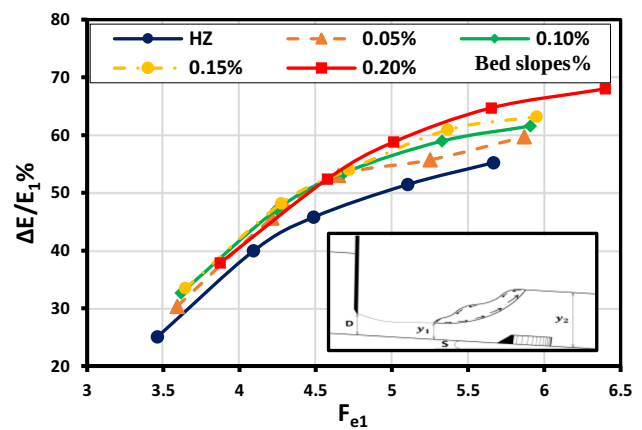
experimental runs ranged from 1.9 to 16 cm, equivalent to prototype depths of 0.19 to 1.6 m. The opening gate is fixed at 3 cm, representing 0.3 m at prototype scale. Discharge rates varied from 9.76 to 17.14 L/s, corresponding to prototype discharges of 3.10 to 5.42 m³/s.

3.2.2 Measuring instruments

A Vernier point gauge is used to measure water depths. The point gauge, mounted on a carriage, moves longitudinally along the flume on two scaling rails and transversely on its carriage scale, as shown in Photo 4. The accuracy of the point gauge readings is approximately ± 0.1 mm.

3.2.3 Slope adjustment mechanism

The flume is stiffened by a light steel truss and is pinned at the downstream end to a rigid support. Two pairs of columns are attached to the flume at intermediate points, and one pair is attached to the forebay. These columns

**Fig. 4** Variations of relative energy loss with Froude number for different values of the channel slopes

are interconnected and can be positioned using longitudinal and vertical screws, providing a means to adjust the slope of the flume. The system is designed to maintain the flatness of the flume bottom at any slope, which can be varied from horizontal to 2 cm/m downstream. This system is shown in Photo 5.

3.2.4 Sill dissipater configuration

In this study, the channel bed is not modified (stilling basins with steps or radial stilling basins), so a trapezoidal curved sill with a 1:1 slope on the upstream (US) face and a vertical downstream (DS) face, featuring a curvature angle of 120° in the opposite direction of the flow is used in the experiment program. This geometry is selected, as recommended by Ashour et al. (2016) in Table 1, and is employed to determine the effect of the channel bed slope on the energy dissipation efficiency of such a dissipater. Bedside, it has the best performance among the other mentioned shapes. This setup is shown in Photo 6.



Photo (1): General view of re-circulating flume.



Photo (2): View of the electrically driven pump



Photo (3): View of the orifice meter

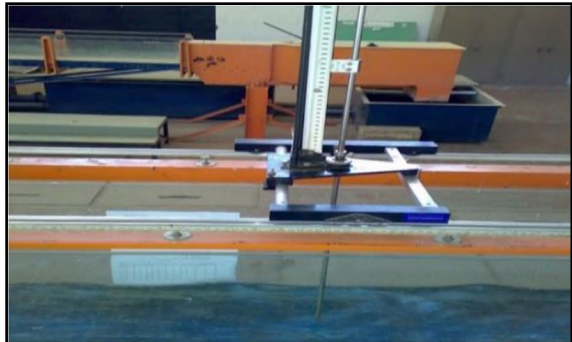


Photo (4): View of the point gauge



Photo (5): the gauge of the sloping channel



Photo (6): the used curved sill

A series of experimental runs are conducted for each discharge rate and bed slope tested. During each run, water depths upstream (U.S.) and downstream (D.S.) of the head structure are measured and recorded. Table 4 summarizes the range of values for the experimental parameters.

3.2.5 Experimental procedure

The experimental procedure is conducted as follows:

1. The intake valve is gradually opened to achieve the desired discharge rate. Flow rate is calculated using:

$$Q = 3.986 \sqrt{H_m} \quad (4)$$

where: Q = the discharge in L/s; and H_m = Differential pressure head between the inlet and outlet of the orifice meter, measured by the manometer in cm

2. The downstream tail gate is adjusted to ensure free flow conditions under the gate.
3. A stabilization period of 15–30 min is observed before measurements are taken.
4. Water depths are measured upstream and downstream of the hydraulic jump using the Vernier point gauge.

- The gate opening (D) is fixed at 3 cm, and the flow rate (Q) varies across five discharge values ranging from 9.76 L/s to 17.14 L/s.
- The process is repeated for each tested bed slope, ranging from 0.05% to 0.30%.

3.3 Uncertainty and error analysis

An uncertainty analysis is performed for all measured and derived parameters to ensure the accuracy and reliability of experimental results. By using a Vernier point gauge with an accuracy of ± 0.1 mm, water depths are measured. The measured water depths ranged between 1.9 cm and 16 cm; the relative uncertainty of the measurements varied between $\pm 0.4\%$ and $\pm 0.9\%$.

The overall uncertainty ranges for the key dimensionless parameters are computed by using standard error propagation techniques to the related hydraulic equations, as follows:

- Relative energy loss ($\Delta E/E_1$): $\pm 0.9\%$
- Sequent depth ratio (y_2/y_1): $\pm 0.4\%$
- Relative jump length (L_j/y_1): $\pm 0.5\%$
- Relative jump height (h_j/y_1): $\pm 0.5\%$
- Relative jump location (D_{jr}/y_1): $\pm 0.5\%$

These uncertainty values are within the permitted range for laboratory-scale hydraulic experiments, confirming the accuracy and consistency of the results.

4 Results and analysis

The effect of irrigation canal bed slopes on the energy dissipation efficiency of downstream control structures is investigated experimentally. This study focused on hydraulic jump

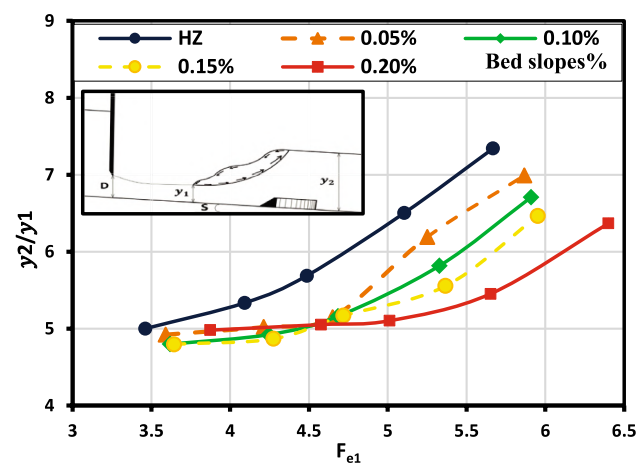


Fig. 5 Variations of sequent depth ratio with Froude number for different values of the channel slopes

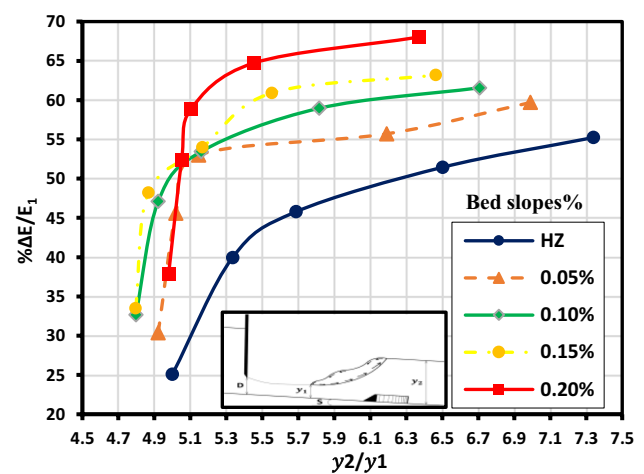


Fig. 6 Variations of relative energy loss with sequent depth ratio for different values of the channel slopes

characteristics, including jump location, jump type, jump length, and sequent depth ratio. Experiments are conducted to examine the variation in these characteristics, and the following relationships are analyzed.

4.1 Effect of canal bed slope on relative energy loss

Data is collected for all examined channel bed slopes at $D/b = 1/10$ and a relative sill location of $L_s/b = 5.83$, as recommended by Wafaie (2001). In Fig. 4 the results demonstrate a positive correlation between relative energy loss and both channel bed slope and Froude number. These findings align with previous research by Gupta and Dwivedi (2024), Laishram et al. (2022), Zabaleta et al. (2022a, b), Abdel-Mageed (2015), and Das et al. (2014), confirming the general validity

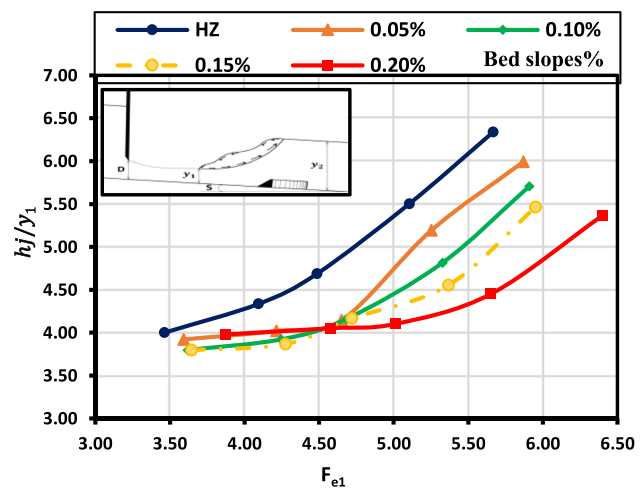


Fig. 7 Variations of the height of the jump with Froude number for different values of the channel slopes

of the observed trends. This is attributed to the fact that steeper slopes result in higher flow velocities, providing more kinetic energy for dissipation. Additionally, when F_{e1} exceeds 4.5, the rate of increase in relative energy loss for different slopes increases slightly, whereas this increase is more pronounced for F_{e1} values less than 4.5. This behavior is due to the transition of the jump from an oscillating to a steady state. Furthermore, increasing the channel slope leads to a corresponding increase in relative energy loss ($\Delta E/E_1$).

4.2 Effect of canal bed slope on sequent depth ratio

At a relative sill height of $D/b=0.1$ and a relative sill position of $L_b/b=5.83$, following the experimental configuration of Wafaie (2001). In Fig. 5 the results demonstrate two key trends: (1) the sequent depth ratio decreases with increasing channel bed slope, contrary to findings by Gupta and Dwivedi (2024), Kateb et al. (2017), Eltoukhy (2016), and Abdel-Mageed (2015); and (2) the ratio increases with higher Froude numbers.

This behavior stems from slope-induced velocity changes, where steeper slopes accelerate flow, reducing both initial (y_1) and tail-water (y_2) depths. However, the tail-water depth reduction exceeds that of the initial depth, yielding a lower y_2/y_1 ratio. Notably, when $F_{e1} > 4.5$, the relative energy loss escalates markedly across slopes compared to more gradual increases observed at $F_{e1} < 4.5$. This threshold effect corresponds to the hydraulic jump transitioning to a more energetic regime, characterized by greater turbulence and energy dissipation.

In Fig. 6, the results indicate that increasing the sequent depth ratio increases the relative energy loss. However, the increase in relative energy is more pronounced for values of the relative sequent depth ratio less than 5.7. The effect of increasing the relative sequent depth ratio is limited when its value exceeds 5.7. Also, at the same value of the sequent

depth ratio, the relative energy loss increases with increasing channel slopes.

4.3 Effect of canal bed slope on hydraulic jump characteristics

As the channel slope increases, the efficiency of energy dissipation decreases because a portion of the flow energy remains in the form of kinetic energy. The turbulence intensity changes with slope. Mild slopes generate stronger turbulent eddies, while steep slopes may lead to weaker jumps and reduced energy dissipation. The strength of the surface roller (a key energy dissipater) is affected by the slope, often becoming weaker as the slope increases. The effect of canal bed slope on hydraulic jump characteristics can be demonstrated as follows:

4.3.1 Relative height of the jump

At a fixed relative sill height ($D/b=0.1$) and relative sill position ($L_b/b=5.83$), consistent with the experimental configuration established by Wafaie (2001). In Fig. 7 the results indicate that the relative height of the jump decreases with increasing channel bed slope, contrasting with findings reported by Jan and Chang (2009), while it increases with increasing Froude number. This is because as the channel slope increases, the flow velocity increases, thus reducing both the initial and tail-water depths. However, the decrease in the tail-water depth (y_2) behind the hydraulic jump is greater than the decrease in the initial water depth (y_1). Also, when F_{e1} is greater than 4.5, the increase in the jump depth is more pronounced, and the greater the slope, the lower the jump depth. This indicates that the location and height of the sill affect the jump depth. As a result, the sill location $L_b/b=5.83$ and height at $D/b=1/10$, as recommended by Wafaie (2001), may need to be adjusted when changing the channel slope.

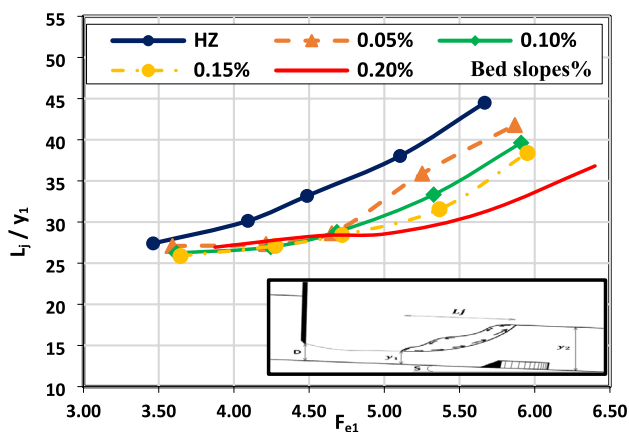


Fig. 8 Variations of relative jump length with Froude number for different values of the channel slopes

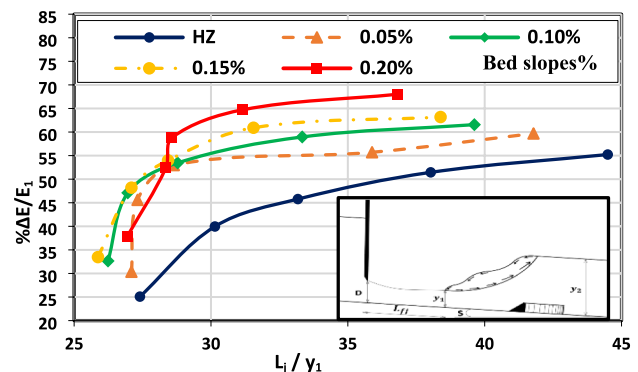


Fig. 9 Variations of relative energy loss with relative jump length for different values of the channel slopes

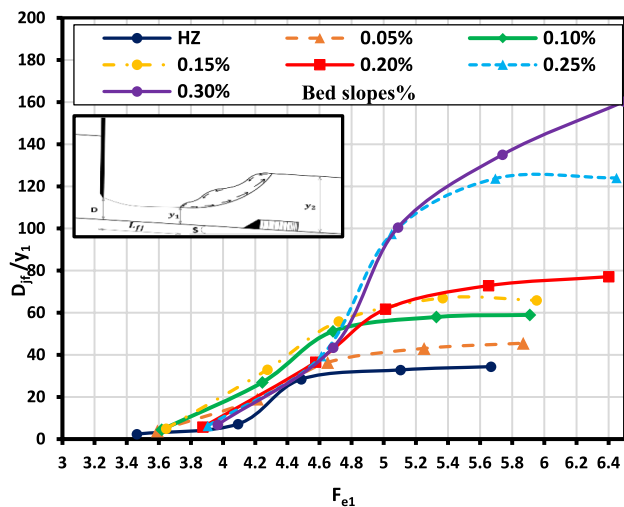


Fig. 10 Distance Variations of the jump formation with Froude number for different values of the channel slopes

4.3.2 Relative jump length

In Fig. 8 the experimental results demonstrate that the relative jump length (L_j/y_1) decreases with increasing channel bed slope, consistent with the observations of Gupta and Dwivedi (2024) but contrasting with those reported by Abdel-Mageed (2015) while it increases with increasing Froude number.

These findings have significant practical implications for hydraulic engineering design. The observed increase in relative jump length with higher Froude numbers suggests enhanced energy dissipation potential, which directly informs the optimal dimensioning of solid aprons. Specifically, the proportional relationship enables reduction of the required protected length downstream of hydraulic structures, yielding both economic and structural benefits in civil engineering applications.

Additionally, the change in depth greatly increases as F_{e1} exceeds 4.5, and the higher the slope, the deeper the jump. The data provided illustrates how the sill's height and placement affect its jump depth. Therefore, by modifying the channel's slope, the sill's recommended placement by Wafaie, (2001) may need to be adjusted. Consequently, increasing the channel slope decreases the relative jump length (L_j/y_1). Also, the value of the relative jump length increases with increasing discharge for all studied channel slopes.

Figure 9 shows that the relative energy loss increases with increasing relative jump length for all the used slopes. For all slopes in Fig. 9, about 95% of the energy loss occurs when the relative length (L_j/y_1) is less than 30; the pattern of increase in the relative energy loss is clearly visible. The range in the loss is less than 5% when the

relative length (L_j/y_1) values are greater than 30. Consequently, the location of the formation of the jump is highly affected by the slope.

4.3.3 Relative jump location

In Fig. 10 the results indicate that the distance of the jump formation (D_{jf}/y_1) increases with increasing the bed slope, which requires a longer length of the protected solid apron. When the Froude number (F_{e1}) almost goes above 4.7, the distance of the formed jump is almost constant for the horizontal state, and the slopes range from 0.05% to 0.20%.

This is due to the increase in the distance of the jump formation decreases when moving closer to the sill dissipater. However, for the slopes 0.25% and 0.30%, the hydraulic jump forms far behind the dissipater because the velocity of water is very high. Therefore, the optimum relative location $L_b/b = 5.83$, as recommended by Wafaie, (2001) for the horizontal state of the channel, is effective up to a canal bed slope of 0.20%, and if the canal bed slope exceeds this limit, this ratio may differ.

4.4 Optimum location for energy dissipater behind control structures in sloping channels

The length of the stilling basin should be sufficient to allow the velocity distribution to regain its normal profile. Therefore, minimizing the basin length is an important economic consideration. The hydraulic jump should form as close as possible to the control structure to protect the structure and its solid apron. The free hydraulic jump is investigated experimentally on various canal bed slopes under different sill locations and flow conditions. Statistical analysis of the experimental results is conducted to determine the effective dissipater location for each canal bed slope.

In Fig. 11a and b, for canal bed slopes of 0.05% and 0.10%, respectively, the relative energy loss ($\Delta E/E_1$) increased with increasing Froude number for all relative locations of the dissipater. The relative energy loss is not significantly affected by the dissipater location. Consequently, the relative location $L_b/b = 3$ is economically optimal.

However, in Fig. 11c, for a canal bed slope of 0.15%, the relative location $L_b/b = 3$ become inefficient when the Froude number (F_{e1}) exceeds 4.5. This is because the high flow velocity causes the hydraulic jump to form at a greater distance behind the dissipater, reducing the dissipation efficiency at that location. The relative locations $L_b/b = 4.5$ yield the highest values of relative energy loss under these conditions.

Accordingly, in Fig. 11d, e, and f, the highest relative energy loss is obtained when the relative locations (L_b/b) are 5.83, 7.5, and 9 for the canal bed slopes of 0.20%, 0.25%,

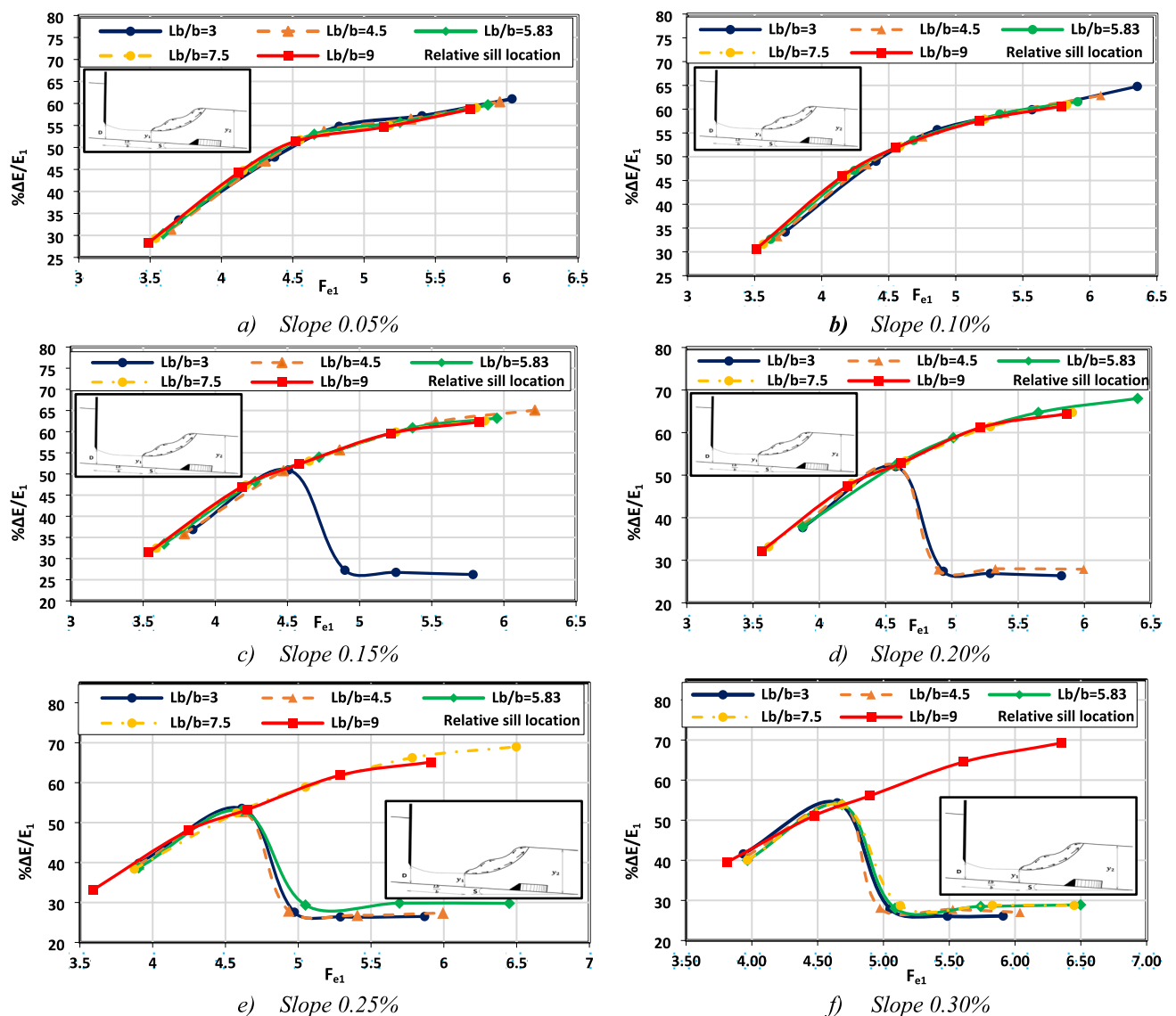


Fig. 11 Relationship between the relative energy loss with Froude number for slopes at different locations of the dissipater

and 0.30%, respectively. These values are observed when F_{e1} is approximately 4.5. This is because the jump transitions from an oscillating to a steady jump, leading to the formation of the hydraulic jump further behind the sill.

Figure 12 suggests that for a given dissipater location, increasing the canal bed slope enhances the efficiency of energy dissipation up to a specific slope value. Beyond this point, the dissipater location becomes less effective, as the increased flow velocity causes the hydraulic jump to form further downstream. Conversely, for a given canal bed slope, positioning the dissipater closer to the control structure generally improves its energy dissipation efficiency, up to certain proximity. Beyond this point, the dissipater's effectiveness diminishes. The relative location

of the dissipater, $L_b/b = 5.83$, as recommended by Wafaie (2001), is effective up to a canal bed slope of 0.20%. For canal bed slopes exceeding 0.20%, this ratio should be increased.

5 Statistical verification of the developed empirical relationships

To ensure the accuracy and reliability of the developed empirical equations describing the hydraulic jump characteristics, a comprehensive statistical verification is conducted. This process aimed to evaluate the strength, significance, and predictive capability of the proposed models that relate

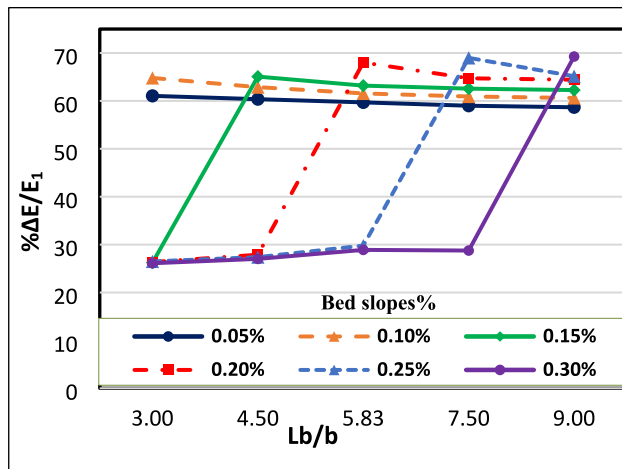


Fig. 12 Relationship between the relative energy loss and relative locations of the dissipater

the key hydraulic jump parameters to the controlling flow and geometric conditions.

The dependent variables investigated in this study include:

- $\Delta E/E_1$ Energy dissipation ratio.
- L_j/y_1 Relative jump length.
- y_2/y_1 Sequent depth ratio.
- h_j/y_1 Relative jump height.

For each of these variables, empirical regression equations are derived from laboratory observations, linking the jump characteristics to the most influential governing parameters, namely the upstream Froude number (F_{e1}) and the bed slope (S).

A rigorous statistical analysis is carried out to assess the significance and reliability of each relationship. The p -values are employed to test the statistical significance of each independent variable, while the Adjusted Coefficient of Determination (Adjusted R^2) is used to evaluate the overall goodness of fit.

The obtained results demonstrate that all proposed models exhibit high explanatory power and statistically significant relationships with their corresponding dependent variables, confirming their reliability. The

Table 6 Statistical validation results between predicted and measured values for hydraulic jump

Dependent Variable	R^2	RMSE
$\Delta E/E_1$	0.9087	0.050968945
L_j/y_1	0.9128	2.789091802
y_2/y_1	0.8956	0.575095619
h_j/y_1	0.9021	0.385523926

regression statistics for each equation are summarized in Table 5.

As shown in Table 5, the developed empirical relationships display strong predictive performance, with Adjusted R^2 values of about 0.94. All predictor variables exhibit statistically significant effects ($p < 0.05$), confirming that both F_{e1} and S are key factors controlling the hydraulic jump behavior. The upstream Froude number (F_{e1}) and the bed slope (S) consistently demonstrate a highly significant influence across all models, reflecting their dominant role in governing jump characteristics.

Overall, the developed models show excellent agreement with the experimental data and demonstrate robust predictive capability, confirming their suitability for representing hydraulic jump characteristics under varying flow and slope conditions.

5.1 Model validation using independent data

To further verify the predictive accuracy of the proposed empirical equations, approximately two-thirds of the experimental dataset are used for model development and calibration, while the remaining one-third are reserved for independent validation.

The comparison between measured and predicted values of the hydraulic jump parameters indicated a strong agreement, as evidenced by high R^2 values and low Root Mean Square Error (RMSE) values, where:

$$RMSE = \sqrt{\frac{\sum (calculated - measured)^2}{n}} \dots \dots \dots (5)$$

Table 5 Statistical parameters of the developed empirical relationships

Dependent Variable	Regression Equation	Adjusted R^2	P-value (F_{e1})	P-value (S)
$\Delta E/E_1$	$0.1012 * F_{e1} + 0.2178 * S$	0.9394	4.45E-18	0.070232
L_j/y_1	$7.2805 * F_{e1} - 29.4384 * S$	0.9390	9.53E-19	0.000956
y_2/y_1	$1.2355 * F_{e1} - 3.4225 * S$	0.9377	1.01E-17	0.029457
h_j/y_1	$1.044 * F_{e1} - 4.02 * S$	0.9386	1.94E-18	0.002011

In which n represents the number of data points. The validation results are presented in Table 6.

Across all cases, the R^2 values range from 0.8956 to 0.9128, indicating that the models explain between 89 and 91% of the total variability in the experimental observations. The corresponding RMSE values are relatively low compared with the mean measured values, suggesting minimal deviation between the predicted and observed data. The computed RMSE to mean ratios are approximately 10.0% for $\Delta E/E_1$, 8.7% for L_j/y_1 , 10.2% for y_2/y_1 , and 8.3% for h_j/y_1 .

Overall, the strong R^2 values and low RMSE confirm the reliability, stability, and physical consistency of the proposed empirical models, validating their use in predicting hydraulic jump behavior over a range of flow and slope conditions.

6 Discussion and limitations

Although the results from the experiments contribute meaningful knowledge relevant to the hydraulic performance of energy dissipaters with respect to varying canal bed slopes, multiple limitations exist when extrapolating their use to actual field conditions as follows:

- The experiments are conducted in a controlled laboratory flume in small-scale and smooth acrylic boundaries, which are different significantly to the masses of sediment and rough surfaces of full-scale irrigation canals. Scale effects in experimental work, in particular, Reynolds number and turbulence characteristics of the flow, can cause a degree of non-linear discrepancies when transitioning to the field (Chanson 2009).
- Secondly, the flume in this study had a rectangular geometry, whereas most irrigation canals have a trapezoidal or compound geometry, which affects the velocity distribution, hydraulic jump formation, and energy dissipation, which can change the effectiveness of dissipater positions (Jan and Chang 2009; Eltoukhy 2016).
- In a real-world scenario, canals are affected by environmental variability with components such as sediment load, vegetation encroachment, and variability of boundary roughness, which are not considered in this controlled setup.
- Although the trends found, including increased dissipation efficiency with slope and the variation of optimal dissipater position depending on slope, are directionally sound, caution should be taken to apply them directly to field conditions.

7 Conclusions

Through examining one of the recommended water energy dissipaters in the literature review, tested with seven canal bed slopes and five different discharges in the Irrigation Lab,

Faculty of Engineering, Assiut University, it is concluded that:

- Canal bed slope is one of the most important parameters affecting the hydraulic performance efficiency of the water energy dissipater due to its significant impact on the characteristics of hydraulic jump formation, which dissipates most of the residual energy of the flowing water.
- The relative location of the dissipater ($L_b/b=5.83$) can be effectively used up to a canal bed slope of 0.20%; for steeper slopes, it cannot be used and must be checked.
- Increasing the canal bed slope up to 0.20% improved the performance efficiency of the water energy dissipater by 31.9%.
- The relative water energy loss increases with both the Froude number (F_{e1}) and canal bed slope.
- As the bed slope approaches the maximum percentage (0.2%), the hydraulic jump height, sequent depth ratio, and relative jump length decrease, which is beneficial for reducing the length of the required expensive solid apron under the structure in the downstream zone.
- Finally, the promising results obtained indicate the importance of conducting similar studies for any type of water energy dissipater to achieve optimal technical compatibility between the type used and the existing canal bed slope for maximum performance efficiency.

8 Recommendations for future work

Future studies should incorporate and validate findings at the field scale and, where possible, consist of non-rectangular geometries and unsteady flow conditions.

In addition, combining computational fluid dynamics (CFD) modeling with experimental work may give the best indication of dissipaters' performance for a range of hydraulic and geometrical configurations (Meshkati et al. 2025; Zabaleta et al. 2022a, b).

Evaluating the performance of various dissipater configurations, sizes, and arrangements under various bed slope conditions.

Verifying the 31.9% efficiency obtained at 0.20% slope using tests at realistic irrigation head structures with different bed slopes.

Analyzing local scour in sloping bed conditions around curved sills.

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author made substantial contributions to the design and conceptualization for optimization methodology, supervision of the work, writing and approval of the final version. The third author performed the experimental work with cooperation with the fourth author. The second, third and fourth authors made substantial contributions to the conception, the literature search, the formal analysis and investigation of experiments, the acquisition, analysis and interpretation of results data, the original drafting and critical revision of the manuscript, and the approval of the final manuscript.

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Data availability The data is available by request from the corresponding author (Abdallah Atef Abdou).

Declarations

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Consent for publication This declaration is not applicable.

Competing interests The authors declare that they have no competing interests.

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