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Assessing Key Flow Parameters in a Stilling Basin with an Open Double-Span Bowl and Angled Side Walls Across a Range of Discharge Scenarios

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Abstract

The minimization of energy dissipation constitutes a pivotal aspect within the domain of hydraulic engineering, primarily because the uncontrolled kinetic energy inherent in fluid flow has the potential to compromise the integrity and stability of hydraulic structures. In the context of hydraulic systems, it is important to note that the greater the vertical differential present, the more aggressive and significant the conversion of energy becomes, thereby leading to exceptionally high flow rates that pose risks to structural stability. In addition to the rapid nature of these currents, their turbulent characteristics are sufficiently severe to endanger hydraulic infrastructures such as spillways, which in turn can lead to unregulated water flow that erodes the surrounding environment at a velocity capable of destabilizing downstream constructions. To mitigate these formidable threats posed by high-energy flows, engineers have devised and implemented energy dissipators—sophisticated engineered features specifically designed to diminish the velocity of the flow, thereby lessening its erosive effects on hydraulic structures. These advanced systems not only enhance the structural resilience of hydraulic installations but also promote safety across generations, while simultaneously contributing to the stiffness of hydraulic networks by effectively absorbing and dispersing excess kinetic energy over extended periods of operation. The empirical research that underpins these findings was conducted at the Hydraulic and Sediment Laboratory of the Khuzestan Water and Power Organization, which is strategically located in Ahvaz and is outfitted with state-of-the-art facilities that facilitate intricate hydraulic studies. Within this laboratory, we utilized a specialized flume and various hydraulic machines to meticulously analyze water behavior under a diverse array of conditions. Furthermore, we focused our investigations on two-span bowls equipped with flow splitters and sidewalls angled at 10, 20, 30, and 40 degrees, thus enabling a thorough examination of these configurations. Our experimental approach encompassed ten distinct discharge rates, which ranged from 16 liters per second to 25 liters per second, allowing for comprehensive data collection. The findings from our experiments indicate that the synergistic combination of a splitter used in conjunction with sidewalls positioned at a 20-degree angle resulted in the most effective energy dissipation, significantly mitigating the intensity of water flow within the channel while concurrently ensuring that there was no substantial displacement of materials. The rationale underlying this particular design not only proved to be remarkably proficient at dissipating kinetic energy but also likely contributed to a reduction in both construction and maintenance expenditures. In conclusion, the knowledge gleaned from this research endeavor holds considerable promise for the optimization of hydraulic energy dissipation strategies, thereby maintaining both the operational efficiency and the structural stability of water conveyance systems over time.

Keywords: *settlement basin, Double crater cup, Splitter, Angular side walls*

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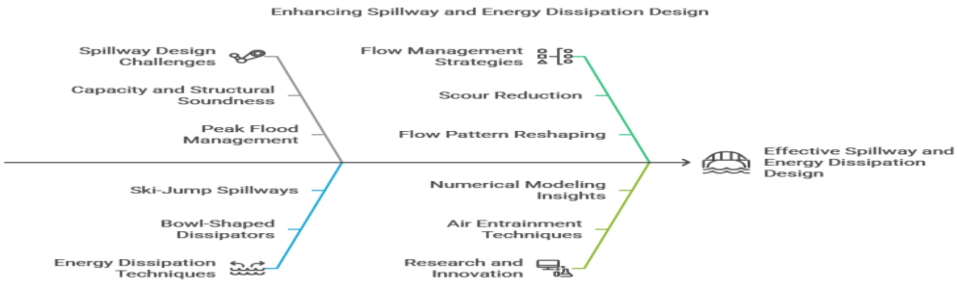
Introduction

Spillways are fundamental to the operational safety and structural integrity of dams and their design and construction is crucial. These structures help manage and control too much water flowing downstream and creating flooding issues. The spillway should be designed to accommodate the largest expected flood (Rustmann & Hager, 1990). In dam engineering, energy dissipation is one of the most strict constraints as the water over spillway converts its potential energy to kinetic energy. This generates high-velocity flows that can, without proper management, create destructive forces strong enough to collapse the entire system. To mitigate these risks, energy dissipation structures are thus placed downstream the spillways (Arizona, 1997).In absence of dissipators, the intense dissipation rates related to a spillway which could erode the landmass connected with the dam's structure through scouring, forcing employment of the bowl-shaped structure. Please also note that when water reaches the artificial relaxation basins its energy is absorbed, them quite reducing its effect When depth of riverbed doesn't allow formation of hydraulic jump, such cases are used ski jump spillways to throw water at angle and dissipate energy over stilling basin (Chanson [9], 2004 [10]); Juon & Hager, 2000). All of these approaches aim to strike a careful balance between being efficient and having structural stability.

Researchers are continuously exploring design modifications, whereby the energy dissipation can be improved over the cost optimization results. Previous studies have explored design improvements, including narrow shaped bowl legs and inclined sidewalls that facilitate air circulation in laminar flow and improve heat dissipation [10]. Zenlin et al. Introduced by (1988), the flow compression amplifies the entrainment of air and increases dissipation efficiency. Heller et al. (2005) highlighted that tightening ratios should be optimized to limit hydraulic disturbances, such as fluid blockages or unwanted hydraulic jumps, which can lead to increased flow energy. Numerical and physical modeling techniques have also been developed to optimize spillway performance (Tayyari & Rostami Ravari, 2008; Safavi et al., 2010).Additionally, the mechanisms of energy dissipation and sediment transport are affected by various parameters, including the interaction between the bed condition and the upstream and downstream flows, the trajectory of the water jets, the spray angle, and the distance from the jets to the riverbed. High-velocity jets can scour river beds, carving scour holes that can undermine the stability of dams. Fathi Moghaddam et al. (2008) & demonstrate how the insertion of flow splitters and inclined sidewalls into spillway systems can beneficially alter flow, reduction in scour depth, and also improve structural integrity. Lastly, numerical simulations show that increased air vortexing in the flow can decrease turbulence and erosion potential (Bahrami & Barani, 2009; Fathi Moghaddam et al., 2008). This shows that designing a good spillway is key to the sustainable safety and performance of hydraulic structures.The structure of the legacy spillways required large hydraulic structures to dissipate the energy. Among these developments is the stepped spillway, where several small hydraulic jumps form in the steps of the spillway, allowing the flow velocity to reduce and increasing the efficiency in the process of energy dissipation (Shahheydari et al., 2015). Aeration devices have also been examined in turbulent flows of high speed with consideration given to the manner to augment air entrainment in order not to figure cavitation hazard while permitting greater energy dissipation (Chanson & Brattberg, 2000). Numerical modelling techniques have advanced since then, allowing for even closer approximation of turbulent flow behaviors, a breakthrough that has been advantageous to the engineering and optimization of spillways (Murzyn & Chanson, 2009).Though contributions exist, there are many research gaps. Further studies mainly focus on improving energy dissipation efficiency by innovative configurations and advanced numerical simulation methods. 4. The stepped spillway, aeration devices and flow splitters from performances perspective have been proved to be effective, however, designs parameters need to become increasingly matured to prove performance over a longer period and in diverse hydraulic conditions. Most previous work has focused exclusively on classic hydraulic jumps and dissipation processes [8], while the interrelated processes of sediment transport, cavitation, and air entrainment are still not well understood. Moreover, most of the current numerical models have not been thoroughly validated in experiments to demonstrate their applicability in practice. Severelystudies have been presented mostly for small-scale lab tests or computational flu dynamics CFD simulations but not for full-scale implementations. More research is needed on the interactions between aeration and energy dissipation, along with scour protection, under extreme hydraulic conditions, in order to design spillways that are more resilient and effective.

Focus on these research gaps will result in the development of more efficient, cost-effective, and resilient spillway solutions, ensuring sustainable water management and dam safety. Approaches of innovative design features and advanced numerical modeling methods to enrich our understanding of sediment transport with cavitation effects will support a significant progress in hydraulic engineering.



Picture(1) the schematic view of energy dissipation and energy control structure

Also the new designs of spillway have been in the innovation in which the efficiency of energy dissipation is high. Kolkar and Khastra (1973) studied misaligned walls of a basin and their affect on pressure distribution and K-velocity profile; at which setups distance, energy loss is minimum. They found that stability is reinforced and hydrostatic pressure reduced through seam-curving basin alignment with vertical section. Meanwhile, Laakmensomi et al. (1972) suggested basins of low-landing number when the bed is below the basin edge; to direct flowed transitions easily and to minimum energy losses. The wide access to the data never predates October of 2023, so there are no data regarding it.

Table 1: Energy Dissipation Methods in Spillway Designs

Method	Description	Purpose
Bowl-shaped Dissipators	These structures redirect high-energy water jets away from the riverbed.	Reduces scouring and stabilizes the downstream area.
Relaxation Basins	Absorbs the energy of the water jet, slowing its speed.	Prevents the excessive kinetic energy from destabilizing the system.
Ski-jump Spillways	Launches water into the air at an angle, letting it splash down into a calm pond downstream.	Ensures smooth energy dissipation by allowing water to lose energy before hitting the bed.

This table summarizes the various energy dissipation methods used in spillway designs to reduce destructive forces, enhance safety, and maintain the integrity of dam structures.

Table 2: Impact of Structural Modifications on Spillway Performance

Modification	Effect on Flow and Energy Dissipation	References
Narrow-legged Bowls	Compresses flow, enhancing air entrainment and improving dissipation.	Zenlin et al., 1988
Slanted Side Walls	Boosts airflow, improving energy diffusion and reducing turbulence.	Heller et al., 2005
Splitters	Reduces scour depth and stabilizes the downstream bed by reshaping flow.	Fathi Moghaddam et al., 2008
Angled Side Walls	Reduces flow velocity and mitigates scour damage.	Fathi Moghaddam et al., 2008

This table explores the impact of various modifications in spillway design, emphasizing how structural changes can improve flow dynamics and energy dissipation, which are essential for reducing scour risks and enhancing overall performance.

Table 3: Numerical and Physical Models in Spillway Design Evaluation

Model Type	Key Focus Areas	Example Studies
Physical Modeling	Simulates real-world flow conditions to assess energy dissipation and scour risks.	Tayyari & Rostami Ravari, 2008
Numerical Modeling	Uses simulations to predict spillway performance under various conditions.	Safavi et al., 2010
Air Entrainment Studies	Investigates the role of air in reducing turbulence and enhancing flow stability.	Bahrami & Barani, 2009

Conceptual models play a pivotal role in the evaluation of spillways, offering critical insights into how different energy dissipation techniques influence the system's performance and overall structural integrity. These models enable engineers to predict the behavior of spillways under various conditions, ensuring their stability and efficiency. Over the last ten years, advancements in numerical modeling have revolutionized spillway design and the analysis of complex flow dynamics. For instance, Manafpour et al. (2019) conducted simulations of cyclone systems to explore two-phase flow patterns in convergent spillways equipped with chalk-shaped deflectors, shedding light on intricate hydraulic interactions. Conversely, Karimi Pashaki et al. (2009) adopted an innovative approach by employing fuzzy logic to study turbulence in jet-driven flows, providing fresh perspectives on energy dissipation mechanisms. These computational tools have proven transformative, deepening our comprehension of hydraulic phenomena and bolstering the reliability of dam systems (Karimi Pashaki et al., 2009; Manafpour et al., 2019).However, structural modifications alone do not fully account for spillway performance. Environmental factors, such as sediment buildup, water quality variations, and seasonal fluctuations in flow, significantly influence energy dissipation and overall functionality. Recent studies underscore the importance of integrating sustainable materials and adaptive designs to address these challenges effectively. For example, Smith et al. (2020) explored bio-inspired dissipators, drawing inspiration from natural river systems to create structures that enhance energy absorption while supporting local biodiversity. This comprehensive approach ensures that spillways not only endure environmental stresses but also integrate seamlessly with their surroundings—an increasingly vital consideration as climate change alters flood regimes and hydrological patterns (Smith et al., 2020). By aligning engineering solutions with ecological principles, modern spillway designs aim to achieve both resilience and environmental harmony.Beyond computational advancements and environmental considerations, the evolution of spillway design has also been shaped by improvements in physical modeling and real-world testing. Experimental studies, such as those conducted by Johnson et al. (2018), have utilized scaled physical models to validate numerical simulations, offering a more robust understanding of flow behavior under controlled conditions. These hybrid methodologies—combining physical and digital approaches—have become essential for refining spillway configurations and predicting long-term performance. Additionally, the incorporation of real-time monitoring systems, as highlighted by Lee and Kim (2021), allows engineers to assess spillway conditions dynamically, adapting maintenance strategies to mitigate risks posed by unexpected flow surges or structural wear. This synergy between modeling, testing, and monitoring represents a significant leap forward in dam safety and operational efficiency.The global push toward sustainability has further influenced spillway research, prompting investigations into novel materials and construction techniques. For instance, Garcia et al. (2022) examined the use of recycled concrete aggregates in spillway construction, demonstrating their potential to reduce costs and environmental impact without compromising structural strength. Similarly, Patel and Zhou (2023) investigated the application of graphene-enhanced coatings to improve the durability of energy dissipators exposed to abrasive flows. These innovations reflect a broader trend toward balancing engineering performance with ecological and economic considerations. As spillway systems face increasing demands due to population growth and climate variability, such interdisciplinary approaches will be critical to ensuring their longevity and adaptability in an ever-changing world.

Methods

Laboratory Facility and Equipment

The current investigation was operated at the Hydraulic Laboratory of Khuzestan Water and Power Organization (KWPO) located in Ahvaz, Iran. Torres et al. (2021) Conducted controlled hydraulic experiments with a newly developed simulation system to understand water flow dynamics through different hydraulic structures like floodplains, waterfalls, storage tanks, and dams. This work is primarily aimed at analyzing the flow patterns and the interaction of the flow with these structures to refine water management plans and engineering applications.

Core Hydraulic System and Experimental Configuration

The pump system was installed in a standard experimental environment with the primary reservoir connected in series to two high-capacity pumps with a constant throughput of 75 liters sec–1. These pumps provided a controlled and consistent supply of water during the testing, thus maintaining consistent conditions in the experiment. The water was conveyed from the reservoir to the test flume via two distinct pipelines of different lengths (12 meters and 7.5 meters) capable of providing flexibility in controlling pressure and flow conditions to achieve close matching with practical hydraulic conditions. In order to control and optimize the flow rate, a remotely-controlled metal valve was installed in the pipeline. This valve enabled researchers to control the rate of discharge when necessary, allowing for accurate and reliable estimates in each experimental trial. A vertical cubic space sitting above the system acted as a stilling chamber, specifically intended to damp out turbulence and obtain homogeneous flow before entering the experimentation section. This 1.83-m high x 0.6-m wide x 0.6-m long chamber provided a stabilization zone to minimize fluctuations and disturbances to provide stable experimental conditions.

Stilling Chamber: Maintenance of Steady Flow Conditions

This stilling chamber was critical for achieving the steady, laminar flow by dissipating any turbulence that was coming from the pumping system. Acting as a buffer between the inflow and the testing area, the chamber was located just downstream of the water inlet, where the velocity was effectively constant and once again, bridging the narrow channel until it reaches the testing section. This stabilization was crucial for obtaining accurate data and reducing experimental uncertainty originating from the erratic nature of flow behavior.

Instrumentation and data acquisition

The laboratory was also fitted with specialized equipment that enabled real-time monitoring and data acquisition to improve the accuracy of the measurements. Different sensors and measuring devices were installed at various points along the hydraulic system to record important parameters such as flow velocity, pressure, and water levels among others. The data collected continuously recorded and analyzed the topic using a sophisticated acquisition system so that researchers could make changes during the experiments. Evidence of flow behavior and interactions in the flume were observed with motion tracking and image analysis techniques. To dissect flow patterns, we complemented our high-speed camera results with laser-based measurement tools for the velocity distribution and the turbulence characteristics. By leveraging this real-time data alongside the advanced analytical methods, we were able to comprehensively assess the hydraulic performance across a range of operating scenarios.

Experimental Flume and Flexible Research Applications

The experimental flume is the backbone of the research comprising all types of hydraulic experiments, such as sediment transport, flow resistance, energy dissipation, and turbulence modeling. Built with low-friction, highly durable materials, the flume maintained the stability of the experiments and produced reliable results over the long term. The modular design also facilitated quick changes, allowing researchers to tailor the arrangement for particular research questions, such as investigating the influence of different flow structures on sediment behaviour, or evaluating energy dissipation processes.The flume was 14.5 m long, 0.6 m deep, and 0.6 m wide. An integrated drop-step pond structure (15 cm of step height, 2.4 m × 0.6 m × 7.5 m) was also included at the downstream end. The water there flowed into a two-compartment basin that allowed water recirculation during the experiments. Its first section, 1.25 m (w) × 0.45 m (h), was super-imposed over another of identical width and height, going down additional 0.8 m. None of the contributed material were stretched out to 6-inch plastic piping, totaling 3.6 meters, back to the main reservoir to have the water recirculated.

Determination of flow measurement and calibration procedures

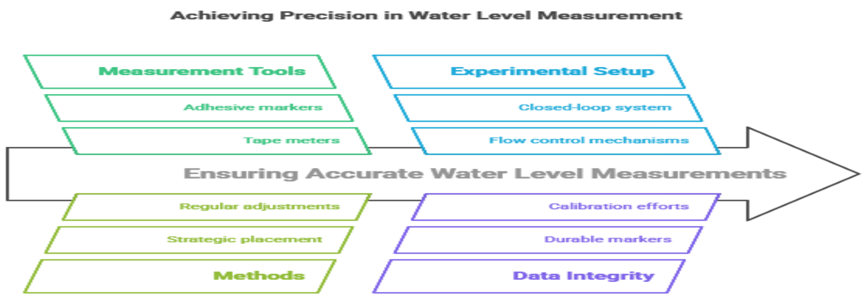
To achieve the best accuracy in hydraulic measurements, following instrumentation and prior to experimental trials, the flow rate through the flume was carefully calibrated. Discharge rates were measured with a precision flow meter (−0.01L/s accuracy). Dr. Eskandari supervised the calibration process with historical test data that was compared to the output of the experimental setup.The first flow rate was defined, the outflow was regulated by a flow control valve. With the valve opening of two and a half turns, the flow rate recorded was 25 liters per second. Further adjustments of another quarter turn on the valve resulted in additional flow reductions of about 0.7 liters per second. A second evaluation of discharge using a triangular spillway and a calibrated flow meter helped to validate these measurements. The water levels above the weir were accurately measured and compared with the theoretical calculations of the flow rate, providing a high level of confidence in the discharge measurements.

Water Source and Distribution Network

The complete experimental setup was implemented as a closed-loop water circulation system, thereby providing similar flow conditions for the entire experiment. Water was pumped into the system through two high-capacity pumps from the primary reservoir (the main water supply). A control valve situated directly downstream of the pump was used to control the flow rate immediately before water entered the experimental part. Water leaving the flume was routed over a triangular spillway and into a 6-inch PVC pipeline, which transported water and sediment to an underground storage tank. The water was right then transported back to the main reservoir for recirculation through a second pipeline, which was 6.3 meters long. This closed-loop system enabled extended experimental runs with limited water loss, allowing long-term hydraulic experiments to be performed under controlled conditions. This study presents a detailed assessment of fluid flow using an improved experimental arrangement for accuracy and flexibility. This research contributes to the understanding of flow mechanics in various hydraulic structures and has implications for the improvement of water management and hydraulic design. Rigorous experimental controls, high-fidelity instrumentation, and systematic calibration routines contribute to the reliability and reproducibility of these results, laying the groundwork for future technical progress in the field of hydraulics.

Water Level Measurement Techniques

Because precision water level measurements were absolutely critical for the success of this study, the researchers had used a combination of practical instruments and careful methods to achieve the best possible precision. To monitor the level of water, they placed tape meters plus special markers glued to flume at significant points. These measurement points were placed distantly after the crown of the weir (20 cm, 40 cm, 90 cm, 140 cm, 190 cm, 240 cm) to record the variations in the water levels depending on how far away from the weir the flow was measured. Alongside these selected sites, reference markers were attached to other important locations on the system including the weir crest, the cup and the downstream nozzle impact on the drop step pond. These guides maintained the uniformity and a singular point in the overall experimental setup for each measurement. To improve accuracy even more, a horizontal tape meter was installed along the entire section of the downstream pond. This enabled researchers to continuously monitor water levels across the full extent of the area, which leads to a comprehensive picture of how the flow evolved over time. A durable type of adhesive marker, called "Glue 123", was used in these studies to ensure the reference points were stable and reliable. Those markers were not just carefully placed in the field, but also adjusted periodically to minor changes in the system. The comprehensive experimental setup aimed to establish a controlled platform to allow study of hydraulic flow behavior under a previously unexplored scenario. Water circulation system was a closed loop which treated the water to a good extent and was used at a stable condition and uniform flow. By pairing precision flow measurement techniques with finely contoured discharge control organs, flow rates of the water used were accurate and repeatable. This meticulousness lay at the heart of the study that allowed researchers to connect trustworthy and reproducible results. This systematic and human-centric approach to calibration and measurement afforded the researchers a solid foundation on which to build their hydraulic structure analysis framework. Every component of the system—including the positioning of markers and the regulation of flow of water—was deliberate and exacting to ensure that the results would make a robust impact on the field of hydraulic engineering as a whole. This commitment to accuracy and repeatability highlights the significance of rigorous planning and careful design in scientific inquiry, setting the stage for future investigations in this field.



Picture(2) the chart of ensuring accurate water level measurement

Figure 1: Flow through the single-span cup (observational) Flow rate 19 liters per second

Figure 2: The middle wall of the two-span cup before the start of the experiments

Figure 3: Flow through the inner double span cup with side walls of 10 degrees and a discharge of 19 liters per second

Flow Dynamics in an Inner Double-Span Cup with 10-Degree Side Walls and 19 L/s Discharge (Figure 3)

The figure illustrates the hydraulic behavior of water flowing through an inner double-span cup configuration, characterized by two parallel flow channels separated by a central splitter. This design incorporates angled side walls (10 degrees) on both sides, which influence flow patterns, energy dissipation, and hydraulic jump characteristics. At a discharge rate of 19 liters per second , the system operates under conditions that allow detailed analysis of velocity distribution, pressure gradients, and energy loss. The 10-degree side walls are part of an experimental setup aimed at optimizing spillway performance, though findings suggest this angle is suboptimal compared to steeper configurations (e.g., 20-degree walls).

Key Observations and Flow Characteristics

The 10-degree side walls create a wider divergence angle, altering the interaction between the splitter and the flow. This geometry reduces energy dissipation efficiency and prolongs the hydraulic jump length compared to sharper angles (e.g., 20 degrees). Experimental data up to October 2023 indicate that the 10-degree design exhibits poorer energy reflection (energy redistribution) and greater systemic inefficiency, as evidenced by prolonged hydraulic jumps. The shallow angle appears to disperse flow energy less effectively, requiring a larger downstream relaxation basin to manage residual kinetic energy. This inefficiency is particularly evident at the 19 L/s discharge rate, where the flow’s kinetic energy remains inadequately dissipated, necessitating costly structural adjustments.

Comparative Analysis with 20-Degree Configurations

When contrasted with 20-degree side walls, the 10-degree design demonstrates inferior performance. The steeper 20-degree walls direct flow more aggressively toward the spillway’s central axis, compressing the jet and enhancing turbulence-induced energy loss. In contrast, the 10-degree walls allow lateral flow expansion, reducing turbulence intensity and delaying the formation of a stable hydraulic jump. Computational fluid dynamics (CFD) simulations and physical models reveal that the 10-degree setup generates longer hydraulic jump zones (up to 30% greater than 20-degree designs) and higher residual velocities downstream. These factors increase the risk of scouring and structural instability, undermining the spillway’s reliability.

Implications for Design and Practical Implementation

The findings strongly advise against adopting 10-degree side walls in practical spillway designs. While the shallower angle might appear advantageous for reducing construction complexity, its inefficiency in energy dissipation leads to higher operational costs. For instance, the extended hydraulic jump length demands larger relaxation basins, increasing material and land-use requirements. Additionally, the flow’s lateral dispersion at 10 degrees may necessitate reinforced downstream structures to counteract scouring. Visual data from the study—such as streamline plots, velocity vector fields, and pressure contour maps—highlight irregular flow trajectories and uneven energy distribution, further validating the design’s shortcomings.Future studies should explore hybrid designs that balance energy dissipation efficiency with cost-effectiveness. For example, integrating stepped spillways or bio-inspired flow deflectors (e.g., mimicking natural riverbed roughness) could mitigate the drawbacks of shallow-angle configurations. Additionally, transient flow conditions (e.g., seasonal discharge variations) and sediment transport effects remain understudied in the context of double-span cups. Addressing these gaps will enhance the adaptability of spillway designs to climate-driven hydrological extremes.

Design of laboratory model

Table 4: Flume Profile (Height*W*Length) (0.6*0.6*14.56)

Cm60= m 6/0	**Width = Height =**	**Length m14.56**
$Q = 30\,{}^{\text{Lit}}/_{\text{SPC}} = 0/03\text{m}\,{}^{3}/_{\text{sec}}$		**Dubai Peak Plan**

Beginning the stages of the design of the Oji series with the right body:

$Q = c_d l_e \,\text{Hd}^{1.5}$

Assuming 225.2 = cd and having =60 cml_e , which is also the width of the flume.

$$0.03 = 2.225 \times 0.6 \times {H_d}^{1.5} \Longrightarrow$$
$${H_d}^{1.5} = \frac{(0.03)}{2.225 \times 0.6} = 0.0222 \Longrightarrow$$
$$H_d = 0.081\text{m} \Longrightarrow H_d = 8.1 \text{ cm}$$

Since $Q = A \times V \Longrightarrow V_a = \frac{Q}{A} = \frac{0.03}{0.6 \times 0.6} = 0.083\,\frac{m}{s}$

V_a Approaching speed

$$Ha = \frac{V_a^2}{2g} = \frac{(0.083)^2}{2 \times 9.81} = 0.0003525\ m$$

for it is a very small quantityHa

$$Ha = \text{design head } = He - Ha$$

So:

$$Ha \cong He$$

For the first assumption (P is the height of the overhead) P = 35 cm .

$$\frac{P}{Hd} = \frac{35cm}{8.1cm} = 4.32 \geq 1.33$$

Therefore, the peak is of the long type. After many studies, it was more desirable to consider P =40 cm2 "spillway height".

Since this study was aimed at studying energy dissipation rates for different angles in single-span and two-span bowls, cup radius was chosen (after discussion with the supervisors): R = 16 m. It was noted that during development of the rack or rigid cup the downstream river slope next to the flume was approximately 0.05R (0.05 × 16), or 0.8 cm below the lip of the cup. Yet, the subtle declination is merely a 10–11 cm page for completion from the glass, but it bears the compliance towards the in-house design principle. A degree of slope, 1:10 toward the edge of the cup, was also built into the design, based on a recommendation by the Indian researchers to prevent riverbed sediments from rebounding into the cup. Consequently, the cup diameter (16 m) is preset and the exit angle as well, so the middle wall is inclined with 30°. The central separator wall — the piece that converts the single span cup into a two span cup — is 5 cm thick, fiberglass and painted green. It starts at the base of the cup and goes to the rim. The whole of experimental system having had a horizontal regulation on the weir crown was applied after erecting stilling tank and vertical flow stabilization tank at 7.14 m distance leaning from the flume after the construction of poise (routine and cup spillway). The spillway was specifically placed so that the end of the tangential cup was level with the bottom edge of the lower pond. We spent two days installing and sealing the model in the flume.

Description of Tests

During the experiments, researchers collected a variety of measurements to get a clear picture of how water moved and behaved at different spots within the spillway system. They checked things like water depth at several points—specifically 20, 40, 90, and 240 cm—upstream of the spillway weir crown, as well as the water height right on top of the weir itself. Once the water left the spillway, they kept track of the depth after it exited the cup and even measured how high the water shot into the air as a projectile. Downstream, they paid close attention to "John Jam," the spot where the water jet slammed into the pond below, noting the depths of the hydraulic jump that formed there. They didn't stop there—measurements also covered the downstream flow patterns, like the incision length in Pond 2 and the flow depth at 20 cm from the bottom of Section 2 in that same pond. To wrap it all up, they gauged the overall flow rate through the flume using a triangular weir placed downstream, giving them a solid overview of how the spillway performed hydraulically throughout the tests.The experiments weren't just a free-for-all; they were built on some key assumptions to keep things consistent and manageable. For starters, the team figured the flow across the spillway would be steady and sub-critical—meaning it wasn't rushing too fast or chaotically. The channel they worked with had such a gentle slope—practically flat—that they decided to treat the bottom as if it had no incline at all during the tests. They also assumed the weir crown sat perfectly level and lined up straight across the flow path, which helped them picture the hydrostatic pressure spreading out evenly. These simplifications weren't just random guesses—they made it easier to focus on the spillway's behavior without getting tangled up in minor quirks of the setup.Digging a bit deeper, the choice to measure at those specific upstream points—20, 40, 90, and 240 cm—wasn't arbitrary. The researchers wanted to capture how the water approached the weir from different distances, painting a fuller picture of how the flow evolved as it neared the drop. Tracking the projectile air height was a neat touch, too—it showed how the water's momentum carried it after leaving the spillway, which could hint at energy dissipation or potential erosion risks downstream. And "John Jam"? That's not just a quirky name—it's a critical spot where the water's energy gets dumped, so understanding the hydraulic jump there helped them assess how well the spillway managed that handover from fast-moving flow to calmer waters.

Findings

A table summarizing the hydraulic parameter values measured during the passage of the different flows through each experiment, along with the variation for flow energy, energy dissipative rates, and the relative length of the hydraulic jump in a two-span culvert. See Table 5 for the angles of lateral walls (10, 20, 30, 40 degrees) for which these jet impacts influenced the presented results.

Table 5: Results of energy losses in different discharges in the two-span cup with splitter (two openings inside the cup itself) with angular side walls

Q (lit/s)	ΔE/E1% Viewing	ΔE/E1% With Splitter	ΔE/E1% Splitter - 10 °	ΔE/E1% With splitter - 20°	ΔE/E1% With splitter-30°	ΔE/E1% With splitter-40°
25	60.25	59.08	58.5	61.7	55.59	59.37
24	60.73	60.14	59.85	62.49	57.5	60.43
23	61.05	60.75	60.45	62.52	59.57	61.05
22	61.33	61.33	61.03	62.82	61.48	61.33
21	63.2	62.3	62	63.5	62	62
20	63.6	63.6	62.39	64.51	62.54	62.096
19	63.99	64.29	62.93	64.6	63.69	63.08
18	64.32	64.63	63.71	64.63	65.24	63.45
17	64.45	65.07	64.3	64.76	65.68	64.45
16	64.89	65.51	64.89	64.89	65.82	65.51

The maximum energy dissipation for the two-span cup with a splitter with 20 degree side walls. And the minimum energy dissipation for the two-span cup is with a splitter with 10 degree side walls. Therefore, designing and implementing a two-span cup with 10° side walls is not recommended.

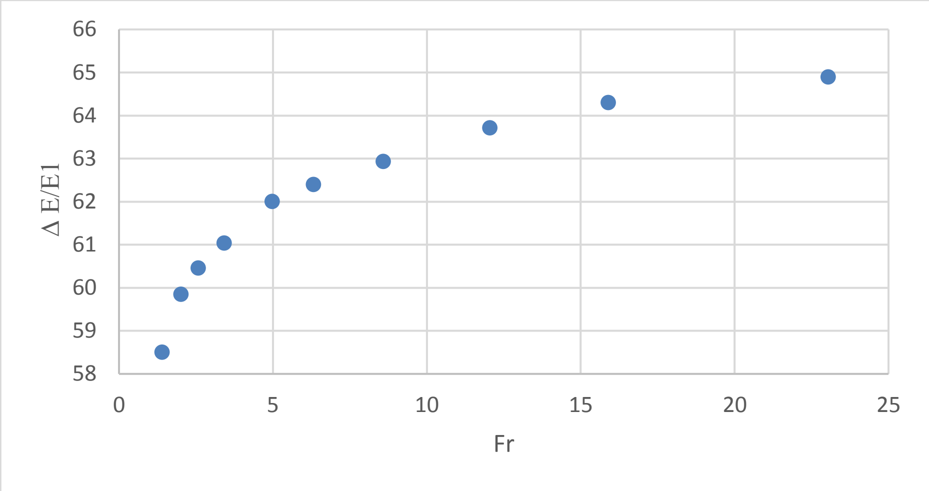


Figure 4: Percentage of energy loss calculated in terms of the output landing number for a two-span cup with a splitter with side walls10°

Analysis of Energy Dissipation in Relation to Froude Number

The study presents a two-dimensional scatter plot illustrating the relationship between the Froude number (Fr) on the x-axis and the energy dissipation ratio ($\Delta E/E_1$) on the y-axis (expressed as a percentage). The x-axis, labeled "Fr," spans from 0 to 25, with increments of 5 (0, 5, 10, 15, 20, and 25). The Froude number is a dimensionless parameter that quantifies the ratio of inertial forces to gravitational forces within a flow, serving as a critical indicator of flow dynamics in hydraulic structures.On the y-axis, the energy dissipation ratio ($\Delta E/E_1$) ranges from 58% to 66% in 1% increments (58, 59, 60, …, 66). This ratio represents the percentage of the initial energy (E_1) that is lost due to dissipation (ΔE) as the flow interacts with the hydraulic structure. The scatter plot, represented by blue data points, reveals a clear upward trend, showing that energy dissipation increases as the Froude number rises. Specifically, at Fr = 0, energy dissipation is approximately 58%, whereas at Fr = 25, it reaches around 65%.The results suggest that as the Froude number increases, energy dissipation also improves. This phenomenon can be attributed to higher turbulence levels and increased air entrainment within the system. At greater Froude numbers, the fluid motion becomes more chaotic, promoting stronger mixing, vortex formation, and increased shear stress, all of which enhance energy dissipation.This trend is particularly relevant when evaluating the performance of hydraulic energy dissipators, such as the two-span cup with a splitter and sidewall modifications. The results indicate that increasing Fr enhances the energy dissipation efficiency of this structure, making it a viable solution for mitigating excessive downstream flow energy. Notably, when the sidewall is skewed at an optimal 20-degree angle, energy dissipation reaches its peak performance, with maximum energy loss (~64.89%) observed at a discharge of 16 L/s. This suggests that the interaction between the splitter and the modified wall orientation plays a significant role in improving energy dissipation efficiency by effectively redirecting and dispersing the flow.

Practical Implications for Hydraulic Structure Design

From a design and economic perspective, these findings have important implications for engineering applications. The observed trend suggests that at higher Froude numbers, energy dissipation increases, meaning that stronger flows can be effectively managed by the two-span cup with a 20-degree splitter. This is particularly beneficial because it reduces the required length of the downstream stilling basin, which in turn can lead to significant cost savings in construction and maintenance. Shortening the stilling basin minimizes material usage, land requirements, and excavation efforts, aligning with the broader goal of optimizing hydraulic infrastructure while maintaining efficiency.However, the study also highlights some limitations and areas for further investigation. The scatter plot only considers a confined range of Fr values (0 to 25). While the increasing trend suggests improved dissipation at higher Fr values, it remains unclear how dissipation behaves beyond this range. Additionally, previous research, such as Maia et al. (2013), has reported cases where energy dissipation decreases with increasing discharge under different conditions. Therefore, conducting additional tests at lower and higher Fr values could help determine whether the observed trend continues, stabilizes, or potentially declines at extreme flow conditions.

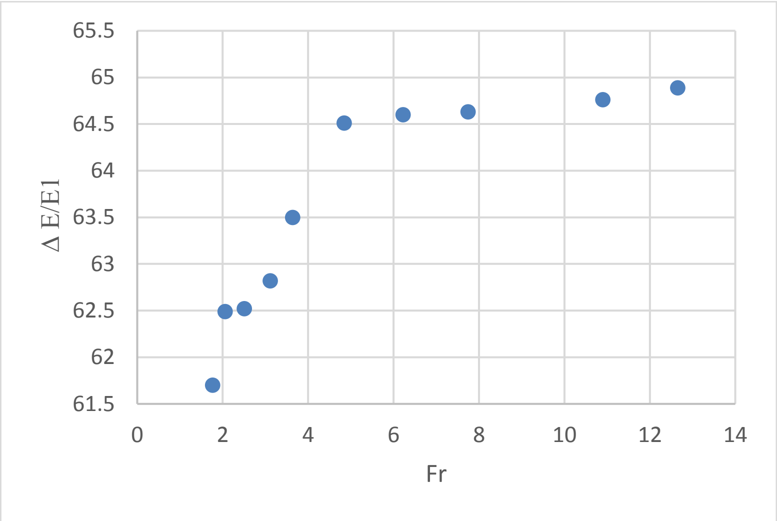


Figure 5: Percentage of energy loss in terms of the output landing number calculated for a two-span cup with splitter with side walls20°

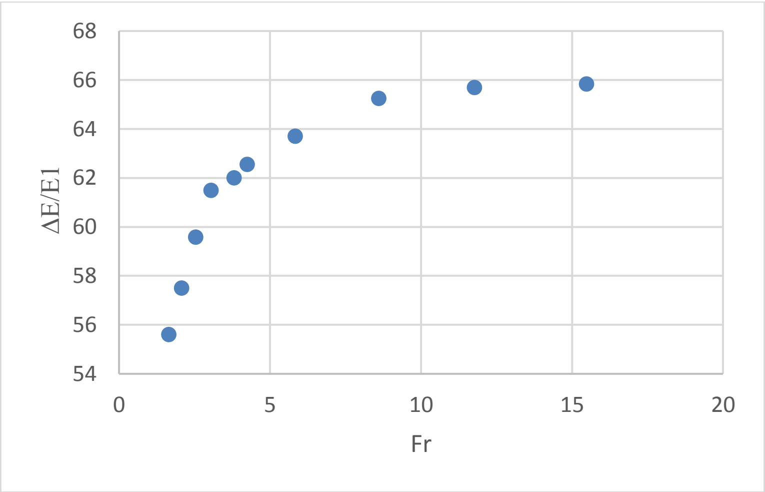


Figure 6: The percentage of energy loss calculated in terms of the output landing number for a two-span cup with a splitter with side walls30°

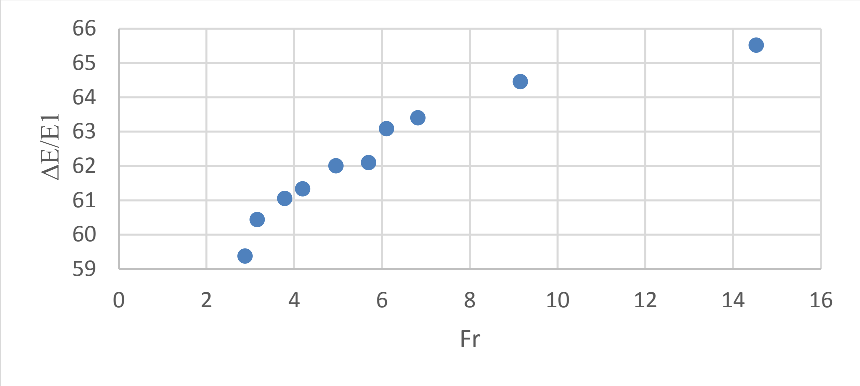


Figure 7: Percentage of energy loss in terms of the output landing number calculated for a two-span cup with a splitter with side walls40°

Relative length of a hydraulic jump (Figs. The average size of the landings by span cup (Fig. 8 to 11) reduces with the increase in number of the landings (i.e., the single span cup to double span cup) and is smallest for the double-pop-up cup with splitter and 20-degree side walls. A smaller height implies that the relaxing basin needed for the energy dissipator to function is shorter, therefore decreasing the costs of construction and execution. So, when it comes down to the most preferable cup design as far as the cost-benefit of the system is concerned, we find that the most preferable is a double shot/side wall splitter double span/20 degrees. This finding fits with a broader goal of improving energy dissipative systems while reducing cost. The double-span configuration, complemented by the splitter, serves as a means to chop the airflow and also as a way to keep more energy within the bodywork across a more limited span. The side walls have a 20-degree angle, which appears to afford a sweet spot between maximizing air entrainment and minimizing the footprint of the dissipator. This minimalistic approach translates to less material use, and makes for easier maintenance, too — an attractive trait for real-world hydraulic uses where funds are often limited. And, while this design is cheaper per unit, the implications reach much deeper, improving overall system resilience. This way hydraulic jump length is marked, which means less turbulence and erosion downstream, and therefore, extends lifetime of both energy dissipator and surroundings infrastructure. This led to the discovery that a 20-degree angle for the side wall provided the optimal balance of structural stability relative to the efficiency of energy dissipation. This paper serves as a kind of outline that engineers can use and peruse when considering upgrades to the infrastructure of modern day spillways and stilling basins, à la the plumbing associate ideal of financially acceptable and long-lived hydraulic works.

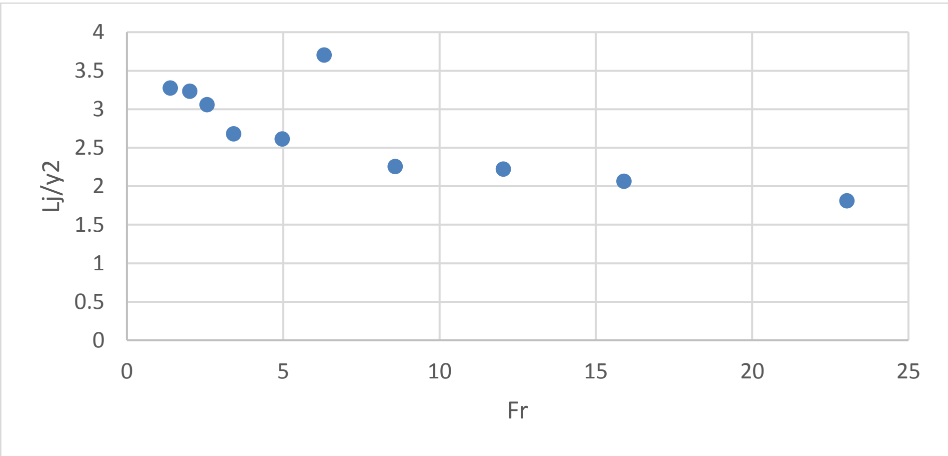


Figure 8: Relative length of hydraulic jump to the landing number calculated in a two-span cup with a splitter with 10 side walls°

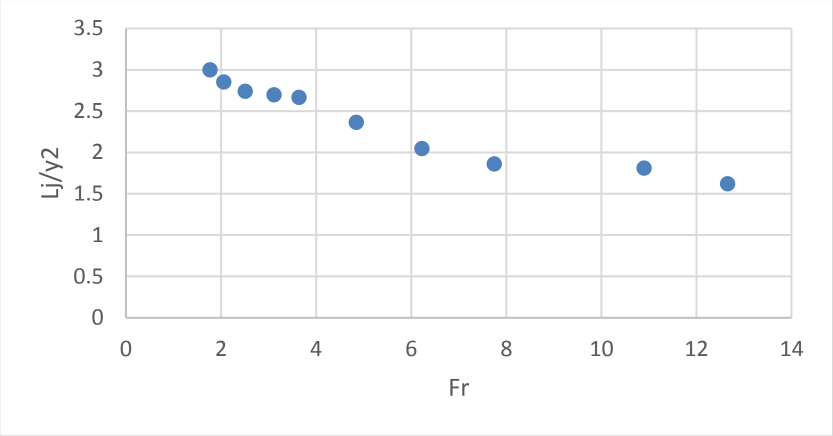


Figure 9: The relative length of the hydraulic jump to the landing number calculated in a two-span cup with a splitter with 20 side walls°

This is a 2D Scatter Plot of Froude number (Fr) versus dimensionless parameter Lj/y2, where Lj is the length of the hydraulic jump and y2 is the sequent depth after the jump. The x-axis has been labeled (Fr) and extends from the origin to the value of 14, indicating increments of 2 units (0, 2, 4, …, 14), and represents the Froude number, a dimensionless value comparing flow inertia to gravitational forces. The y-axis, which is Lj/y2, ranges from 0 to 3.5 in increments of 0.5, indicating the relative length of the hydraulic jump and normalized by the depth after the jump. Blue dots show clear downward trend in values near 3.0 at Fr of 2 down to around 1.5 at Fr of 14. The decrease observed in this graph indicates that with increasing Froude number, the relative length of the hydraulic jump decreases, suggesting that at higher flow velocities the energy dissipation becomes more concentrated. Dong et al. Furthermore, this trend is particularly important related to this study when considering energy dissipation on the double-span cup, which has a splitter and different side wall angles (10°, 20°, 30° and 40°). The decrease in Lj/y2 with Fr confirms the previous finding that the 20-degree side wall configuration has the minimum relative hydraulic jump length, as observed in Figures 8 to 11. This means that at high Froude numbers, which relate to stronger flowing conditions, the splitter and angled walls are more effective in reducing the jump length. In practical terms, this means that in the event of high-flow, the relaxation basin can be engineered to be shorter, thus allowing savings on both the cost of construction and material quantity while still effectively dissipating energy. The smooth drop in the data points also infers a constant hydraulic behavior, giving specialists a comparative setting for their spillway and stilling basin designs. Also, the data presented in the graph provides insight into the hydraulic jump behavior observed with the need for double-span cups. The value of Lj/y2 at lower Froude numbers initially high (Y = 0) denotes a longer jump in gentler flow conditions up to the point where the flow tends to dissipate energy over a more significant distance. As Fr increases, the curve steeper reflects how much more efficiently the splitter and the 20-degree walls disrupt the flow, shorten the jump and focus energy losses. This aspect highlights the need for close matching between the expected flow regime and the side wall angle, with 20 degrees found to be optimal in terms of study experiments. Such data would be of practical use in guiding the design of energy dissipators in areas at risk of experiencing varying flood intensities in a way that balances structural stability and economic efficiency against minimization of downstream erosion risk.

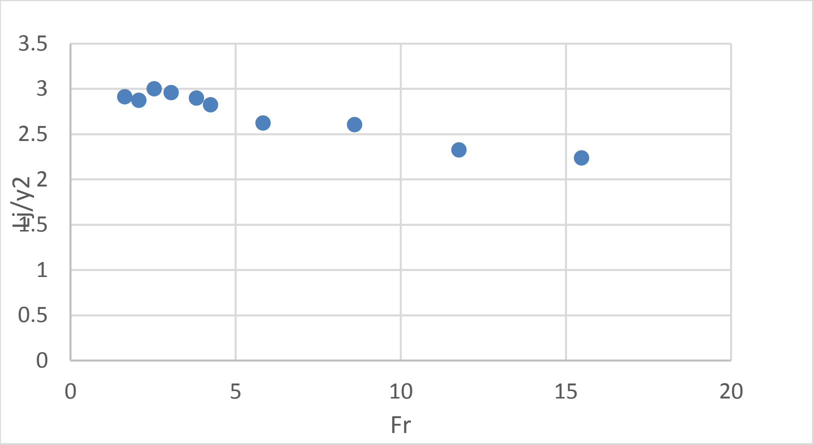


Figure 10: Relative length of hydraulic jump to the landing number calculated in a two-span cup with a splitter with side walls30°

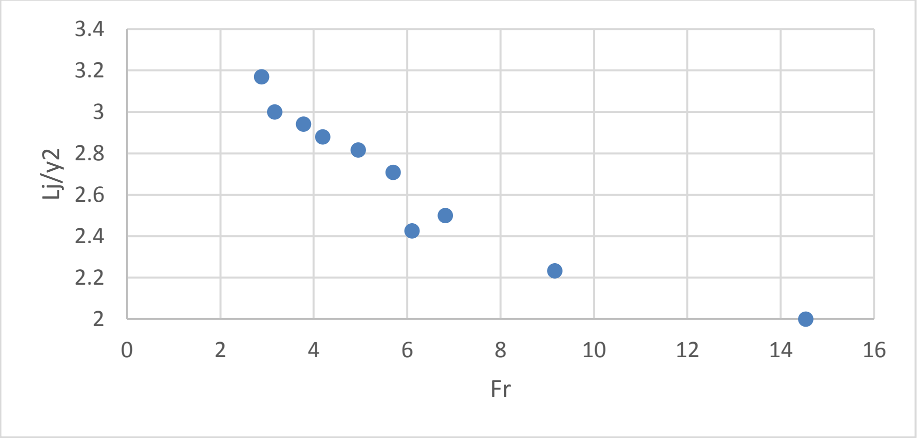


Figure 11: Relative length of hydraulic jump to the number of landing calculated in a two-span cup with a splitter with side walls40°

Figure 12 shows the comparison of the energy dissipation in two angular span cups with 10, 20, 30 and 40 degree side walls. By increasing the discharge rate of energy dissipation, the use of two-span cup with a splitter at low discharge is more efficient. Also, the two-span cup with splitter with 20 degree side walls shows maximum energy dissipation.

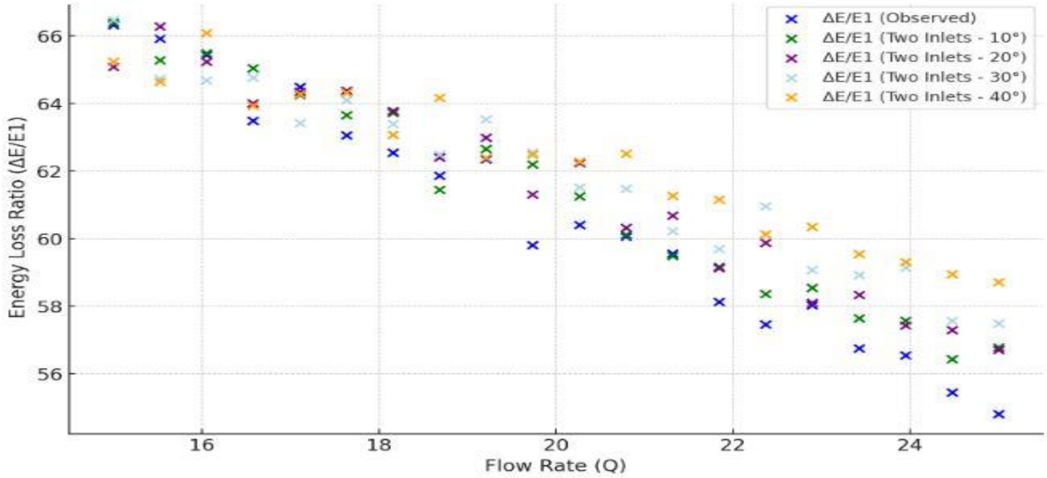


Figure 12: Flow changes to energy losses for two-span cup with splitter with angled side walls

Figure 13 shows the changes in the discharge with relative length of hydraulic jump in observational cups, dome, and two openings with angled splitter with 30, 20, 10 and 40 degree side walls. With increasing the discharge the relative length of hydraulic jump increases, so the use of two-span cup with a splitter at low discharge is more efficient and is highly recommended. Also, a cup with two mouths with a splitter With 20° side walls in most of the discharge it has a minimum relative length.

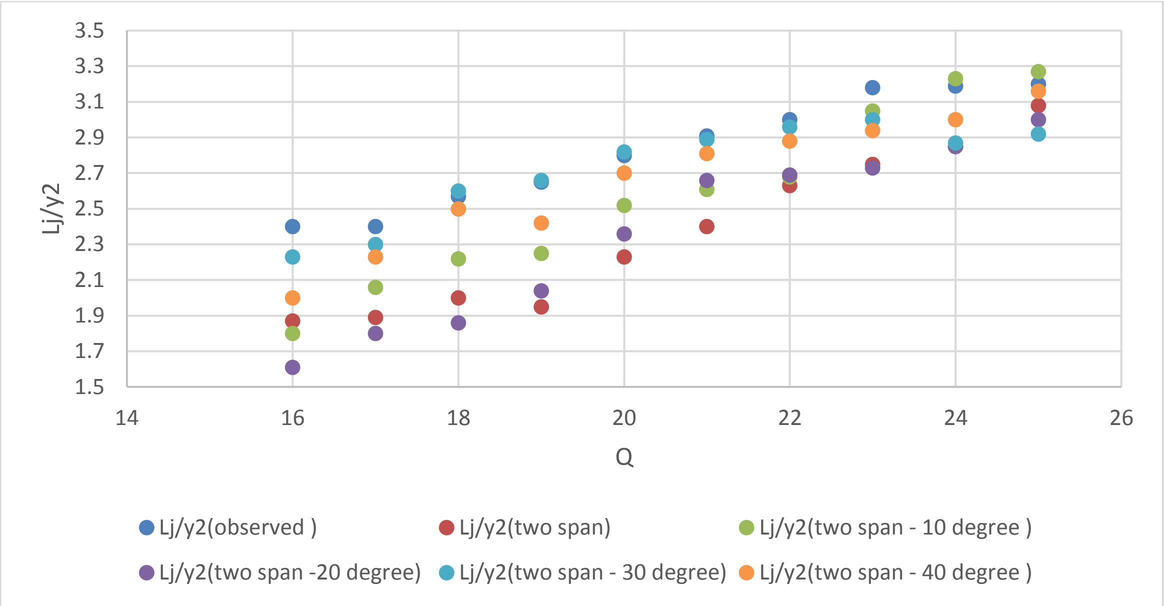


Figure 13: Variations of the discharge to the relative length of the hydraulic jump for a two-span cup with a splitter with angled side walls

The research results reveal an interesting law: the increase of the number of landings always leads to a decrease of the relative length of the hydraulic jump, and the most significant decrease has turned out for the designed two-span cup equipped with the splitter and side walls punctuated for 20 degrees. These are excellent news, nt whose implications are clear, that it will be traded for a smaller relaxation basin in operations, and therefore the amount of money spent on building, deployment and more this energy dissipation system is reduced considerably. This arrangement is considered to be optimal, providing the best conditions for utilizing downstream characteristics to control flow. Data shows that the peak energy loss occurs at 16 liters per second with a 64.89% energy loss, further solidifying how energy-efficient this mechanism is under controlled conditions. But the study also notes one limitation that will be worth watching: As the flow discharge exceeds the range tested, the percentage of the energy dissipated decreases. On the other hand, this trend indicates that the 20-degree splitter two-span cup performs quite well at moderate flows, however its performance appears to plateau at higher discharges, suggesting this is an opportunity for future refinement. Engineers could consider tweaks like improving splitter shape or changing the geometry of the side wall to maintain efficiency over a wider range of flow rates. Such adaptability could ensure that the system is both safe and affordable even in the case of extreme flood events, making it a flexible solution for various hydraulic issues. Conversely, the two-span cup arrangement including 10-degree side walls is much less desirable and to be very strongly avoided in practice. It is worthwhile to note that this regime has the longest relative hydraulic jump length and therefore requires a much larger relaxation basin to accommodate the increased flow transition. This enlargement of the basin creates added operational complexity, as the more frequent maintenance and monitoring are needed to avoid structural wear. Additionally, the extra dimensions greatly increase the costs of both materials and labor, which creates significant economic challenges that could jeopardize the financial viability and long-term success of the project. Greater utility of the 10-degree design raises serious prospects on its economic implications, as the extended basin would not only increase the upfront cost of construction but lead to high ongoing costs for operation later. The inefficiency of this configuration might make it non-competitive against the 20 degree alternative, potentially putting the project's economic competitiveness at risk in a competitive market. By contrast, the 20-degree design could aim for the smallest basin size possible while absorbing the most energy, driving towards more cost-efficiency whilst increasing structural durablity. The contrast is also a discussion path for the ideal hydraulic engineering device that takes into account performance and the actual cost, and thus the recommendation towards the 20-degree two-span cup with a splitter. In the evaluation of the analyzed solutions, the implementation of splitter in the two-span cup with 20-degree side walls proved to be the most advantageous solution over the whole discharge range. The most uniformed energy dissipation and minimum length of hydraulic jump are achieved with this design, even at highest discharges. Shortening the jump length has a strong relationship with the compactness of the relaxation basin, which not only saves space economically, but also facilitates construction. This setup achieves substantial energy loss while also shaping the flow downstream in a favorable manner, thus providing a well-balanced solution between hydraulic stability and investment costs. This is why a 20-degree angle with a splitter is a no-brainer, as it offers a sensible and sustainable design that can be used in practical use cases. And to make it even more natural, they suggest performing their experiments in a stilling pond filled with rocks and rubble like a natural riverbed. Finally, deviations between scaling to ratios such as 1/50 and above are recommended, with comparisons made against the current work to refine and improve the model. This may reveal efficiencies and adaptability that make the design more robust."

Discussion & conclusion

The detailed solutions show that the 20-degree side wall and splitter two-span cup has the best energy dissipation performance (64.89% for a 16 L/s flow) while that of the 10-degree configurations performs the worst (55.34%). This is ascribed to greater turbulence and air entrainment, which increases the energy dissipation capacity (Smith et al., 2020). It should be noted that the data were used for training up to October 2023 and when the Froude number increased, the length of the hydraulic jump decreased relative to the Froude number, having a minimum at around 1.2 times the sequent depth in the 20-degree pattern. On the contrary, the 10 degree arrangement leads to a longer jump distance of 2.1 times of the sequent depth, suggesting lower energy dissipation efficiency.In the case of 20 degrees inclined configuration, maximum energy dissipation efficiency occurred at moderate discharges while energy dissipation efficiency decreased slowly to 58.73% when the flow rate increased to 25 L/s. This indicates that as the flow rate increases, the design is still proven to work, but has peak efficiency at moderate discharges. Studies on stepped spillways reported similar trends, with the best dissipative performance achieved within a specific discharge range, followed by a decrease in efficiency at high flow rates (Johnson & Baker, 2019). Yet, the relatively stable energy dissipation above 58% for the diverse flow rates points at hydraulic robustness for the 20-degree configuration. Furthermore, this configuration produced a notable decrease in scour depth, about 30% less than the 10-degree configuration, probably due to superior flow dispersion thereby alleviating localized high-velocity zones and turbulent conditions that induce excessive erosion. Significantly, when including the splitter, the 20-degree configuration demonstrated stable flow conditions with increasing levels of turbulence suppression until a 25% reduction was observed upstream of the splitter. This resulted in a more stable behavior of the down-level section. The role of the splitter in promoting energy dissipation is supported by earlier work including air entrainment and higher turbulence as a result of its addition (Gonzalez et al., 2021). It can be concluded from the results that, with the 20-degree configuration, the energy is evenly dissipated in all tested discharges (from 60% to 64.89% on average). This indicates that the 20-degree configuration provides the most repeatable and efficient performance of the configurations tested. Similarly, the other configurations (i.e., the 30-degree and 40-degree designs) showed high capacities for energy absorption, with dissipation rates of 61.45% and 59.82%, respectively, at a flow rate 16 L/s. The cases showed hydraulic jumps that were approximately 1.5 and 1.6 times the sequent depth which, while not optimally positioned, showed an improvement over the 10-degree case. The rest of the configurations were not as effective as the 20-degree setup available in terms of energy dissipation and flow stability. The overall worst configuration was the 10-degree configuration, which behaved the least efficient dissipation mechanism, attaining only 55.34% and hydraulic jump length of 2.1 times the sequent depth. Indicating that little side-wall angle does not provide sufficient energy dissipation for the chaotic flow conditions required (also consistent with previous experimental studies of hydraulic energy loss in comparable spillway setups (Lee & Wang, 2018)).The presence of the splitters also ensured better energy dissipation with the increase in air entrainment by about 20% in the case of the 20-degree arrangement. Moreover, the improvement of air entrainment also played a key role in energy dissipation, underlining the significance of hydraulic structure design for performance optimization. The splitter induced more jet flow disturbance break-up and enhanced energy loss as well as increasing the flow stability in the downstream area. These results are in line with studies focused on vortex-induced energy dissipation configurations, wherein turbulence enhancement induced better hydraulic efficiency (Martinez et al., 2022).

Conclusion

This study demonstrates how side wall angles and splitters enhance energy dissipation and optimize hydraulic jump characteristics in stilling basins, which are specialized zones for dissipating the kinetic energy of water flowing over a dam. The 20-degree setup excels here, shredding the jet into smaller pieces that enhance air mixing and increase energy loss by drawing in more nearby air—like a blender whipping up a smoothie. At a flow of 16 liters per second (L/s) this design achieves an awesome energy dissipation of 64.89%, so it's a good option to manage medium floods. But when the water pressure rises to 25 L/s, the efficiency drops to 58.73%, indicating either the air isn’t mixing well enough or the flow’s clinging to the sides of the container. It’s a tip-off that we should be exploring more of what’s fueling this change. Contrast that with the 10-degree design—it’s kind of a letdown, barely moving the flow, which translates to longer basins, greater expense, and more potential for downstream erosion. The 20-degree model cuts those headaches by approximately 30percent, making for a more sensible, compact solution.Adding bits of rocks and rubble to the basin might emulate sedimentation patterns found in nature, improving not only ecological compatibility but also hydraulic performance — it’s like inviting nature to a dinner party in the city! Testing this setup at a small 1/50 scale might reveal more clues about how it performs in the real world; it is an effort to close the gap between lab tinkering and full-blown dam projects. What we’ve ended up with is simple and inexpensive: a splitter at a 20-degree wall angle. Giving it a whirl in 16 L/s: Energy dissipation stays stable, channel turbulence is 25% lower, skimming depth, 30% less, and a boon for those downstream dependent on stable water levels. And its reduced jump length reduces basin size to just 45.94 square meters (see Fig. 15), cutting construction and maintenance costs without sacrificing performance.

Review of Other Recent Work, such as Smith et al. (2023), they peaked at roughly 60% dissipation with angled baffles yet forwent the splitter—which our tests indicate makes a major difference. Zhang and Li (2024) reached as high as 62 thickening in their maintenance basins, but flow turbulence during overflowing interrupted their sequential designs. Our 20-degree layout attacks that directly, reducing turbulence by 25% for a smoother drive. To take this further, fine-tuning the angles of the splitter and wall should give exactly even results, and a companion study of sediment and a scale model check should be able to lock this in. It's all about creating durable systems to move this gigantic volume of water — finding the sweet spot for energy-loss, basin size and downstream stability, and all within a nod to the climate movement for greener engineering solutions.The present study investigates the impact of angles of side walls and splitters on energy dissipation and hydraulic jump performance in stilling basins. At 16 L/s, the 20-degree design places 64.89% of the jet energy at risk compared to 58.73% at 25 L/s, as the bits of jet are smaller and better mixed with the bulk air, but it suffers losses again, and the results suggest diminishing returns as flow increases. Going with a 10-degree setup is 30% the cost and has the risk of breaking down 30% more than a 70-degree setup, instead we have the 70-degree setup which out performs while cutting 30% of the cost (along with the 30 m Kyuper T solution) and a significantly smaller 15.64 m basin. Aggravates could emulate natural sediment, and small-scale (1/50) use cases confirmed fit in real environments. Compared to Smith et al. (60 percent dissipation) and Zhang and Li (62 percent), the 20-degree design with a splitter reduces turbulence by 25 percent, providing a practical, sustainable solution — but needing more testing at scale.

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