Al-Farouk journal of sciences
Volume (2), Issue (3) (JUNE, 2026)
ISSN: 3135-2359

مجلة الفاروق للعلوم
المجلد (2) العدد 3 يونيو 2026
ردمد: 3135-2359

Evaluation of Water Energy Dissipation over Spillway through the Improved Reversed Flow

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تاريخ الاستلام: 2026/04/20 تاريخ المراجعة 20/05/ 2026 تاريخ القبول:2026/06/07- تاريخ النشر: 22/06/ 2026

Abstract

In order to avoid downstream scouring and structural failure, efficient energy dissipation is essential to the safe and cost-effective operation of dam spillways. The use of a counter-flow or cross-jet to regulate hydraulic jumps is the main topic of this paper's analysis of the mechanics and effectiveness of an enhanced reversed flow energy dissipation technique. Reversed flow techniques greatly reduce the necessary stilling basin length by generating a forced hydraulic jump, which lowers construction costs and improves structural safety. This study summarizes analytical and experimental results from important studies, showing that these techniques can significantly shorten stilling basin length and hydraulic jump length. The results demonstrate the potential of reversed flow dissipators as a reliable and effective substitute for traditional energy dissipators, especially in high-velocity flow situations where abrasion and cavitation present serious risks.

Keywords: Spillway, energy dissipation, reversed flow, hydraulic jump, stilling basin>

الملخص:

يعتمد التشغيل الآمن والاقتصادي لمفيضات السدود على فعالية تبديد الطاقة لمنع التآكل النهري والفشل الإنشائي. تبحث هذه الورقة في آليات وأداء طريقة التدفق العكسي المحسّنة لتبديد الطاقة، مع التركيز على استخدام التدفق المعاكس أو النفاث المتقاطع للتحكم في القفزات الهيدروليكية. من خلال توليد قفزة هيدروليكية قسرية، تعمل تقنيات التدفق العكسي على تقليل طول حوض التهدئة المطلوب بشكل كبير، مما يقلل تكاليف الإنشاء مع تعزيز السلامة الهيكلية. تجمع هذه الدراسة النتائج التحليلية والتجريبية من الأبحاث الرئيسية، موضحة أن هذه الطرق يمكن أن تقلل طول القفزة الهيدروليكية وطول حوض التهدئة بشكل ملحوظ. تسلط النتائج الضوء على إمكانية استخدام مبددات التدفق العكسي كبديل قوي وفعال لمبددات الطاقة التقليدية، خاصة في ظروف التدفق عالي السرعة حيث تشكل مخاطر التكهف والتآكل تحديات كبيرة.

الكلمات المفتاحية: المفيض، تبديد الطاقة، التدفق العكسي، القفزة الهيدروليكية، حوض التهدئة.

1. Introduction

1.1 The Challenge of Spillway Discharge

Prevention dam overtopping and potentially disastrous failure, dam spillways are essential hydraulic structures that release excess water during flood events. High-velocity, supercritical flow is produced when water is released over a spillway, especially over an ogee crest. This turbulent flow carries immense kinetic energy, which, if unchecked, can cause severe local scour in the downstream riverbed composed of alluvial materials such as sand, clay and silt. This flow's high bed shear stress causes substantial sediment transport downstream, which could weaken the spillway foundation and jeopardize the stability of the entire structure. In the worst case, repeated or ongoing scouring may weaken the spillway's foundation and ultimately cause the structure to fail (Alghwail et al., 2018).

1.2 The Role of the Hydraulic Jump

The channel downstream of the spillway needs to be shielded until the flow returns to a subcritical state, where velocities are significantly lower, in order to reduce scouring. River flow is typically subcritical under natural conditions, and when a supercritical flow happens, it eventually returns to subcritical. A hydraulic jump, which dissipates a sizable amount of the flow's mechanical energy through turbulent mixing and internal friction, is always present during this transition from supercritical to subcritical flow (Alghwail et al., 2018). The hydraulic jump's location and features are important. The distance between the hydraulic jump and the spillway toe directly correlates with the cost of channel protection. Hydraulic engineers therefore aim to "force" the hydraulic jump upstream in order to minimize the necessary stilling basin length and related construction expenses.

1.3 Purpose and Scope

The mechanics and effectiveness of an enhanced energy dissipation strategy; using a reversed flow, or counter-flow, to regulate the hydraulic jump are examined in this paper. Even though conventional techniques like stepped spillways and stilling basins with baffle blocks work well, they can experience cavitation and abrasion at high flow rates. Because of the possibility of erosion and cavitation damage to the structure, a stilling basin with baffle blocks is not advised when the flow velocity exceeds 20 to 30 m/s (Alghwail et al., 2018). Boes and Hager (2003) found that the critical velocity for cavitation inception in the flow, before air entrainment, was about 20 m/s on stepped spillways, whereas Amador et al. (2009) suggested a mean velocity of 15 m/s at the point of inception based on the likelihood of extremely negative pressures detected close to the vertical step faces' edge. By optimizing turbulent diffusion and velocity gradients through the collision of opposing flows, the reversed flow concept presents a potentially more effective and economical substitute. In order to describe the theoretical underpinnings, operational mechanics, and energy dissipation efficiency of enhanced reversed flow systems, this paper summarizes results from groundbreaking research, especially the methodical experimental and analytical work by Alghwail, Stević, and Abourohiem (2018).

2. Mechanics of Reversed Flow Energy Dissipation

2.1 Fundamental Principles

Energy dissipation in fluid flow is fundamentally dependent on turbulent diffusion and viscous effects (internal friction). Diffusion is dependent on turbulence intensity, whereas the frictional head loss is directly proportional to the velocity gradient (Alghwail et al., 2018). While a high velocity jet striking a stationary or low velocity liquid increases both the level of turbulence and the velocity gradient, as in the case of stepped spillways, air entrainment intensifies the turbulence. When baffles are installed in a stilling basin, the flow is forced to change direction suddenly, creating a highly non-uniform flow, an increased velocity gradient, and head loss, also referred to as local head loss. Obstacles in the way of water flow also cause turbulence. Therefore, any technique used in the energy dissipation process must maximize the velocity gradient and turbulence. The counter flow approach provides the best illustration of this.

The inelastic collision principle underlies the reversed flow method. Momentum is conserved when a high-velocity water jet strikes a stationary object or another body of water, but because of the work required to deform the objects, a significant amount of kinetic energy is transformed into other forms, such as heat, acoustical energy, and potential energy (Alghwail et al., 2018). When two opposing water flows collide, the impact increases and more kinetic energy is converted into heat. At the same time, the magnitude of the velocity gradient increases along with the level of turbulence, increasing the head loss in the flowing water. By reducing the average relative velocities of colliding particles, water particle deformation and friction during flow collision and through a severe turbulent-flow zone caused by hydraulic jump formation will essentially remove a portion of the mechanical energy from the water particles (Alghwail et al., 2018).

2.2 Configuration of an Improved Reversed Flow Dissipater

A cross-jet or slot placed on the channel floor is usually used in the enhanced reversed flow dissipator. According to research, the idea entails dividing the incoming flow into two sections: one is drawn into the slot and directed upward and upstream, while the other passes over the slot (Alghwail et al., 2018). This strategy expands on previous research by scholars who investigated similar ideas. According to Komora (1970) proposed a method that significantly reduces the volume of the earth and concrete work for the spillway by installing three spreader blocks at the channel, which causes jets to collide in the air. Vollmer and Khader (1970) designed a splitter block with a V-shaped structure that was placed on the stilling basin floor to split the incoming flow into two sections. According to Alghwail et al., it results in a significant loss of water energy due to collisions. In order to investigate the impact of floor jet on hydraulic jump formation, Kao (1974) conducted an experimental and theoretical analysis. Experiments demonstrated that hydraulic jump can be controlled by using a submerged cross-jet in place of solid chute blocks and baffle piers, and that, in contrast to a free hydraulic jump, reverse jet reduces the tailwater depth and dissipates a significant amount of energy.

The counter-flow width, the slot's location in relation to the spillway toe, and the slot's angle which affects the collision dynamics are the design parameters that control how well such a system performs (Alghwail et al., 2018). The real process of energy dissipation, which involves intricate structures and flow impacts, is extremely complex and necessitates physical modeling in controlled laboratory settings in order to properly understand the flow behavior. To create different counter-flow configurations, a number of physical models with various designs have been built, and the impact of these parameters is investigated experimentally to determine appropriate design values (Alghwail, 2016).

2.3 The Forced Hydraulic Jump

A forced hydraulic jump is the main result of the reversed cross-jet. The reverse flow causes a quick transition by introducing a low-velocity jet upstream against the high-velocity incoming flow. In contrast to a free hydraulic jump, this produces a "forced perfect jump" that begins at the contracted section, much closer to the spillway toe (Alghwail et al., 2018). This is a crucial improvement because it directly shortens the stilling basin's necessary length, which lowers the quantity of concrete and earthworks required for construction. Other situations have also been investigated in relation to the idea of a forced hydraulic jump. In comparison to standard hydraulic jumps, Bhowmik (1975) conducted laboratory tests for the Froude number range of 2. 5 to 4. 5 and demonstrated that jumps forced by appurtenances like baffle blocks and an end sill can increase energy loss, reduce the required downstream water depth, and form the jump in a much shorter basin. In comparison to a traditional hydraulic jump, research on stilling basins with a single tall end sill also demonstrated a significant impact on energy dissipation over a shorter distance (Meshkati et al., 2012). The idea that forced hydraulic jumps, whether accomplished by fluid-based counter-flow techniques or solid appurtenances, provide significant increases in energy dissipation efficiency is supported by these studies taken together.

3. Performance and Efficiency

3.1 Key Findings from Experimental Research

Alghwail, Stević, and Abourohiem (2018) carried out the most thorough study of the reversed cross-jet method, combining analytical solutions with physical modeling to evaluate performance. According to the study, the reversed flow can accelerate the change from supercritical to subcritical flow by causing a forced hydraulic jump. This shortens the protection length required to prevent scouring issues downstream of the channel. When compared to the scenario without a dissipator, the results showed that the hydraulic jump's length was shortened by 19% and the stilling basin's length was shortened by nearly 80%. The technology is economically appealing because of this significant reduction, which directly results in lower construction costs. According to the study, which looked at energy dissipation under various flow conditions, reversed flow may increase flow turbulence, which results in significantly more energy dissipation than a free hydraulic jump. To forecast variables like the discharge through the slot, relative energy loss, and the condition of a perfect hydraulic jump, the study used basic energy, momentum, and continuity equations (Alghwail et al., 2018).

It was discovered that when the cross-jet creates a significant amount of turbulence, the energy dissipation process is most effective. It is possible to increase flow turbulence and significantly increase energy dissipation by manipulating the jet discharge and geometry. Through measurements of several important process parameters, the study gained a basic understanding of the process, in contrast to earlier related studies that concentrated on the energy dissipation that resulted. As a result, both an energy and an economic perspective are used to evaluate the efficacy of energy dissipation techniques (Alghwail, 2016).

3.2 Advantages Over Conventional Methods

Compared to conventional techniques, the reversed flow dissipater has a number of benefits. Because the length of the stilling basin is drastically reduced, less concrete and earthworks are needed, which makes it extremely economical. At high velocities, cavitation damage can occur in conventional methods such as stepped spillways and baffle blocks. Cavitation may develop on the lateral and rear faces of baffle blocks, sills, and protuberances at the stilling basins' outlets and spillways (Alghwail et al., 2018). Many spillway components and hydraulic structure components worldwide suffer significant damage as a result of the creation of vapor-filled bubbles and cavities and their ongoing collapse. By avoiding sharp obstacles and emphasizing fluid–fluid interaction, the reversed cross–jet lowers the possibility of cavitation–causing low–pressure zones. Because of the possibility of erosion and structural damage, the technique is especially appropriate for high–velocity flows where conventional dissipators are not advised. When spreader or splitter blocks are used in counterflow techniques to deflect a portion of the flow into the air or to direct flows against one another, the water may separate when it collides with the blocks, resulting in cavities. However, Alghwail et al.'s study of the reversed cross–jet configuration seems to use a slot instead of solid obstacles to reduce this risk.

4. Conclusion

An important development in hydraulic engineering is the enhanced reversed flow energy dissipation method, which uses a cross–jet to create a counter–flow. Its superior performance over traditional methods is demonstrated by Alghwail, Stević, and Abourohiem's (2018) methodical experimental and analytical work. The reversed flow method efficiently lowers the energy of the supercritical flow by creating a forced hydraulic jump, which significantly shortens the hydraulic jump length and the necessary stilling basin length. By shifting the high–energy dissipation zone away from sensitive downstream areas and closer to the spillway, this reduction improves structural safety and results in significant cost savings. The cavitation and abrasion issues that beset conventional dissipators at high flow velocities may also be resolved by the method's reliance on fluid–fluid collisions rather than solid obstructions. To fully realize the potential of this technology for large–scale dam projects, more research and field–scale validation are advised. Combining numerical and physical modeling could improve the geometry of counter–flow dissipators for a variety of site–specific circumstances and offer deeper insights into the intricate turbulence dynamics.

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