

A Review of Hydraulic Performance and Energy Dissipation in Vertical Drops with Screen-Based Dissipators

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Abstract

The existing literature indicates that vertical drop structures equipped with screen-based dissipators, particularly horizontal screens, significantly enhance hydraulic performance compared with plain vertical drops. Experimental studies consistently report increased energy dissipation, greater downstream flow depths, reduced Froude numbers, and mitigation of bed scour. These improvements result mainly from plunging jet disruption, intensified turbulence, enhanced air entrainment, and more effective redistribution of flow momentum within the downstream pool.

Among the configurations investigated, horizontal screens are especially effective due to their direct interaction with the plunging jet, promoting jet fragmentation and distributing energy dissipation over a larger flow volume, thereby reducing localized bed impact. In contrast, vertical screens primarily affect downstream flow by stabilizing hydraulic jumps and modifying flow depth and velocity distributions, with performance strongly dependent on their placement.

Despite these advantages, important research gaps remain. Most studies rely on laboratory experiments, while CFD applications are limited. Furthermore, existing research typically examines individual parameters in isolation, with few systematic comparisons of screen orientation, inclination angle, and placement under consistent flow conditions, leaving their combined effects on energy dissipation efficiency and downstream stability insufficiently understood.

Keywords: Horizontal screens; Energy dissipation; Vertical Screens; Vertical drops; Plunging jets; Screen Porosity; Hydraulic jump; Scour control.

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Abbreviations

E_u Total energy in the upstream of the drop (L)

E_d Total energy in the downstream of the vertical drop (L)

ΔE Change in energy dissipation (L)

v_d Downstream velocity (LT^{-1})

v_{cr} Critical velocity (LT^{-1})

v Mean fluid velocity (LT^{-1})

D Hydraulic Depth (L)

R Hydraulic Radius (L)

μ Water dynamic viscosity ($ML^{-1}T^{-1}$)

g Gravitational acceleration (LT^{-2})

y_d Downstream depth (L)

y_{cr} Critical depth in the upstream drop (L)

y_b Brink depth of drop (L)

y_u Upstream depth of the drop (L)

y_p Pool depth under the falling jet (L)

h Drop height (L)

P Porosity of screens (dimensionless)

q	Discharge inflow per unit width (L^2T^{-1})
ρ	Water density (ML^{-3})
Q	Discharge (L^3T^{-1})
t	Screen thickness (L)
L_{mix}	Mixing length (L)
L_{wet}	Wetting length (L)
ANN	Artificial Neural Network
ANFIS	Adaptive Neuro-Fuzzy Inference System
CFD	Computational Fluid Dynamics
DS	Double Screen configuration
GP	Gaussian Process
GRNN	Generalized Regression Neural Network
SS	Single Screen configuration

I. Introduction

Vertical drop structures are commonly employed in hydraulic engineering to accommodate changes in channel elevation and bed slope while controlling flow energy. Although structurally simple, these structures often generate highly supercritical flows that produce excessive downstream velocities, strong turbulence, and significant bed scour. As a result, effective downstream energy dissipation has long been a critical challenge in hydraulic design. To address these issues, numerous dissipative measures have been investigated over the past decades, including stilling basins, baffle blocks, end sills, and more recently, porous elements such as screens.

This paper presents a comprehensive review of energy dissipation downstream of vertical drop structures, with particular focus on screen-based dissipators. The review examines the progression of research from early studies of fundamental dissipation mechanisms to recent investigations addressing screen geometry, porosity, configuration, and placement. Key outcomes are synthesized, and existing research gaps are highlighted to support the need for continued and systematic investigation.

One of the earliest systematic investigations of flow behavior downstream of vertical drops was conducted by Gill [1], whose laboratory experiments laid the foundation for understanding the mechanisms of energy dissipation. His work demonstrated that energy loss occurs predominantly downstream of the drop, rather than along the drop face, where the free-falling jet interacts with the receiving pool. This insight shifted the perception of vertical drops from passive geometric features to active hydraulic elements governed by flow processes.

Gill [1] showed that as the flow leaves the upstream brink, potential energy is converted into kinetic energy, forming a high-velocity plunging jet. Upon impact with the downstream pool, the jet undergoes rapid deceleration and momentum redistribution, generating intense turbulence characterized by strong velocity gradients and unsteady flow structures. Turbulence production at the jet impact zone was identified as a primary mechanism of energy dissipation, driven by shear-layer development and vortex formation that enhance mixing between the jet and surrounding water.

In addition, Gill [1] highlighted the role of air entrainment in increasing energy loss, noting that entrained air disrupts jet coherence, intensifies turbulence, and promotes momentum exchange within the pool. His findings also emphasized the importance of downstream pool depth, showing that deeper pools enhance jet diffusion and energy dissipation, while shallow pools concentrate energy near the bed. These conclusions provided a fundamental framework for subsequent studies on vertical drop hydraulics.

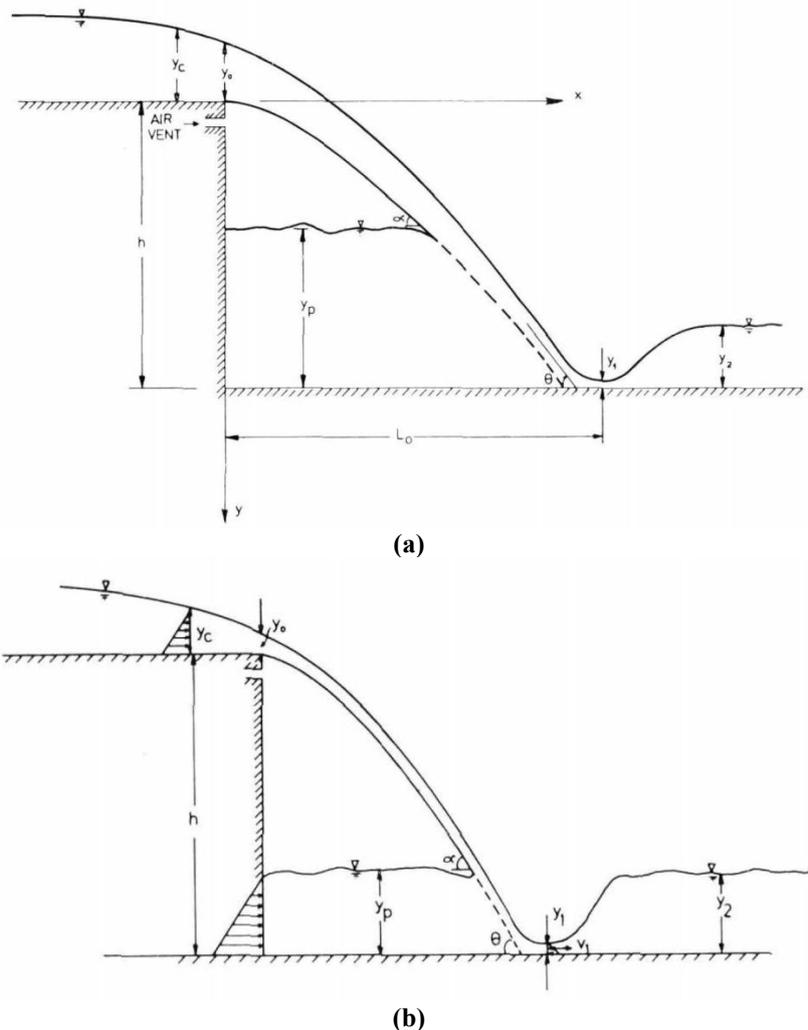


Figure 1 : Conceptual illustration of flow over a plain vertical drop: (a) development of the plunging jet, jet impingement region, and downstream recirculation zones[1], (b) distribution of momentum forces and locations of high turbulent energy dissipation[1].

Building upon this foundational understanding, Rajaratnam et al.[2] expanded the investigation of energy dissipation mechanisms by focusing specifically on the characteristics of plunging jets downstream of vertical drops. Their work provided a more detailed description of the internal flow structure within the downstream pool and clarified the relative importance of different dissipation processes. Rajaratnam et al. [2] reported that energy dissipation is governed primarily by three interrelated mechanisms: jet impact, turbulent mixing, and vortex formation.

Their experimental observations showed that the plunging jet retains a significant degree of coherence as it enters the downstream pool but rapidly breaks down as it interacts with surrounding water. This breakdown is accompanied by the formation of large-scale vortices, which play a crucial role in redistributing momentum throughout the pool. These vortical structures extract energy from the jet core and transfer it to the surrounding fluid, thereby extending the spatial and temporal scale of energy dissipation.

Rajaratnam et al.[2] further demonstrated that turbulent mixing within the downstream pool is sustained well beyond the initial impact zone. The interaction between the jet, vortices, and pool boundaries creates a highly unsteady flow field in which energy is continuously dissipated through shear and mixing processes. Their work reinforced the view that energy dissipation at vertical drops is not a single-event phenomenon, but rather a sequence of interacting processes that evolve downstream of the drop.

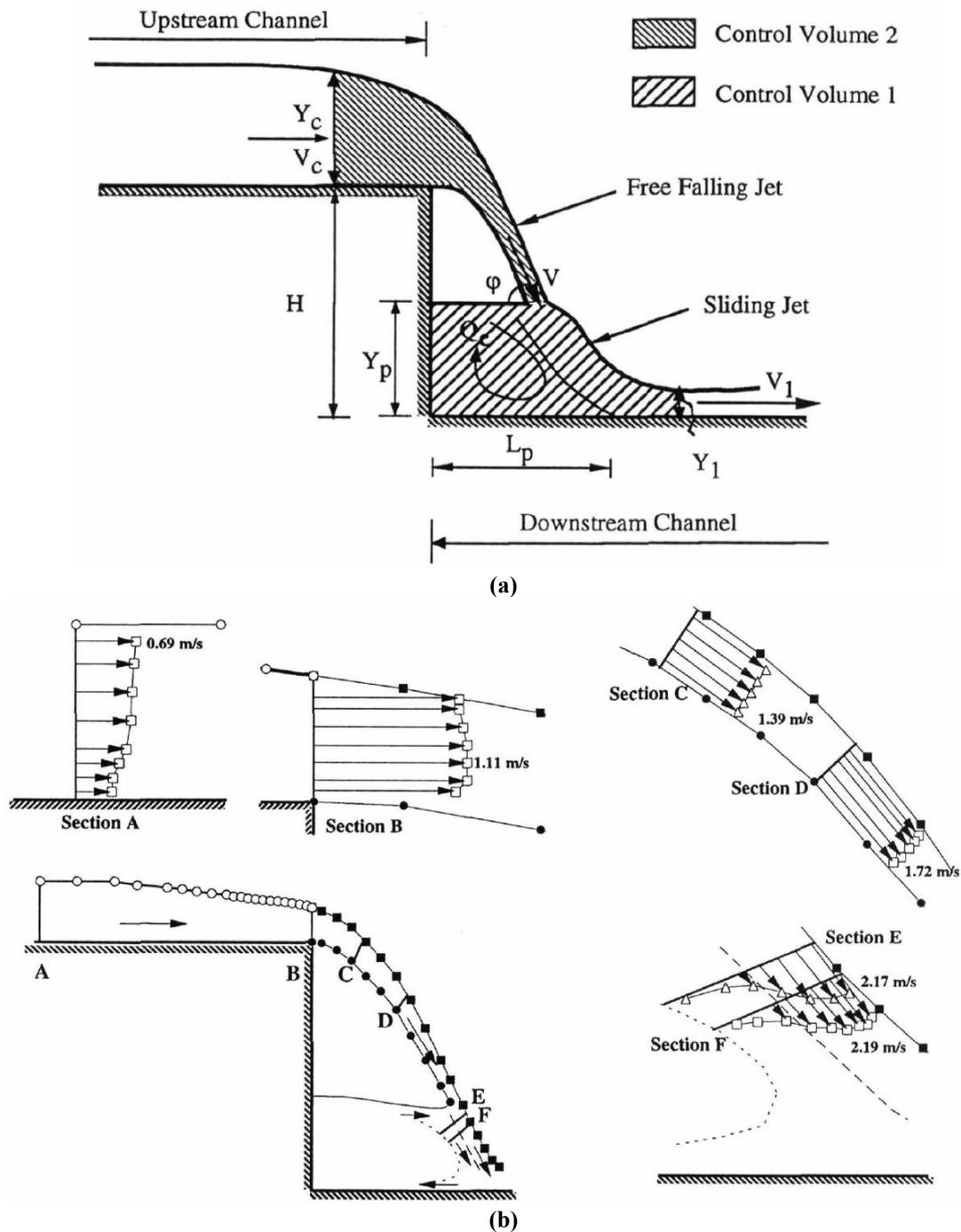


Figure 2 :A schematic representation for the flow over a plain vertical drop illustrated by Rajaratnam [2] : (a) the control volumes per each sector of the free fall jet [2], (b) the velocity profile distribution at various locations of the jet [2].

Rajaratnam et al.[2] further demonstrated that turbulent mixing within the downstream pool is sustained well beyond the initial impact zone. The interaction between the jet, vortices, and pool boundaries creates a highly unsteady flow field in which energy is continuously dissipated through shear and mixing processes. Their work reinforced the view that energy dissipation at vertical drops is not a single-event phenomenon, but rather a sequence of interacting processes that evolve downstream of the drop.

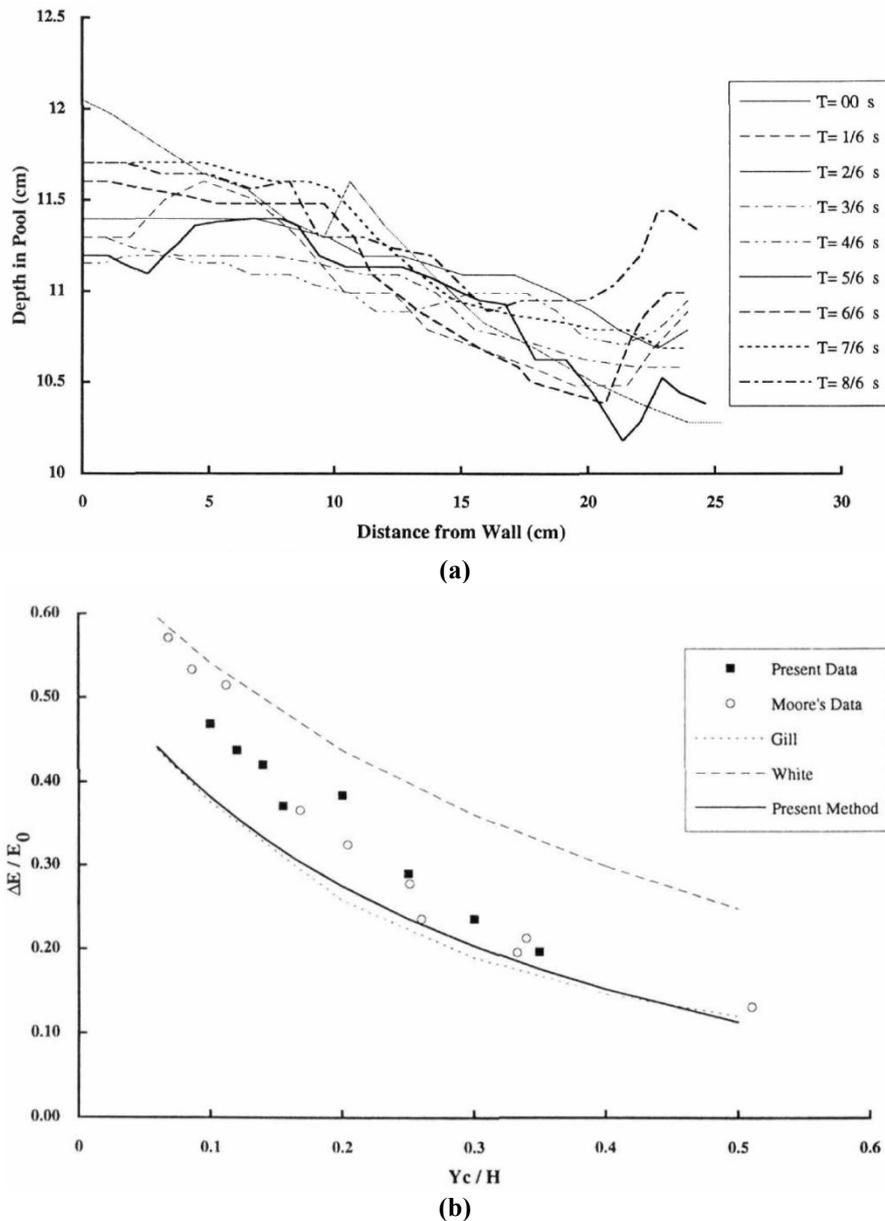


Figure 3 :A graphical representation for the hydraulic parameters for the flow over a plain vertical drop illustrated by Rajaratnam [2] : (a) the relation between the water pool depth and distance from the vertical drop wall against various time intervals [2], (b) the relative energy dissipation resulted from plain vertical drop for different previous research [2].

The importance of sustained turbulence and flow recirculation was further confirmed by Chamani et al. [3], who examined the structure of the flow field downstream of vertical drops in greater detail. Their studies highlighted the presence of distinct recirculation zones within the downstream pool, particularly near the bed and along the side boundaries. These recirculation regions are characterized by reversing flow directions, low mean velocities, and high turbulence intensities.

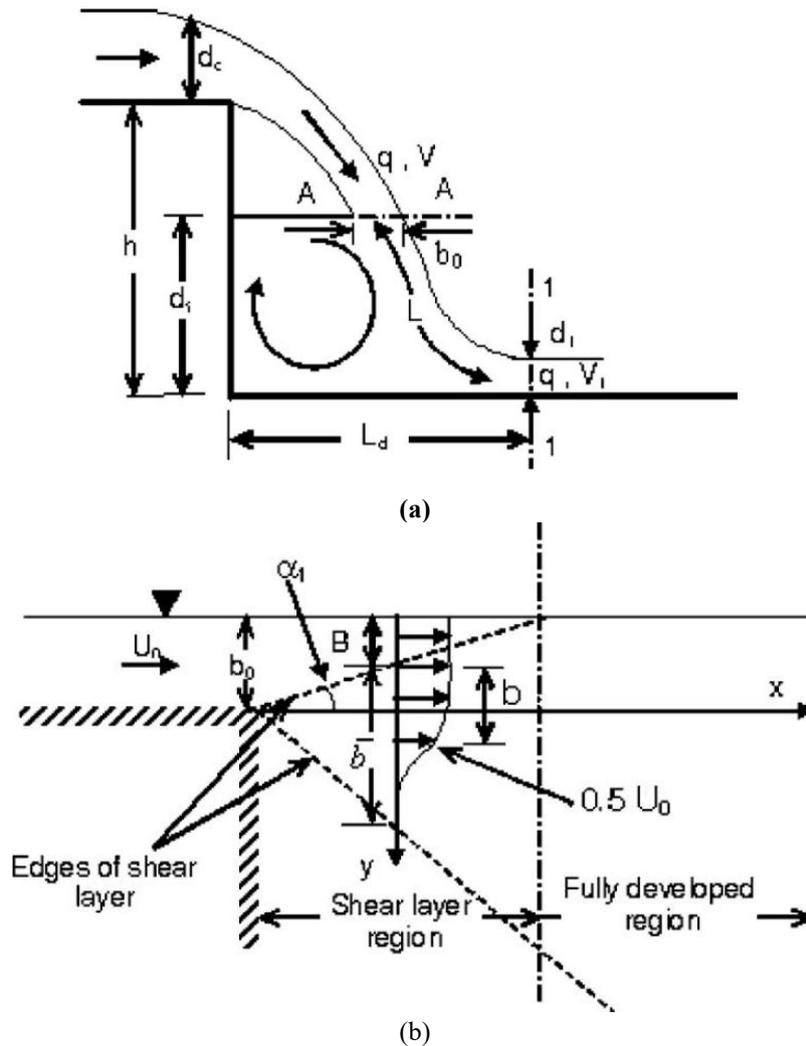


Figure 4 : A definition sketch prepared by Chamani [3]: (a) represents the vertical drop free fall jet parameters [3], (b) represents the surface jet, and the shear layer models [3].

Chamani et al.[3] demonstrated that these recirculation zones act as persistent energy-dissipating regions. As water becomes trapped within these zones, it undergoes repeated cycles of mixing and momentum exchange, leading to continued energy loss even as the mean flow velocity decreases. The strength and extent of these zones were found to depend on flow conditions and pool geometry, further emphasizing the role of downstream configuration in controlling dissipation efficiency.

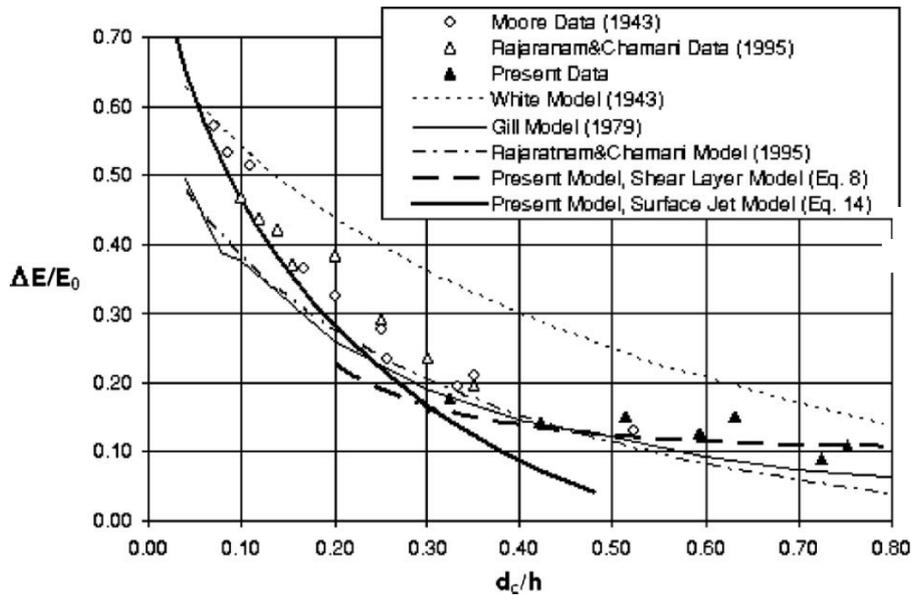


Figure 5 : A graphical representation for the relative energy dissipation resulted from Chamani model compared with previous research[3].

Collectively, the findings of Gill [1], Rajaratnam et al. [2], and Chamani et al. [3] established that the downstream pool is the primary region where energy dissipation occurs in vertical drop systems. Rather than being confined to the drop face or upstream reach, energy loss is concentrated in the complex flow field formed by jet impingement, turbulence production, vortex dynamics, and recirculation within the pool. This understanding has become central to both experimental investigations and practical design approaches for vertical drop structures.

Despite the effectiveness of these mechanisms in reducing flow energy, early studies also revealed important limitations associated with vertical drops. The intense turbulence and concentrated jet impact responsible for efficient energy dissipation also generate high bed shear stresses downstream of the drop. These stresses can exceed critical thresholds for sediment motion, leading to localized scour and progressive erosion of the downstream bed.

Gill [1] and later researchers[2],[3], [4] and [5] observed that scour typically develops near the jet impact point and within recirculation zones, where fluctuating pressures and vortical motion repeatedly act on the bed material. Over time, this erosion can undermine structural elements, alter flow patterns, and reduce the long-term stability of the drop. Recognition of these adverse morphological impacts motivated subsequent research aimed at modifying vertical drop designs to maintain effective energy dissipation while minimizing downstream scour.

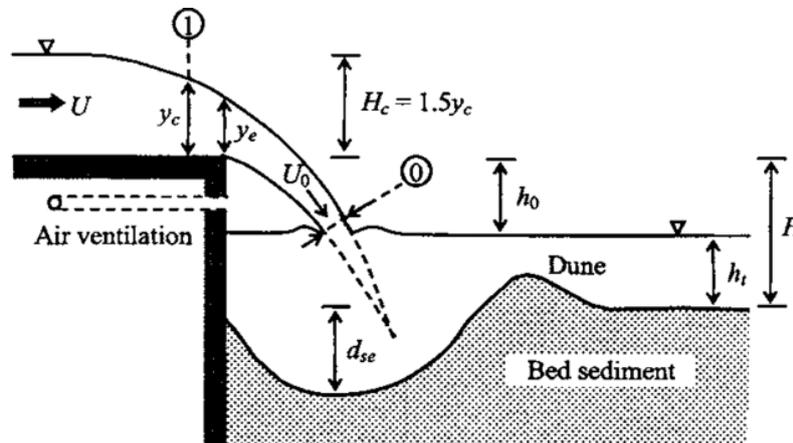


Figure 6 : Schematic representation of downstream scour characteristics associated with a plain vertical drop, as described by Dey[5].

II. Evolution of Screens as Energy Dissipating Devices

Recent advances in hydraulic engineering have stimulated growing interest in alternative energy dissipation devices that extend beyond conventional stilling basins, plunge pools, and solid drop structures[6]. This evolution has been driven by the increasing demand for compact, efficient, and adaptable dissipation systems capable of handling high-energy flows while minimizing downstream impacts such as excessive turbulence concentration and bed scour[7].

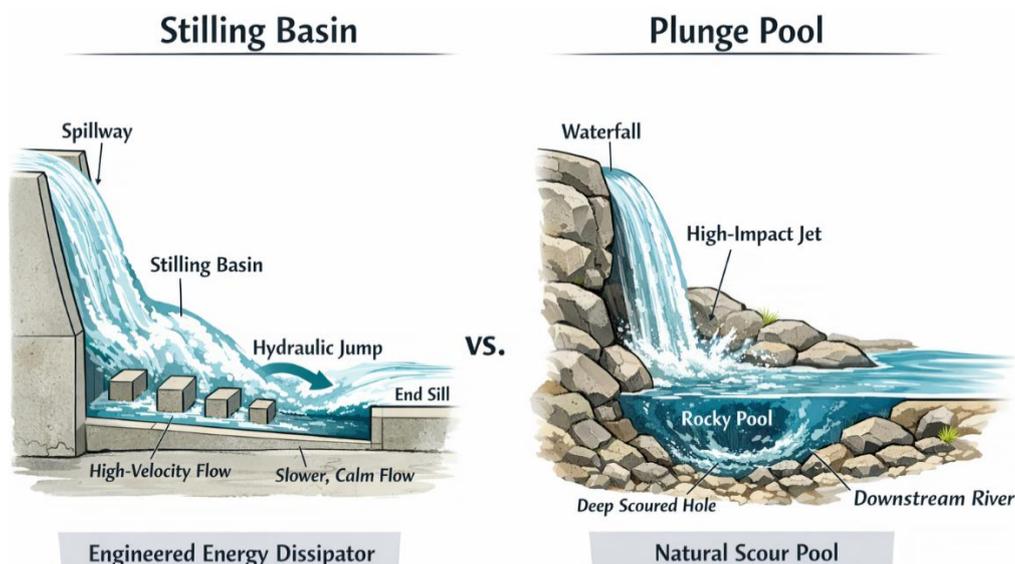


Figure 7 : Schematic comparison between a stilling basin and a plunge pool as energy dissipation mechanisms. Within this context, porous elements particularly screens have emerged as a promising class of energy dissipators and have received increasing attention in experimental, numerical, and applied research studies [5],[8],[9].

Screens are generally defined as rigid porous barriers composed of regularly or irregularly distributed openings that permit partial flow passage. Their hydraulic behavior is governed by geometric parameters including opening size and shape, thickness, spacing, and overall porosity ratio. Unlike solid obstacles, screens do not completely block the flow; instead, they introduce controlled resistance that induces gradual momentum reduction, enhanced turbulence generation, and redistribution of flow energy across multiple spatial scales [8],[9],[10],[11],[12]. This controlled permeability distinguishes screens from traditional dissipators and makes them particularly attractive for applications downstream of vertical drops, where flow energy is highly concentrated and difficult to manage using conventional methods alone.

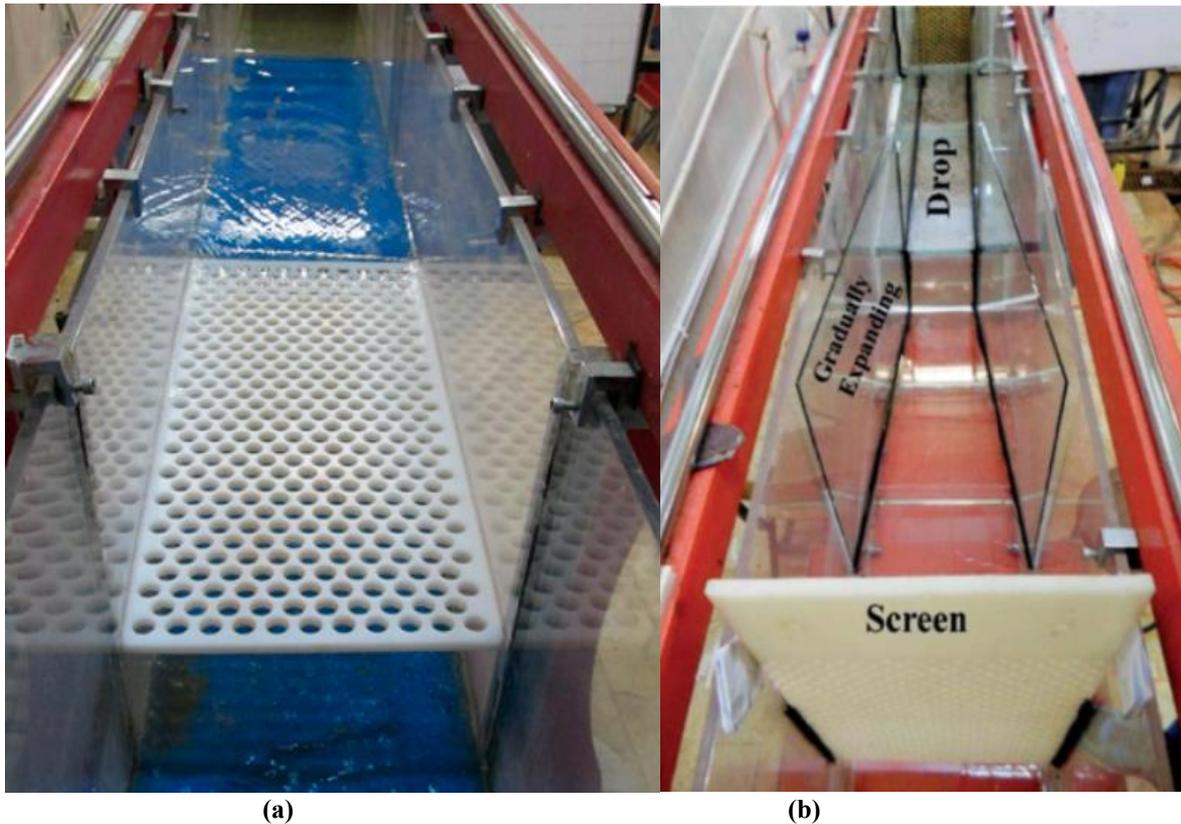


Figure 8 : Representative configurations of screen-based hydraulic energy dissipation structures: (a) horizontal screen at a vertical drop [13], and (b) vertical screen located downstream of a vertical drop[12]. Experimental investigations have demonstrated that screens may be installed either vertically or horizontally relative to the principal flow direction, with each orientation producing distinct hydraulic responses and dissipation mechanisms[10],[14],[15]. The flexibility in screen orientation allows dissipation strategies to be tailored to specific hydraulic conditions, geometric constraints, and design objectives. Norouzi et al. [14] conducted one of the earliest systematic experimental investigations of horizontal screen installations at vertical drops, demonstrating that screens can significantly enhance energy loss while simultaneously modifying downstream flow structure and reducing scour potential.

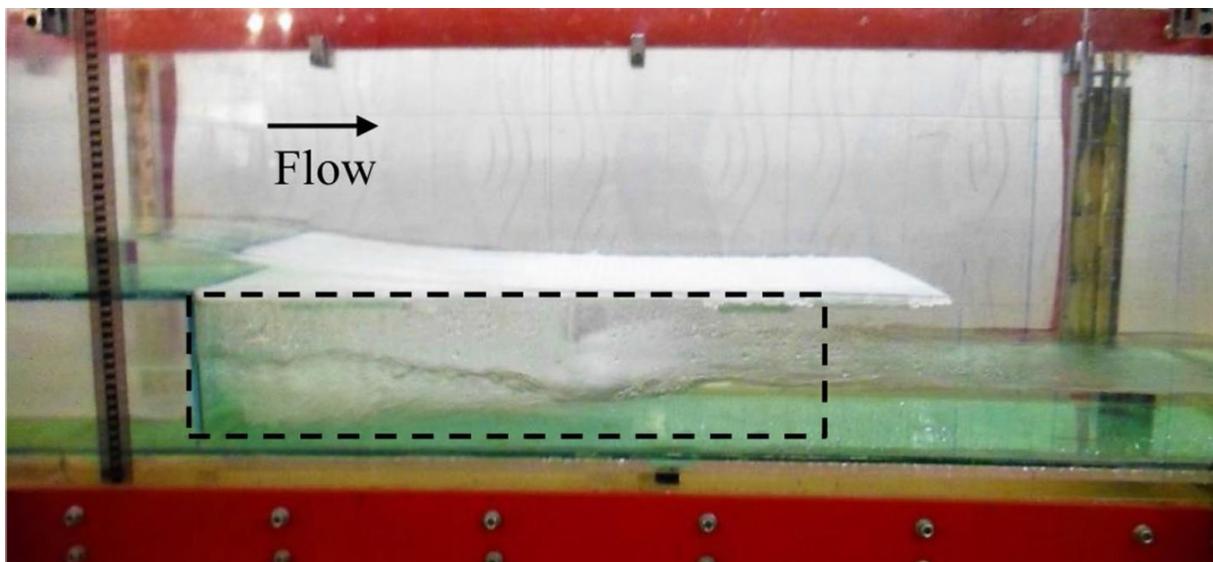
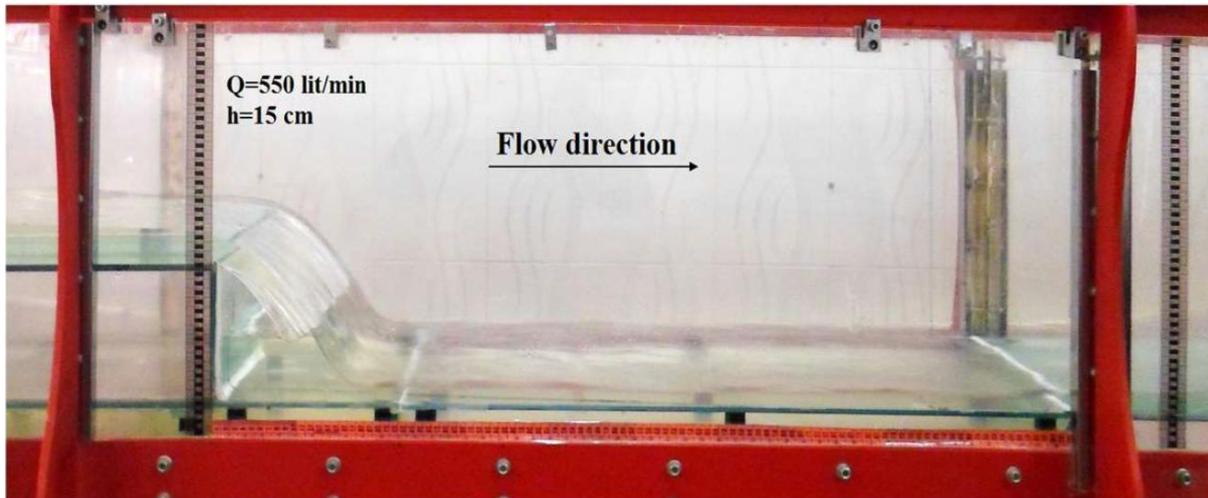


Figure 9 : Vertical drop equipped by horizontal screen [14].

When installed vertically, screens act as porous obstructions placed within the downstream channel. In this configuration, partial blockage of the flow leads to an increase in upstream water depth and a corresponding

reduction in velocity. The resistance imposed by the screen promotes momentum redistribution and facilitates the formation of a hydraulic jump downstream of the drop. Unlike classical hydraulic jumps, whose locations are governed primarily by tailwater depth, screen-induced jumps can be spatially controlled through adjustments in screen porosity, thickness, and placement [8],[16],[17],[18].



(a)



(b)

Figure 10 : Flow overview in plain vertical drop: (a) Vertical drop without installing vertical screen [18], and (b) Flow behavior after installing vertical screen downstream of a vertical drop [18].

The hydraulic jump formed downstream of a vertical screen is associated with substantial energy dissipation resulting from intense turbulent mixing, flow separation, and air entrainment. As flow passes through the screen openings, multiple jets emerge and interact with the downstream water body, generating localized shear layers and highly unsteady flow structures. These interactions disrupt the coherence of the incoming flow and accelerate energy loss. Several experimental studies have reported that vertical screens can stabilize hydraulic jump location, reduce oscillatory behavior, and improve overall dissipation efficiency compared to uncontrolled jump conditions [11],[14],[18],[19].

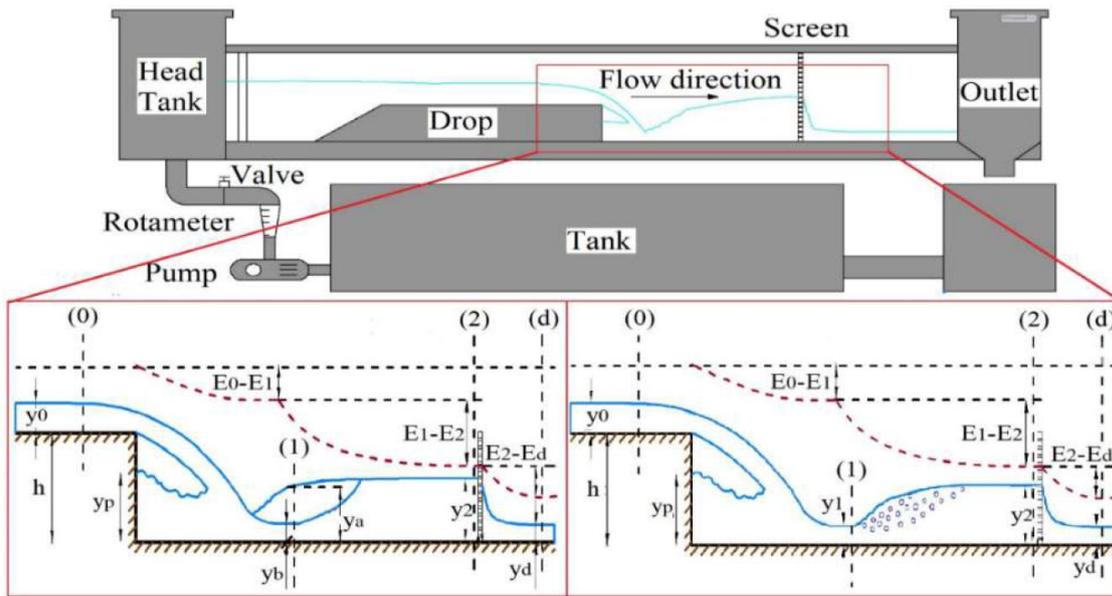


Figure 11: Schematic sketch representing the hydraulic behavior of water downstream the vertical drop equipped with vertical screen [18].

In contrast, horizontally installed screens interact directly with the plunging jet downstream of the vertical drop. In this arrangement, the screen is positioned within or just above the downstream pool, intercepting the falling jet before it impacts the bed. This direct interception significantly alters jet dynamics by fragmenting the plunging jet into multiple smaller jets as flow passes through the screen openings. The resulting increase in jet surface area intensifies turbulence production and promotes rapid momentum exchange with the surrounding water [10],[11],[15],[20].

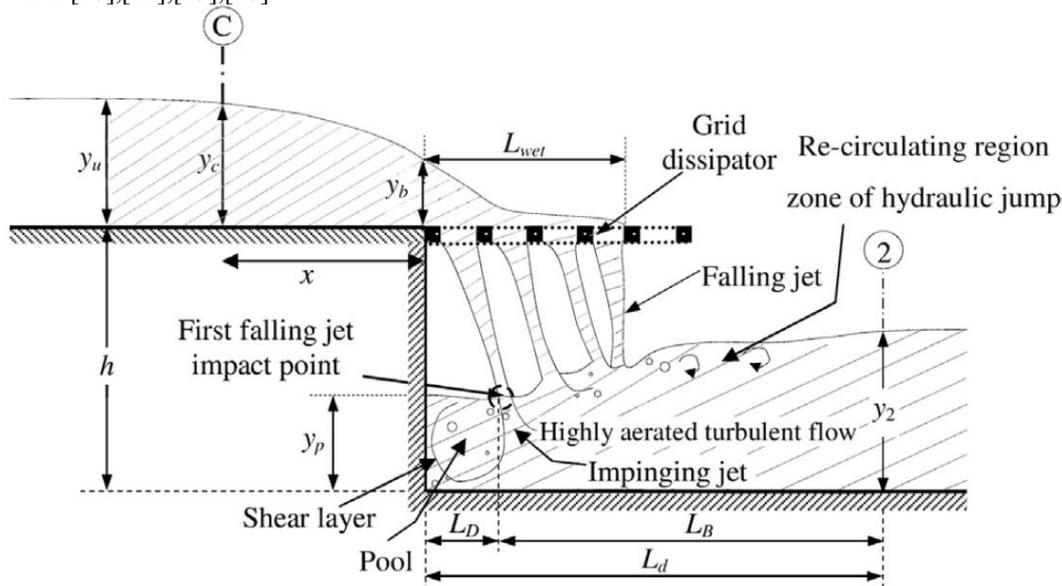


Figure 12 : Schematic sketch representing the hydraulic behavior of water downstream the vertical drop equipped with horizontal screen [11],[15],[20].

Experimental studies have shown that horizontal screens are particularly effective in reducing jet penetration depth and lowering near-bed velocities, thereby decreasing the likelihood of downstream scour [5],[14],[21],[22]. By redistributing energy dissipation over a larger water volume, this configuration avoids the concentration of impact forces at a single point on the bed which leads to decreasing the bed scour downstream the vertical drop. Such behavior has been shown to improve both hydraulic performance and structural safety in high-head applications by [4],[5],[9].

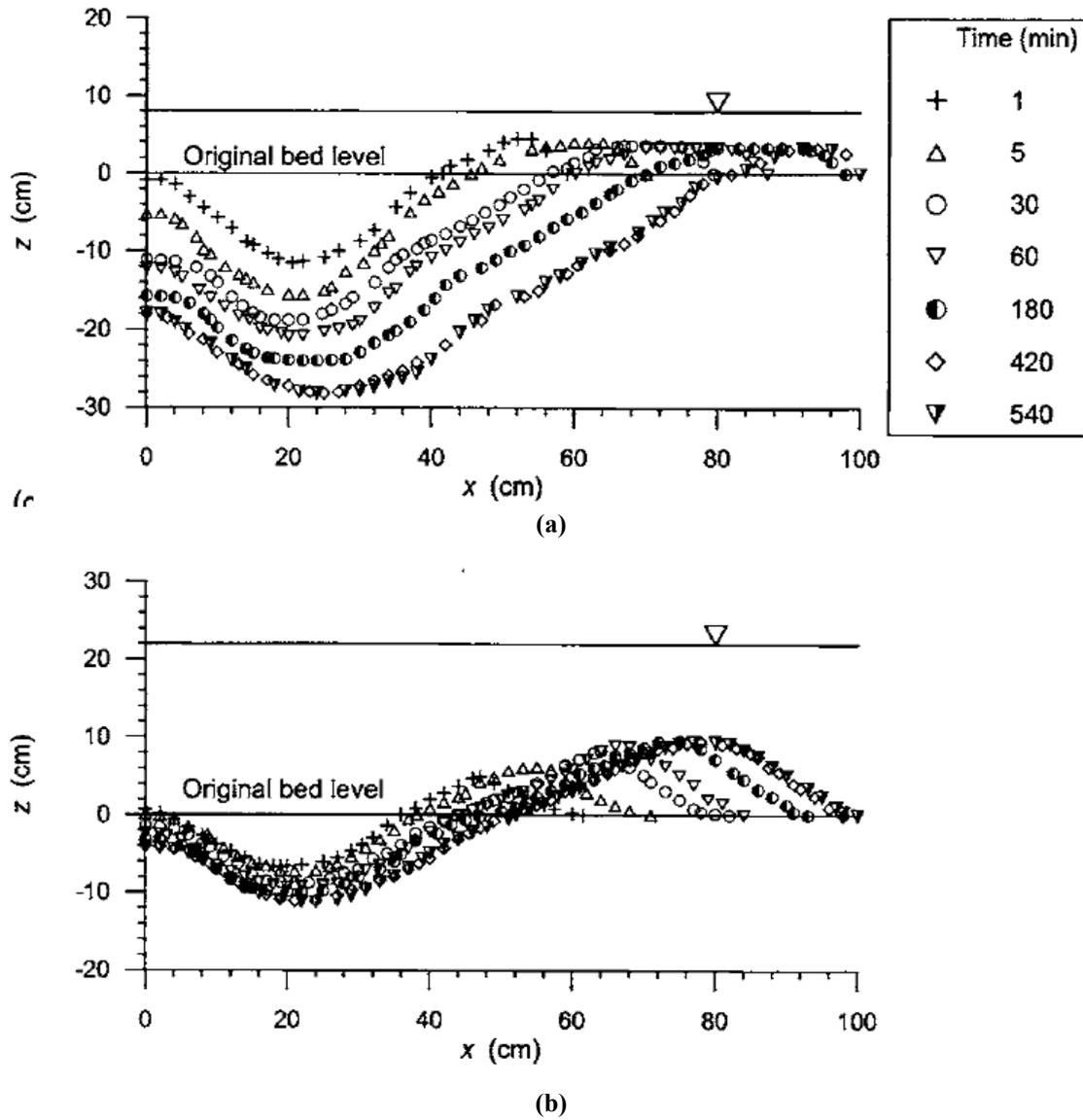


Figure 13 : Schematic sketches representing the scour profiles below the vertical drop with time [5],[14],[21]: (a) scour profiles with low downstream water depth (low tailwater), (b) scour profiles with high downstream water depth (high tailwater).



Figure 14 : Schematic figure representing the vertical drop structure equipped by horizontal screen 40% and 50% porosity using high rough bed material [20].

For both vertical and horizontal configurations, additional energy losses arise from frictional interactions between the flow and the edges of the screen openings. As water passes through the porous structure, it undergoes repeated acceleration and deceleration accompanied by boundary layer development along the opening edges. These processes generate localized shear stress and contribute to sustained turbulence production downstream of the screen [11],[16],[17],[23]. The cumulative contribution of these frictional losses becomes increasingly significant for screens with lower porosity ratios or more complex opening geometries.

Screen porosity has been consistently identified as a key parameter governing hydraulic performance. Low-porosity screens impose higher flow resistance, resulting in increased upstream water levels and greater energy dissipation, but may also introduce excessive head losses or operational blockage. Conversely, highly porous screens allow greater flow passage with reduced resistance, producing lower dissipation levels but offering limited control over downstream flow conditions [11],[14],[24]. Consequently, numerous studies have focused on identifying optimal porosity ranges that balance dissipation efficiency with acceptable hydraulic and structural performance.

Despite their demonstrated effectiveness, screens also introduce practical and hydraulic challenges, including debris accumulation, time-dependent changes in flow resistance, and potential structural vibrations induced by unsteady flow forces. Accordingly, experimental and applied studies have emphasized the importance of appropriate material selection, structural rigidity, and maintenance considerations when implementing screens in real-world systems.

Overall, the emergence of screens as energy dissipators represents a significant advancement in the management of high-energy flows downstream of vertical drops. By combining partial obstruction with enhanced turbulence generation and controlled permeability, screens provide an effective means of increasing energy dissipation while mitigating adverse morphological impacts. The experimental insights gained from early and recent studies have established a strong foundation for continued research aimed at optimizing screen geometry, orientation, and placement for integration into modern hydraulic design practice.

Energy dissipation is evaluated by calculating the difference between the specific energy upstream and downstream (E_d) the vertical drop installed in a rectangular cross-section as shown in Eqs.1, While the upstream and downstream specific energy (E_u & E_d) will be calculated using Eq. 2 & 3 [14],[25].

$$\begin{aligned} \Delta E &= E_u - E_d \text{ (Equation 1)} \\ E_u &= 1.5 * y_c + h \text{ (Equation 2)} \\ E_d &= y_d + \frac{q^2}{2 * g * y_d^2} \text{ (Equation 3)} \end{aligned}$$

2.1 Vertical Screens as Energy Dissipators

Vertical screens represent one of the earliest and most systematically examined applications of porous elements for energy dissipation downstream of vertical drops. Their fundamental operating principle is based on introducing controlled resistance into the flow, thereby reducing momentum and promoting turbulence without completely blocking discharge. Because of their simplicity and structural robustness, vertical screens have attracted sustained interest in experimental hydraulics research, particularly in relation to optimizing geometric parameters that govern their hydraulic efficiency.

The pioneering experimental work of Rajaratnam and Hurtig [9] provided a fundamental basis for understanding energy dissipation mechanisms associated with vertical screens equipped downstream a vertical sluice gate. Their study comprised two main experimental series. The first series examined the hydraulic performance of single, double, and triangular screen configurations, denoted as SS, DS, and TS, respectively. In the second series, particular attention was given to double-screen arrangements, where the spacing between screens was systematically varied. The inter-screen distances were set to 26 mm for experiments 2DS (1–4), 54 mm for 2DS (5–8), 85 mm for 2DS (9–12), and zero spacing for 2DS (13–16). The findings indicated that screens with a porosity close to 40% produced the most effective energy dissipation. This porosity level offered an optimal balance by sufficiently reducing flow velocity while preventing excessive upstream head losses that could adversely affect structural integrity or operational efficiency. The identification of this optimal porosity range represented a significant contribution to the hydraulic design of vertical screen energy dissipators.

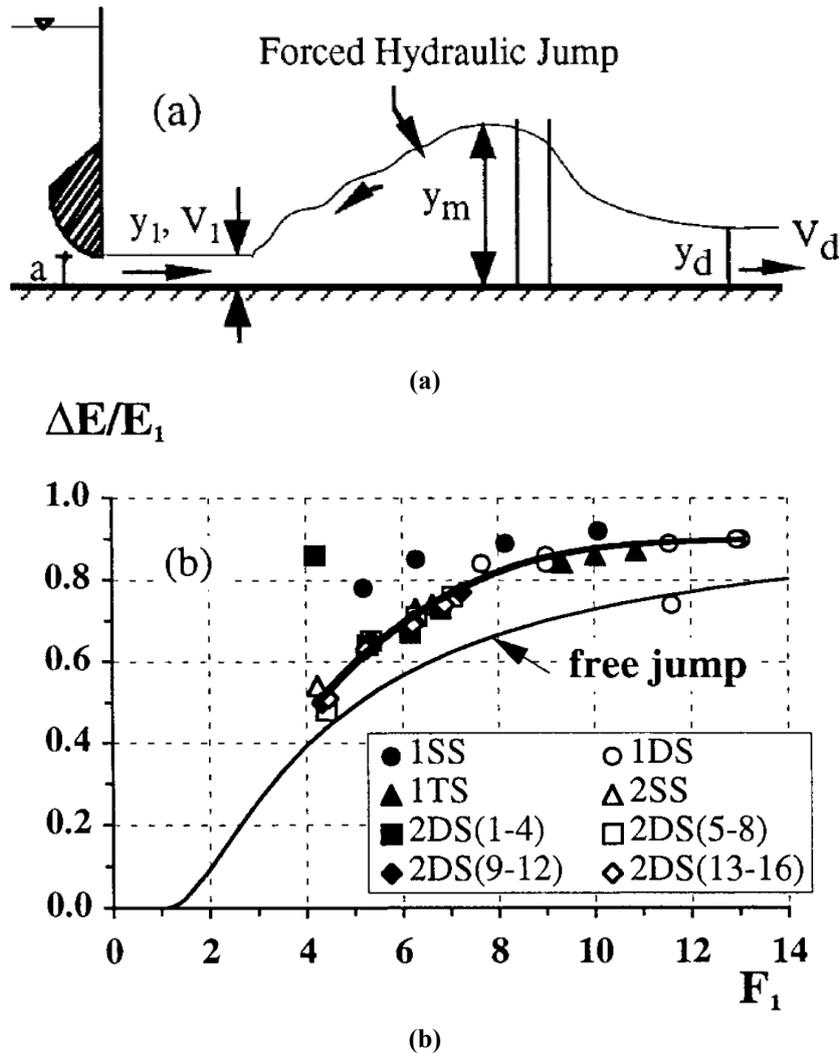


Figure 15 : Schematic sketches representing the vertical screens configurations conducted by Rajaratnam and Hurtig [9]: (a) Schematic representation of a vertical screen-type energy dissipator, (b) Relationship between relative energy loss and upstream Froude number for hydraulic jumps formed by screen structures.

Subsequent investigations aimed to determine whether other geometric parameters could further enhance dissipation efficiency. Çakir [10] examined the influence of screen thickness and found that its effect on energy dissipation was negligible compared with porosity and opening geometry. This finding suggested that the dominant dissipation mechanisms occur primarily at the entrance and exit of the screen openings, where flow contraction, expansion, and jet interaction generate turbulence. As a result, vertical screen performance is largely governed by two-dimensional flow processes rather than frictional losses along the screen thickness.

The role of opening geometry was later explored by Güngör [16], who investigated vertical screens with triangular openings featuring internal angles of 60°. His results indicated that these triangular openings did not produce a noticeable improvement in energy dissipation relative to conventional circular openings. This outcome implies that, for vertical screens, the overall blockage effect and porosity distribution exert a stronger influence on hydraulic performance than the detailed shape of individual openings. Consequently, circular openings remain a practical choice due to their ease of fabrication and predictable hydraulic behavior.

Further extending the applicability of vertical screens, Daneshfaraz et al. [26] examined their performance downstream of inclined drops. By varying drop angles, heights, and relative critical depths, they demonstrated that vertical screens substantially improved hydraulic conditions compared with plain inclined drops. Their results showed increases in relatively downstream depth ranging from 105% to 130% and dramatic increases in energy dissipation between 407% and 903%. Moreover, downstream Froude numbers were reduced to values between 1.66 and 2.11, indicating a transition toward more stable, near-subcritical flow conditions. These findings confirmed that vertical screens remain effective even when the drop geometry deviates from a purely vertical configuration.

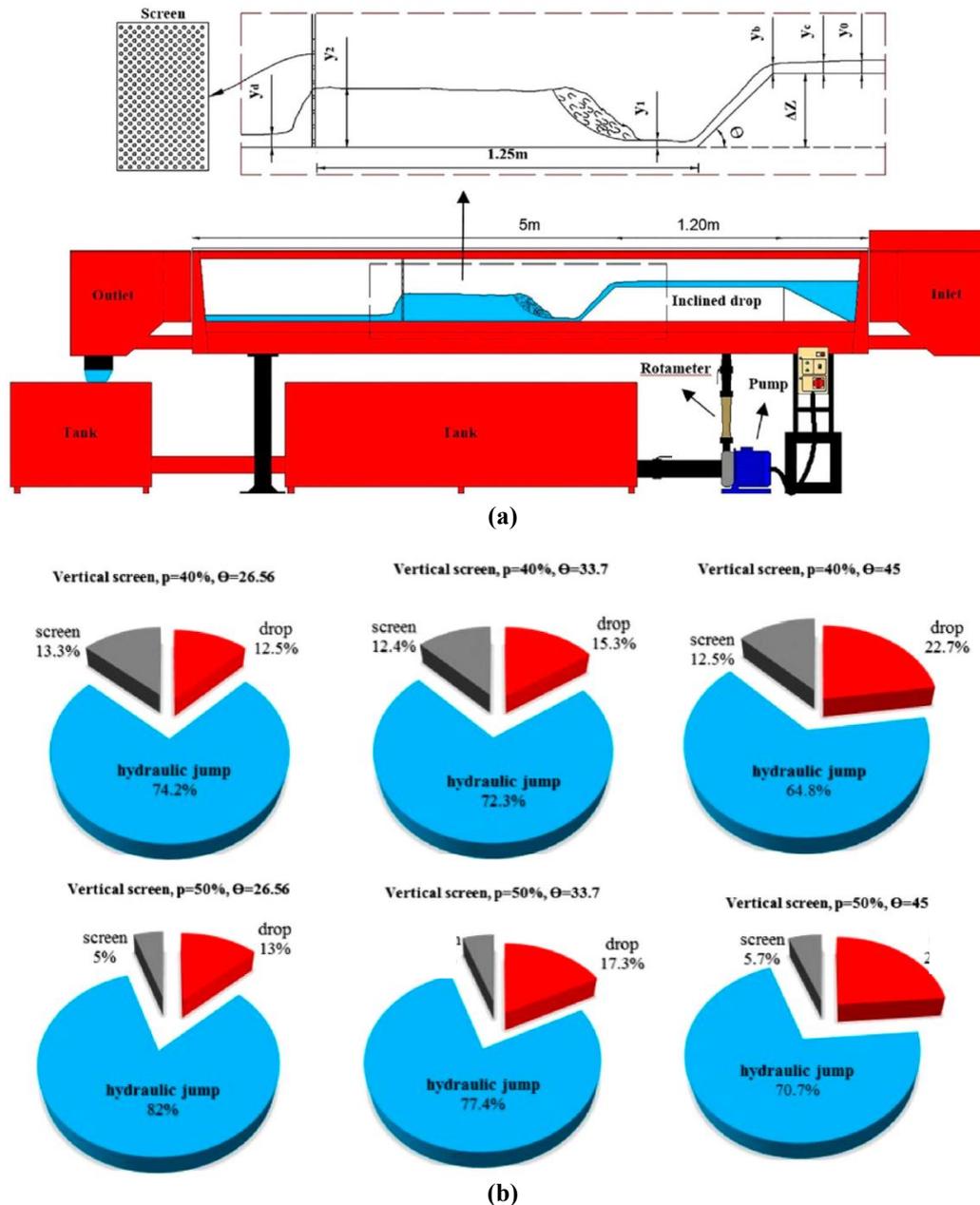


Figure 16 : Schematic sketches representing the inclined drop configurations equipped with a vertical screen and the experimental results conducted by Daneshfaraz et al. [26]: (a) schematic of a laboratory model and flume, (b) Percentage of energy dissipation changes for each setup.

Expanding the scope of vertical screen applications, Daneshfaraz et al. [18] investigated screens with porosities of 40% and 50% positioned at distances of 30, 60, and 90 cm downstream of the drop brink. Their experimental results demonstrated that increasing screen distance and porosity enhanced downstream depth and energy dissipation while reducing pool depth. These trends indicate that allowing the jet to develop before encountering the screen promotes more effective turbulence generation and energy loss.

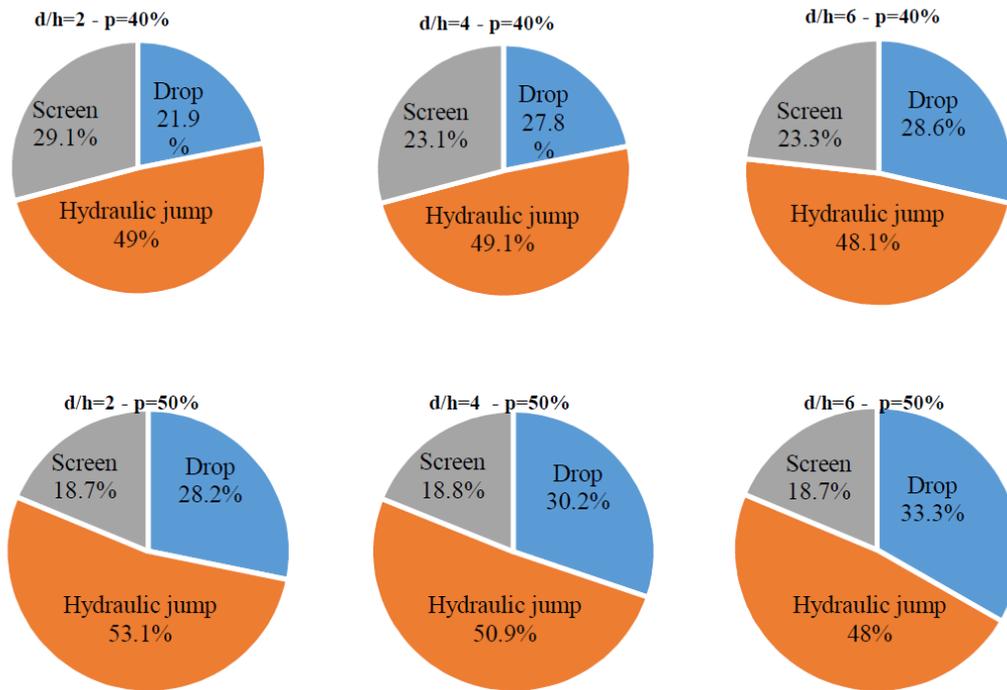
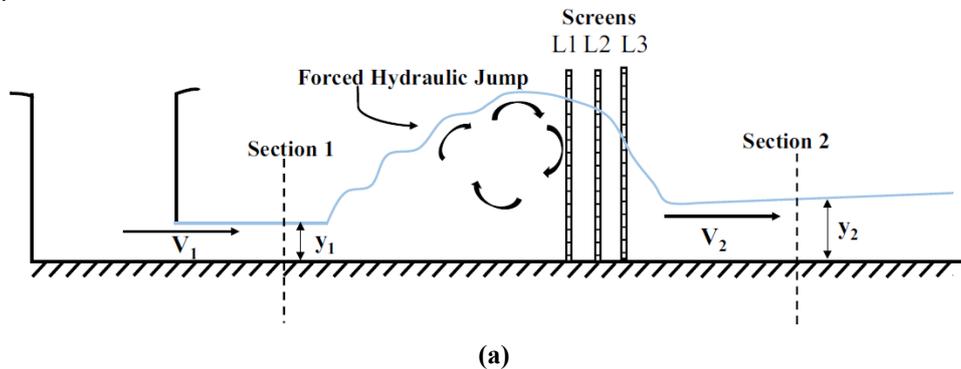


Figure 17 : Schematic sketches representing Percentage of energy dissipation changes per each setup[18]. Singh et al.[6]experimentally investigated energy dissipation in hydraulic jumps using a triple-layer perforated screen system arranged in a mixed multi-wall configuration. Vertically installed screens with circular, square, and triangular openings were tested, each having a uniform porosity of approximately 45%. The experiments covered supercritical flows with Froude numbers ranging from 3.2 to 19.3, with the screens placed downstream of a sluice gate at small inter-screen spacing.

The results showed that the triple-screen system achieved substantially higher relative energy dissipation (74–94%) than conventional hydraulic jumps and reduced downstream Froude numbers to near-critical conditions. Among the tested arrangements, the CST configuration provided slightly superior performance, particularly at higher approach Froude numbers. Overall, the study demonstrated that mixed triple-layer screen systems offer an efficient and flexible alternative to traditional hydraulic jump dissipators across a wide range of flow conditions.



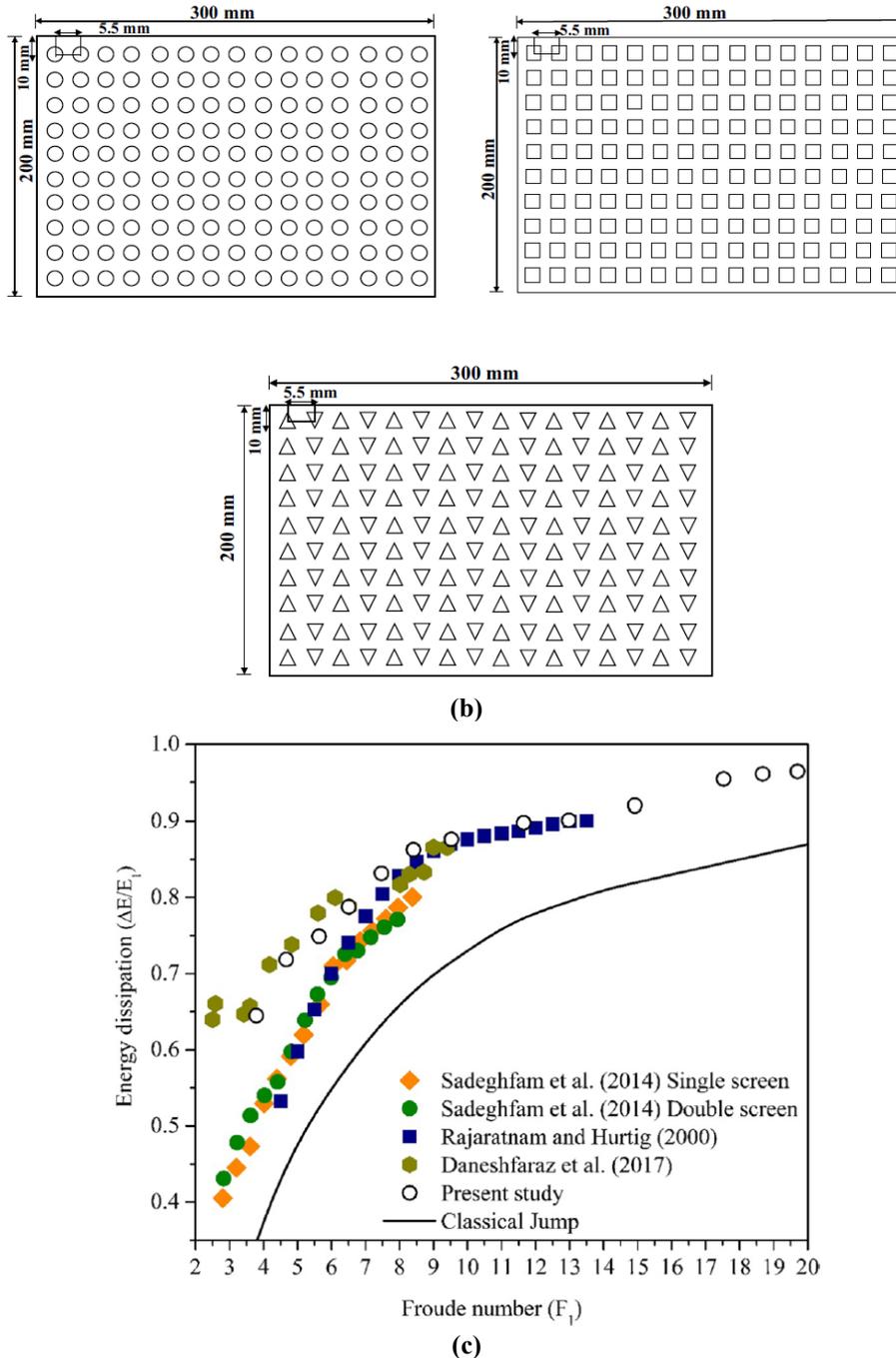


Figure 18 : Schematic illustrations of sluice gate equipped with triple vertical screens and the associated experimental results reported by Singh et al. [6]: (a) schematic representation of the laboratory hydraulic model (b) configuration and fabrication details of the vertical screen arrangements, (c) relative energy loss versus relative upstream Froude number for different previous studies compared to Singh et al. study.

2.2 Horizontal Screens and Grid-Type Dissipators

Horizontal screens and grid-type dissipators have been widely studied due to their direct interaction with the plunging jet formed downstream of vertical drops. Unlike vertical screens, which primarily influence the downstream flow field, horizontal screens intercept the jet itself, fundamentally altering its structure, trajectory, and penetration depth. This direct interception leads to more rapid energy dissipation and a redistribution of turbulent activity within the downstream pool.

Kabiri-Samani et al. [15] conducted one of the earliest experimental studies on horizontally installed grid-type dissipators with square openings and porosity ratios of 40% and 50%. Their findings demonstrated that horizontal grids could increase energy dissipation by up to 33% relative to plain vertical drops.

Additionally, the required pool length was reduced by 60–75%, indicating that horizontal screens offer substantial spatial efficiency advantages. These results highlighted the suitability of horizontal grids for applications where space constraints limit the size of conventional energy dissipation structures.

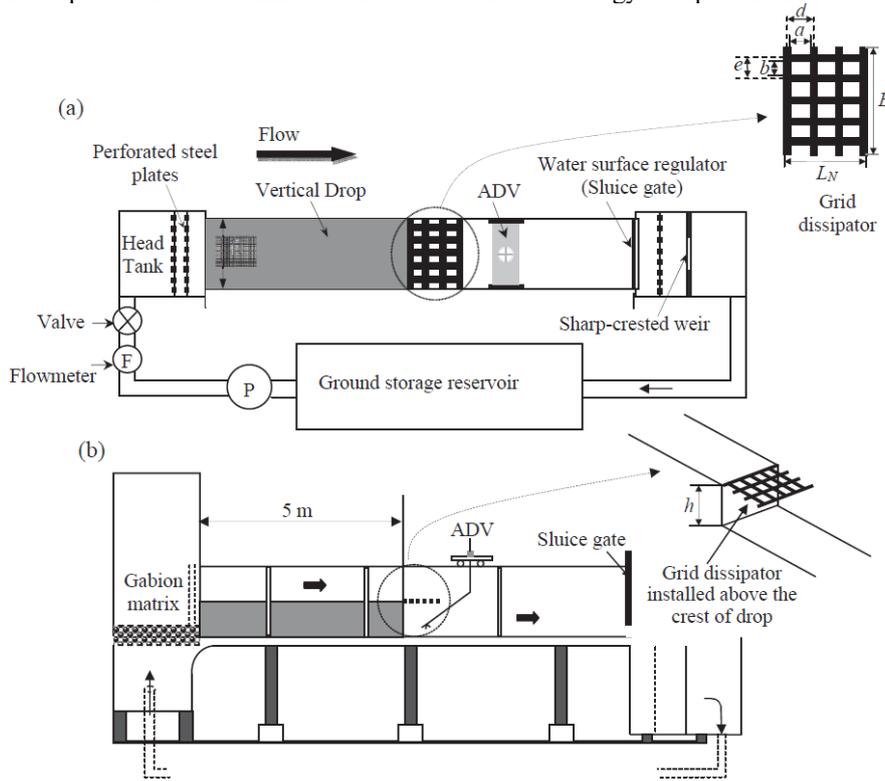
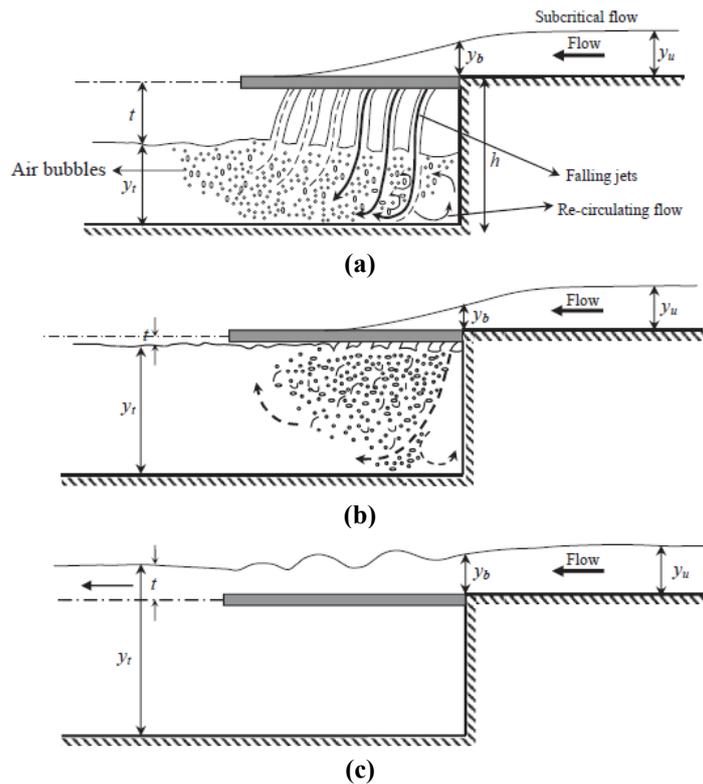
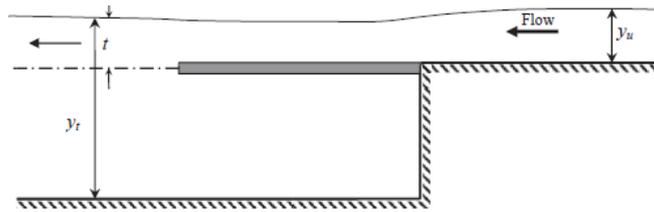


Figure 19 : Schematic illustrations of vertical drop equipped with horizontal grid dissipator reported by Kabiri-Samani et al. [15].

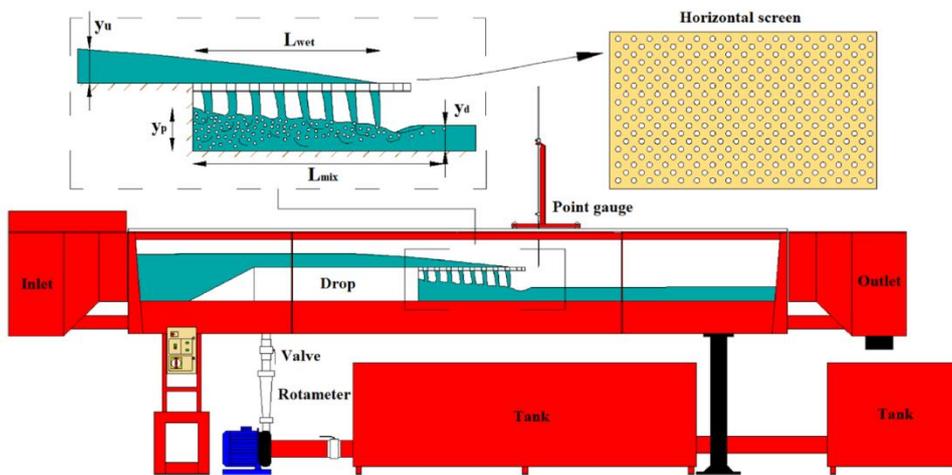




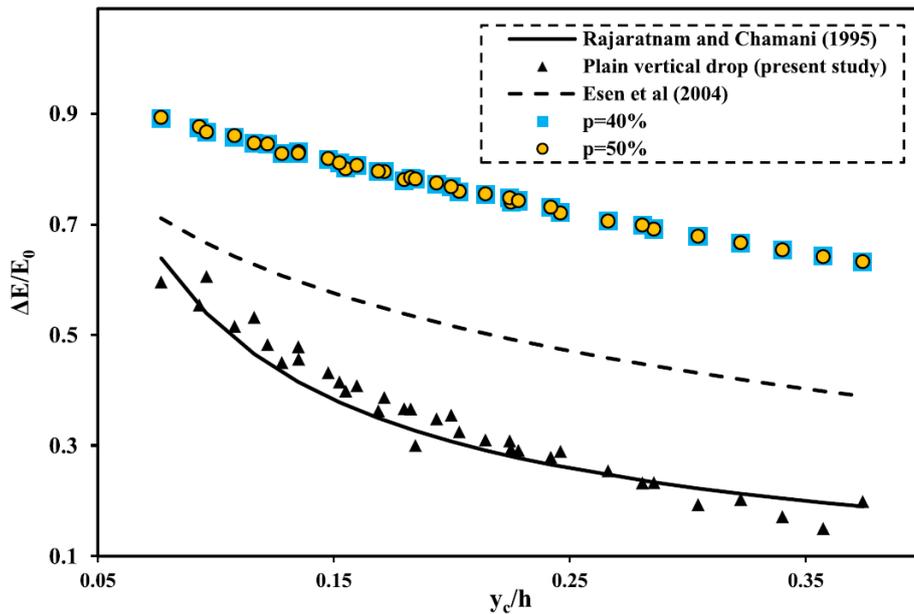
(d)

Figure 20 : Flow regimes downstream of a vertical drop equipped by grid dissipater [15].: (a) bubble impinging jets regime, (b) bubble zone regime, (c) surface wave regime, (d) surface jet regime.

Daneshfaraz et al.[17] experimentally investigated the hydraulic performance of vertical drop structures equipped with horizontal screens. A total of 105 laboratory experiments were conducted covering three drop heights, two screen porosities (40% and 50%), and a wide range of discharges. The study examined key hydraulic parameters including relative pool depth, downstream depth, wetted screen length, mixing length, and energy dissipation. The results demonstrated that incorporating a horizontal screen significantly enhances hydraulic performance compared with a plain vertical drop, leading to increased relative pool and downstream depths and higher energy dissipation. Moreover, the downstream Froude number was substantially reduced from supercritical values of 3.7–6.1 to near-critical or subcritical conditions ranging between 0.67 and 1. The influence of screen porosity was found to be relatively minor for downstream depth, pool depth, and energy dissipation; however, lower porosity screens produced longer mixing lengths. The authors concluded that vertical drops equipped with horizontal screens represent an effective energy dissipation alternative, while emphasizing the need for further studies considering broader porosity ranges, flow conditions, hydraulic jump stabilization, and potential scour induced by jet flow through the screen.



(a)

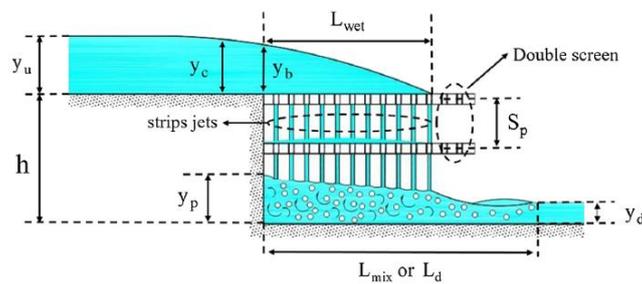


(b)

Figure 21 : Schematic illustrations of vertical drop equipped with horizontal screen and the experimental results conducted by Daneshfaraz et al.[17]: (a) schematic of a laboratory model and flume, (b)variation of relative energy loss against relative critical depth.

Daneshfaraz et al. [19] expanded the scope of research by investigating dual horizontal screen configurations. Their experiments considered variations in porosity, drop height, and screen spacing, revealing that screen spacing had minimal influence on relative pool depth and downstream energy. In contrast, increasing drop height reduced relative depth, reflecting the increased momentum of the plunging jet. Importantly, dual horizontal screens were shown to be highly effective in transforming supercritical flow into subcritical flow, underscoring their potential for stabilizing highly energetic flow regimes.

However, Daneshfaraz et al.[19] also demonstrated that maximum energy dissipation does not necessarily correspond to optimal morphological performance. While double screens were effective in dissipating energy, single screens with 50% porosity were more successful in reducing bed scour for similar energy losses. This finding highlighted an important trade-off between hydraulic efficiency and bed stability, emphasizing the need to consider sediment response when evaluating vertical screen performance.



(a)

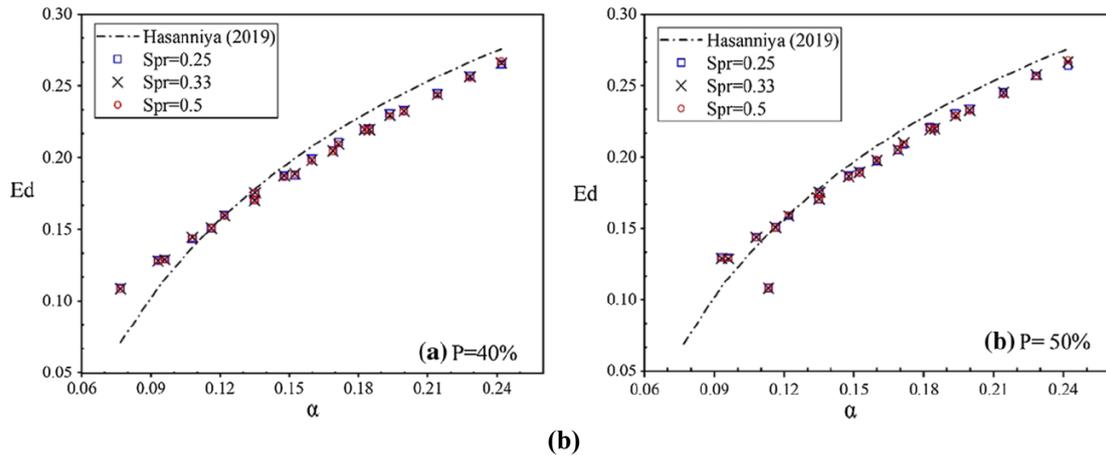


Figure 22 : Schematic illustrations of vertical drop equipped with horizontal screen and the experimental results conducted by Daneshfaraz et al. [19]: (a) schematic of a laboratory model and flume, (b) variation of relative energy loss against relative critical depth.

Rashdan et al.[27] experimentally investigated vertical drops fitted with horizontal screens of 50% and 60% porosity using three-hole geometries: circular, square, and rectangular. Among all tested configurations, the square hole geometry exhibited the greatest energy dissipation, attributed to the strong turbulence generated at its sharp corners. The 60% porosity square-hole screen demonstrated the best overall performance, achieving the highest reductions in downstream energy, velocity, wetted length, and mixing length compared with all other shapes and porosities. These findings clearly identify the 60% square-hole configuration as the most effective option for enhancing the hydraulic efficiency of vertical drop structures.

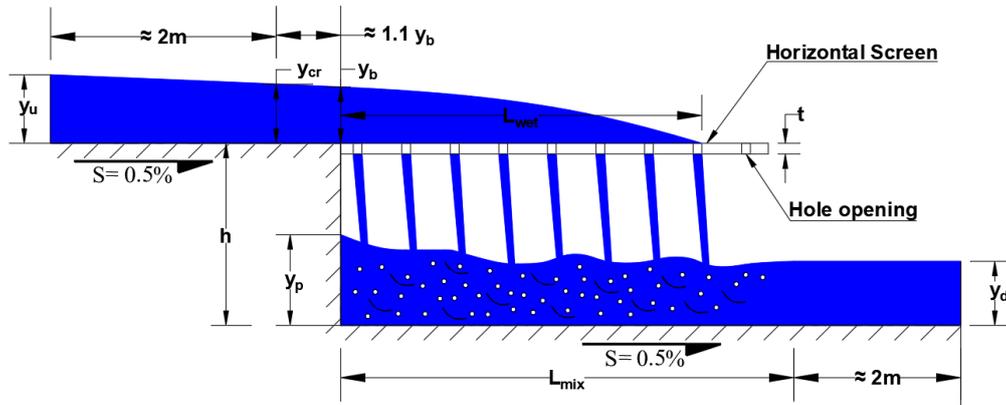


Figure 23 :The schematic sketch for the elevation view for a vertical drop equipped with a horizontal screen[27].

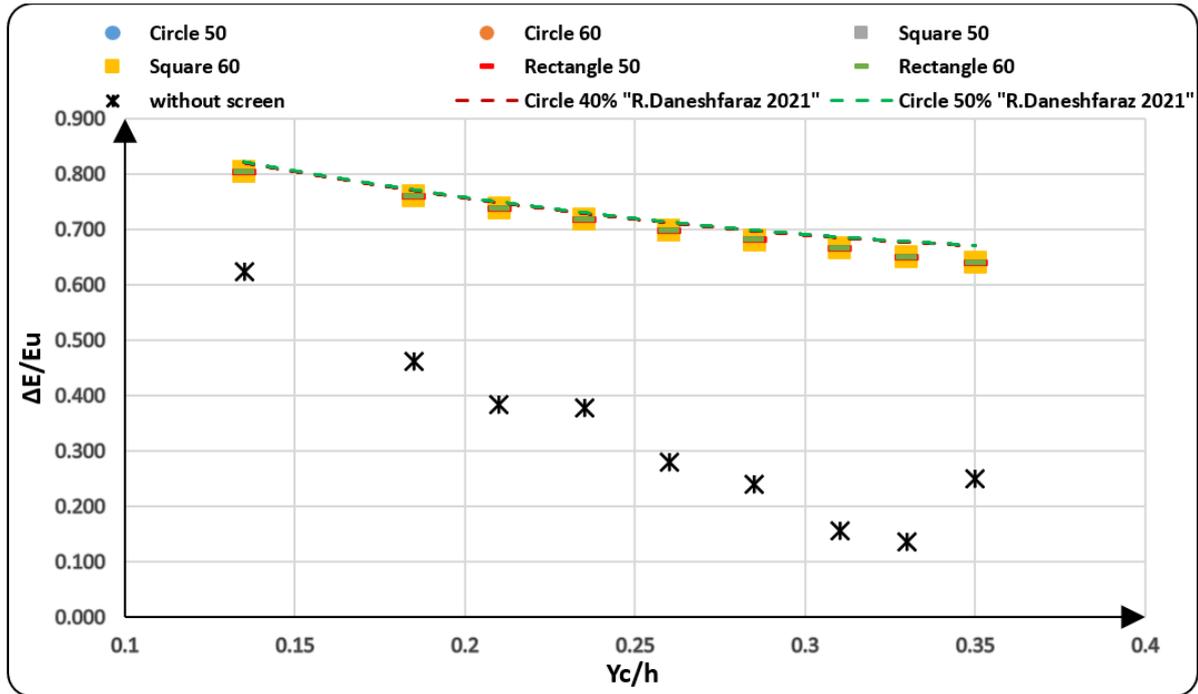
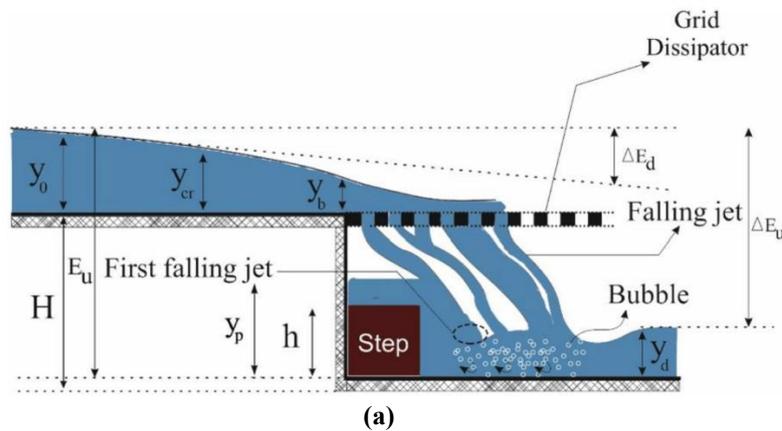


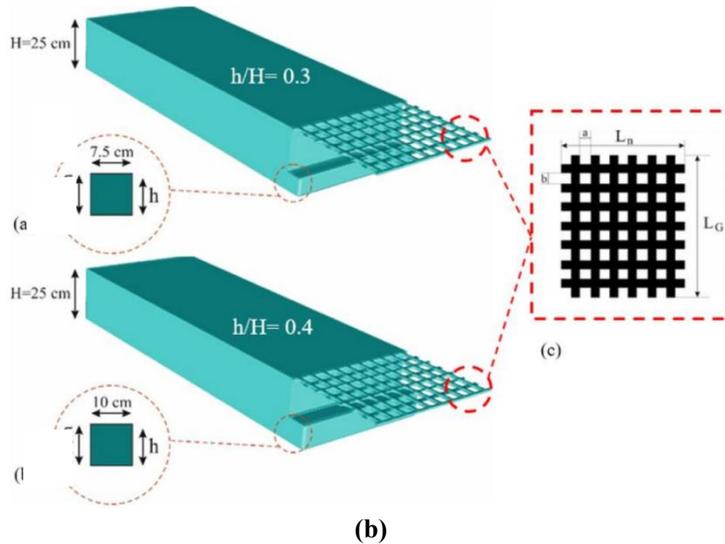
Figure 24 :Relation between relative energy dissipation and relative critical depth for all examined horizontal screens[27].

III. Numerical Modeling in Screen-Based Energy Dissipation Studies

3.1 CFD Modeling of Screen-Based Dissipators

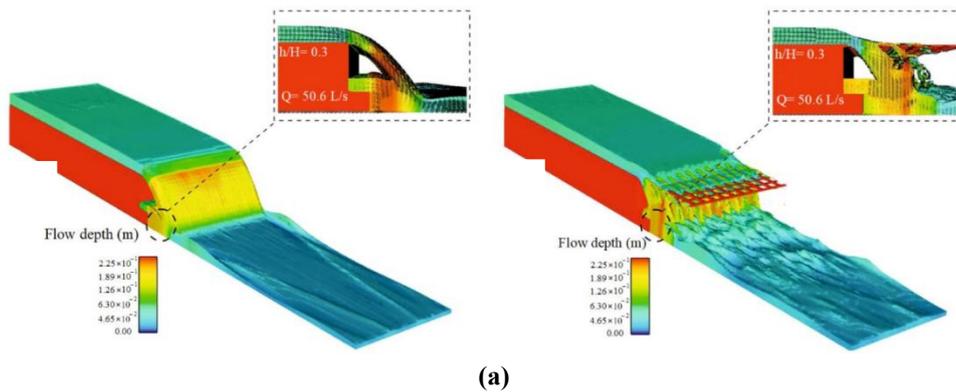
Numerical investigations have also been conducted by Daneshfaraz et al.[28], In order to assess the effectiveness of combined dissipative devices downstream of vertical drops. Using three-dimensional simulations with FLOW-3D, researchers examined the simultaneous application of steps and horizontal grid dissipators under supercritical flow conditions. The hydraulic model incorporated the volume of fluid (VOF) method for free-surface tracking and the RNG $k-\epsilon$ turbulence model, with relative critical depths ranging from 0.24 to 0.50.

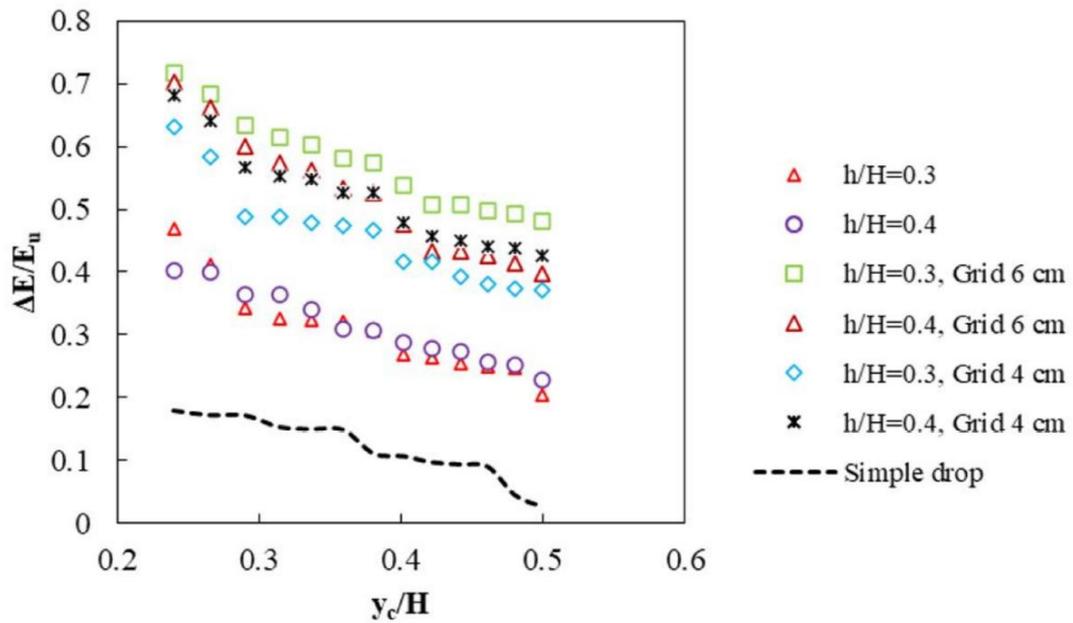




(b)
Figure 25 : Schematic illustrations of vertical drop equipped with combined setup of horizontal grid dissipator and a step conducted by Daneshfaraz et al. [28]: (a) Geometric and flow-related characteristics of a vertical drop fitted with step and grid dissipator systems, (b) Three-dimensional view of a vertical drop fitted with steps and grid dissipators.

The results conducted by Daneshfaraz et al.[28], showed good agreement with available laboratory measurements, particularly for relative downstream depth. Compared to a simple vertical drop or a drop equipped only with steps, the combined use of steps and grid dissipators significantly enhanced energy dissipation and increased relative pool depth. Variations in grid cell size were found to have a negligible influence on pool depth, while larger step heights and grid dissipators substantially reduced downstream Froude numbers from 3.83–5.20 to 1.46–2.00. In some configurations, relative energy dissipation increased by more than 4.8 times compared to a plain vertical drop, highlighting the strong potential of integrated step–grid systems for controlling flow energy and improving hydraulic stability downstream of drop structures.



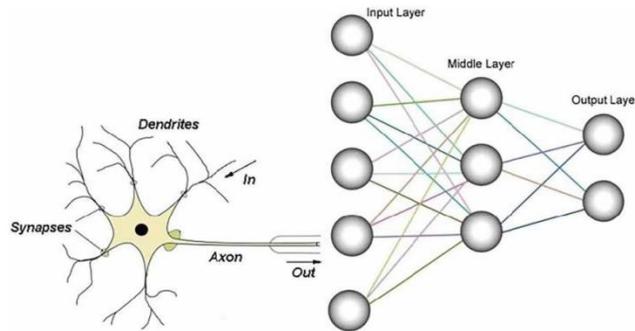


(b)

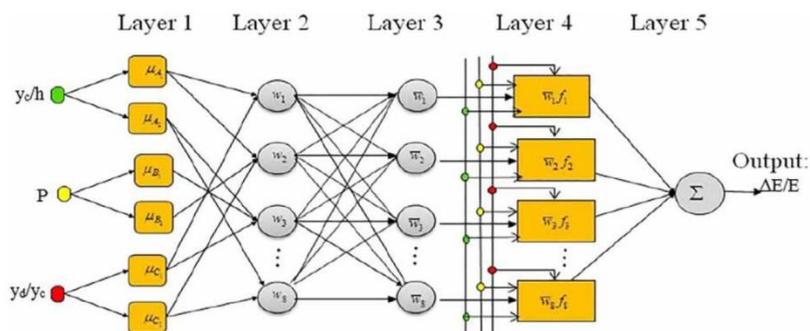
Figure 26: graphical illustrations and verifications of the numerical results for the vertical drop equipped with combined step and horizontal grid dissipator conducted by Daneshfaraz et al. [28]: (a) schematic 3D view for the flow3D module results, (b)variation of relative energy loss against relative critical depth.

3.2 AI-Based Modeling of Screen Dissipators

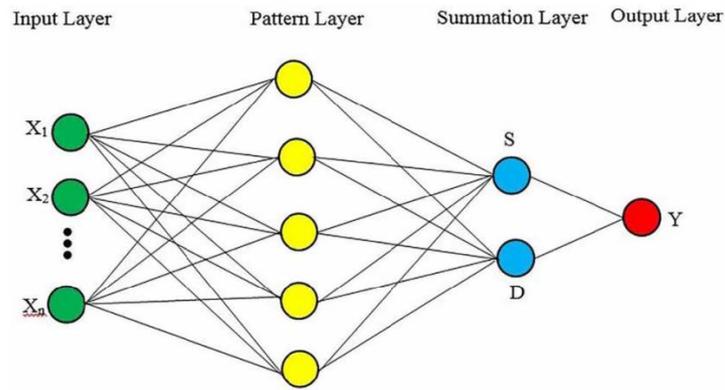
Norouzi et al. [29] investigated the capability of artificial intelligence and regression-based models to predict relative energy dissipation in vertical drops equipped with horizontal screens. Using an extensive experimental database of 108 laboratory tests with varying discharge, drop height, and screen porosity, several models including ANN, ANFIS, GRNN, SVM, GP, linear regression (LR), and multiple linear regression (MLR) were evaluated.



(a)



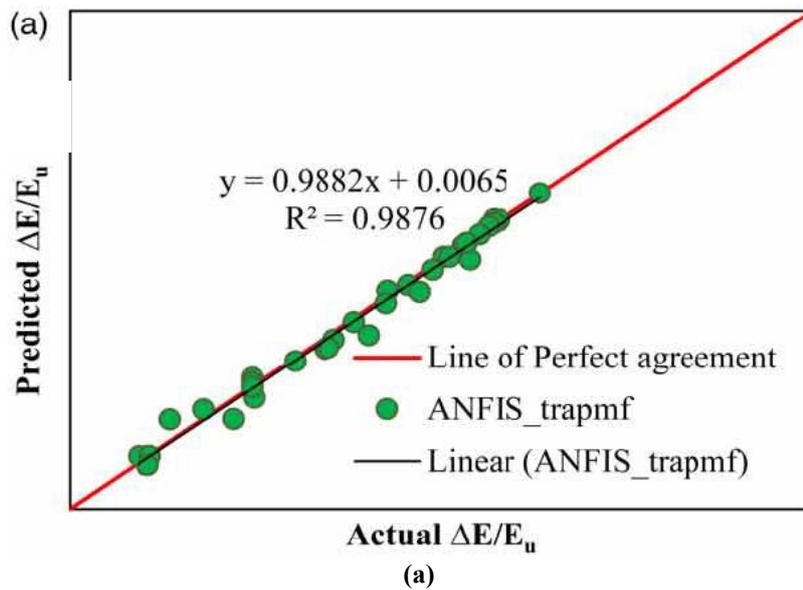
(b)



(c)

Figure 27 : Physical structure for different SVM algorithms conducted by Norouzi et al. [29]: (a) ANN, (b) ANFIS, (c) GRNN.

The results demonstrated that the ANFIS model with a generalized bell membership function provided the highest prediction accuracy, outperforming both soft-computing and conventional regression approaches. Sensitivity analysis further revealed that the relative critical depth ratio was the most influential parameter governing energy dissipation. The study highlighted the strong potential of AI-based techniques as reliable and high-precision tools for estimating energy losses in screen-equipped vertical drops and recommended their use in future hydraulic design and analysis.



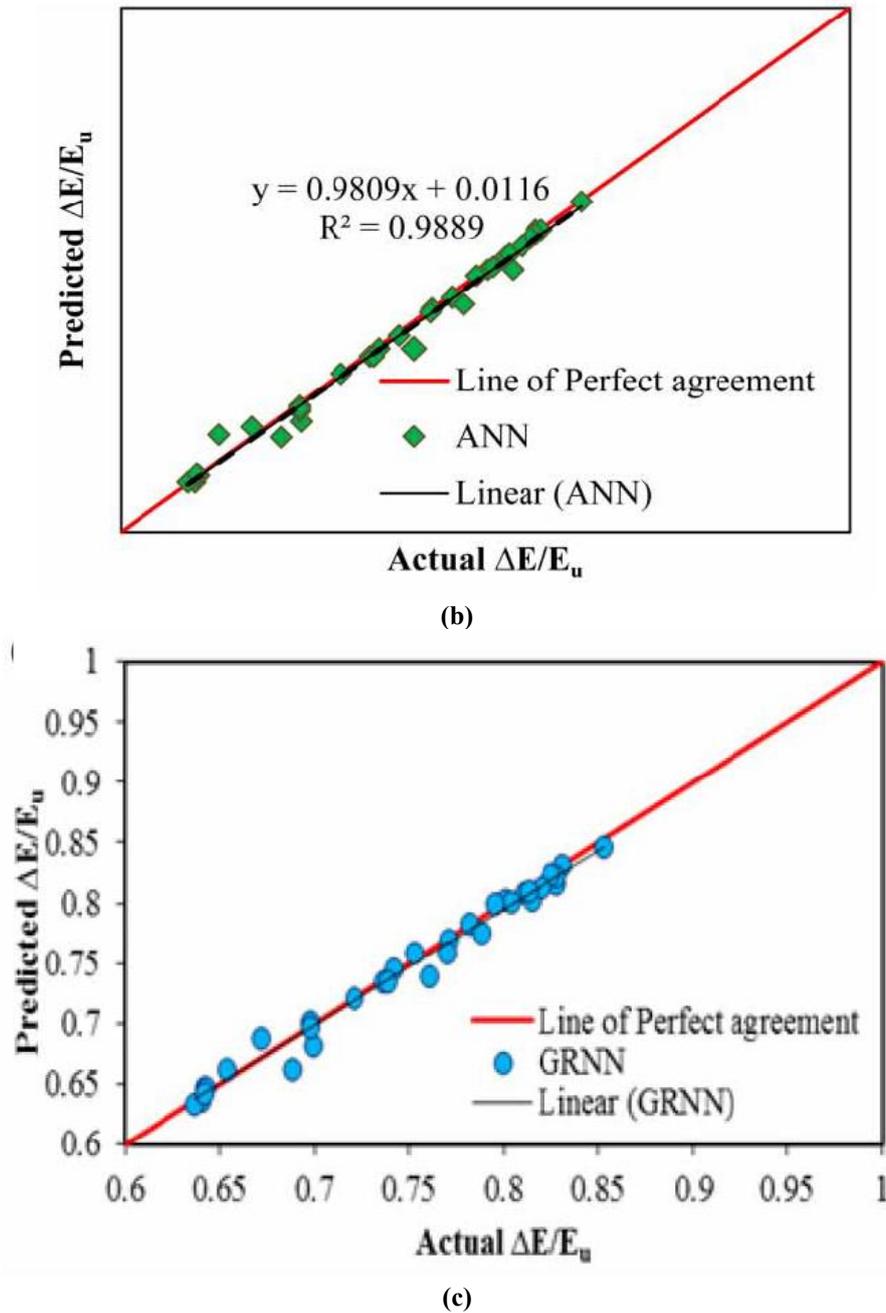


Figure 28 : Comparison of actual and predicted values of $\Delta E/E_u$ using different algorithms conducted by Norouzi et al. [29]: (a) ANFIS, (b) ANN, (c) GRNN.

IV. Conclusion

The reviewed literature clearly demonstrates that vertical drop structures equipped with screen-based dissipators, particularly horizontal screens, exhibit substantially improved hydraulic performance compared with conventional plain vertical drops. A broad range of experimental investigations consistently report significant increases in energy dissipation efficiency, enhanced relative pool depth and downstream flow depth, reduced downstream Froude numbers, and effective mitigation of bed scour. These improvements contribute to improved downstream flow stability and reduced structural and environmental impacts, highlighting the hydraulic and practical advantages of incorporating screens into vertical drop designs.

The enhanced hydraulic performance of screen-equipped vertical drops is primarily attributed to the effective disruption of the plunging jet, intensified turbulence generation, enhanced air entrainment, and improved redistribution of flow momentum within the downstream pool. By intercepting the jet and promoting rapid jet breakup, screens transform concentrated high-energy flow into a more diffused and uniform turbulent

field, thereby reducing localized impact forces and lowering scour potential. This mechanism leads to more uniform energy dissipation and improved hydraulic conditions downstream of the structure.

Among the various configurations examined, horizontal screens have consistently proven to be the most effective due to their direct and immediate interaction with the plunging jet. By intercepting and fragmenting the jet prior to its impact on the channel bed, horizontal screens distribute energy dissipation over a larger flow volume, reduce peak pressure fluctuations, and minimize localized bed stresses. As a result, horizontal screens offer a compact, efficient, and adaptable energy dissipation solution, particularly suitable for situations where spatial constraints, high discharge intensities, and stringent downstream protection requirements govern hydraulic design. Consequently, the existing literature strongly supports the adoption of horizontal screen dissipators as a reliable and high-performance alternative to traditional energy dissipation systems in vertical drop structures.

V. Future Research Directions

Despite the demonstrated effectiveness of screen-based dissipators in enhancing energy dissipation and downstream flow stability, several critical research gaps persist, limiting their broader application, optimization, and integration into engineering practice.

- **Limited systematic evaluation of screen orientation and inclination angle:**

Existing studies have largely investigated individual screen orientations in isolation, typically focusing on a narrow range of inclination angles. As a result, comprehensive comparative assessments under identical hydraulic and geometric conditions are lacking. The combined influence of orientation and inclination on jet interception, turbulence generation, air entrainment, momentum redistribution, and downstream flow stability remains insufficiently understood. This gap hinders the identification of optimal screen configurations for varying flow regimes and structural constraints.

- **Insufficient investigation of vertical screen placement relative to the drop brink:**

The downstream location of screens plays a critical role in controlling jet development prior to interception, turbulence intensity, spatial energy dissipation distribution, and the formation and stability of hydraulic jumps. However, systematic experimental studies examining a wide range of screen locations are scarce. The absence of such data limits understanding of how screen placement affects energy dissipation efficiency, downstream scour potential, and flow uniformity, thereby restricting the development of rational placement guidelines.

- **Inadequate application and validation of computational fluid dynamics (CFD):**

Although CFD provides powerful capabilities for resolving complex three-dimensional turbulent flow structures and multiphase interactions, its application to screen-based energy dissipators remains limited and insufficiently developed. Existing numerical studies frequently rely on simplified turbulence closures, steady-state assumptions, coarse mesh resolutions, and reduced-order multiphase modeling, which may not accurately capture jet breakup, air entrainment, vortex formation, and turbulent energy transfer processes. Furthermore, rigorous validation against high-quality experimental datasets is often lacking, reducing confidence in predictive accuracy and limiting the practical applicability of CFD as a design and optimization tool.

- **Lack of integrated experimental–numerical frameworks:**

Most existing investigations adopt either experimental or numerical approaches independently, with limited efforts toward coupled experimental–CFD methodologies. This separation constrains comprehensive flow-field interpretation and hinders the calibration and validation of numerical models. Integrated frameworks are essential for achieving reliable prediction of flow behavior, enabling parametric optimization, and extending laboratory-scale findings to prototype-scale applications.

- **Restricted understanding of scale effects and prototype applicability:**

The majority of available data originates from laboratory-scale models, while systematic investigation of scale effects and prototype-scale behavior remains scarce. This limits the reliability of extrapolating laboratory results to real hydraulic structures, particularly under extreme flow conditions. Improved understanding of scale dependence is therefore essential to ensure robust and safe design implementation.

Addressing these research gaps through coordinated experimental programs, advanced CFD modeling, and comprehensive validation strategies is crucial for developing a fundamental understanding of the hydraulic mechanisms governing screen-based dissipators. Such efforts will enable the establishment of rational, performance-based design guidelines and promote the reliable application of screen dissipators in modern hydraulic engineering practice.

Declarations

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest in reporting.

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Consent to participate: The authors declare their consent to participate in this work.

Consent to publish: The authors have participated in the preparation or submission of this paper for publication in Innovative Infrastructure Solutions.

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