Numerical Investigation of Energy Dissipation Efficiency in Stepped Spillway Designs under Flow Conditions

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Abstract: *Stepped spillways are widely applied in dam engineering due to their ability to dissipate water flow energy and mitigate cavitation risk. However, the efficiency of energy dissipation depends strongly on step geometry, slope and flow conditions. This study presents a comprehensive numerical analysis of novel stepped spillway configurations, including rectangular, trapezoidal and curved step profiles, under a range of discharges corresponding to skimming and transition flow regimes. Three-dimensional Computational Fluid Dynamics (CFD) simulations were carried out using the Volume of Fluid (VOF) method and a Reynolds-Averaged Navier–Stokes (RANS) turbulence model to resolve free surface flow, velocity and pressure distribution. The results obtained are showing good agreement in velocity profiles and energy dissipation rates. Parametric analysis revealed that stepped spillways excel in localized energy dissipation, particularly for steep slopes and moderate flows, while labyrinth spillways excel in maximizing discharge capacity while maintaining lower flow velocities, making them efficient for high-flow, low-footprint designs.*
Overall, the proposed geometrical constructive versions provide higher energy dissipation efficiency compared with conventional designs. These findings highlight the potential of optimized step geometries to improve hydraulic performance and ensure the safety of spillway structures under extreme hydrological conditions.

Keywords: *Water flow, spillway constructive versions, stepped, labyrinth, numerical analysis*

1. Introduction

Energy dissipation in spillway design is crucial for downstream safety and structural integrity. Stepped spillways characterized by their unique geometrical configuration are widely recognized for enhancing energy dissipation, fostering aeration, and mitigating cavitation risk, ultimately reducing stilling-basin dimensions and construction cost.
Research shows that stepped chutes dissipate more energy as smooth chutes under similar conditions, for instance, energy dissipation ranged between 43% and 46% in stepped chutes versus about 20% in smooth types. Further experimental data suggest that downward-inclined steps can significantly reduce dissipation (by around 21%), while upward-inclined steps improve it by up to 6%.
Regarding the impact of step geometry several studies underscore how step geometry profoundly influences hydraulic performance.
Pooled configurations often outperform flat ones in fostering aeration and enhancing energy dissipation, offering better pressure profiles and higher turbulent kinetic energy.
The novel geometries on trapezoidal and circular (or labyrinth-shaped) stepped spillway types show superior dissipation compared to traditional flat steps. For example, trapezoidal steps proved especially effective in the skimming flow regime.
Circular-stepped designs achieved up to 50% higher energy dissipation, particularly with smaller radii and increased step depth.
Meanwhile, circular labyrinth configurations (e.g. two- to four-cycle designs) enhanced dissipation by 28 %, with three-cycle patterns yielding the highest efficiency and further introducing curved risers an improved energy dissipation by around 3% at low flow rates is observed, with negligible effect under higher discharges.
While extensive numerical and experimental work validates the potential of stepped spillways, a meaningful gap remains, related to the combined effects of innovative geometric modifications on energy dissipation, cavitation risk and aeration under varied flow regimes, which are still under-

explored. Furthermore, the relative performance of novel configurations through rigorous numerical simulation, supported by field or lab validation, remains limited [1-5].
This study addresses these gaps by conducting numerical analysis via CFD method, employing VOF and a validated turbulence closure, to assess stepped spillways with hybrid geometries of labyrinth constructive version. The analysis will examine key performance metrics such as energy dissipation, pressure distribution, cavitation index across water flow regime. The goal is to determine whether the novel hybrid geometry substantially improves hydraulic performance compared to traditional configurations, offering actionable guidance for resilient spillway engineering [3-9].

2. The 3D virtual model and methodology

The study employs a computational approach to evaluate the total energy value described by the following equation:

$$E = \frac{v^2}{2} + \frac{p}{\rho} + gz \qquad (1)$$

where v is the local water velocity magnitude, p is the static pressure, ρ is water density, g gravity and z is the point elevation. The equation is used to compute inlet/outlet energy heads and sectional average values.
The specific head *(H)* value per unit weight can be calculated as:

$$H = \frac{\alpha v^2}{2g} + \frac{p}{\rho g} + z \qquad (2)$$

With α as the kinetic-energy correction coefficient which is obtained from the equation:

$$\alpha = \int A \frac{u^3}{v_m^3 A} dA \qquad (3)$$

The head loss or energy dissipation per unit weight, for a control volume between section 1 represented by water inlet and section 2 considered as water outlet:

$$\Delta H = H_1 - H_2 \qquad (4)$$

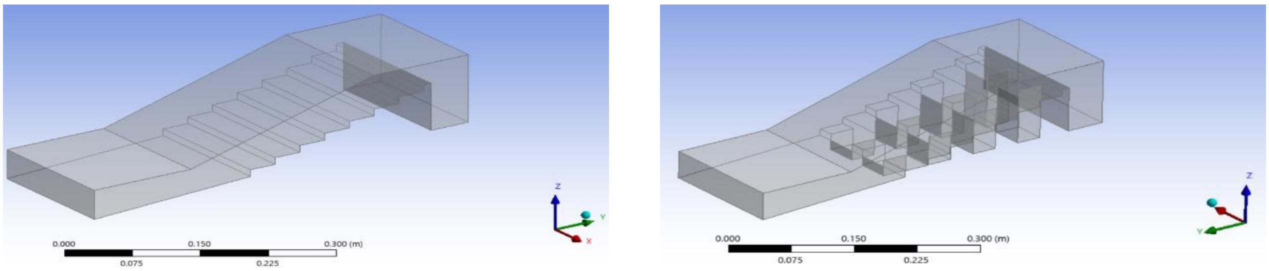
The total dissipated power or rate of energy loss in this case is described by the following relation:

$$P_D = \rho \cdot g \cdot Q \cdot \Delta H \qquad (5)$$

where Q is volumetric flow rate as discharge (m³/s).
For this water flow regime it is of importance to consider the cavitation index, as a safety metric, in order to check flow cavitation risk at local minimum values of pressure:

$$\sigma = \frac{2(p - p_v)}{\rho v^2} \qquad (6)$$

where p_v is the vapour pressure. Low σ indicates a higher cavitations risk.
Based on two constructive versions of spillway made to be introduced into the numerical flow analysis with ANSYS CFX, the construction possibilities and the solution of problems related to the controlled direction and capture of water flows are shown. The models are related to stepped and labyrinth versions (figure 1) in order to counteract the water flow potential energy and further proportional conversion into kinetic energy.
For a smooth spillway constructive version the potential energy of the upstream water head is mostly converted into kinetic energy at the outlet region with high-velocity jet. This often requires a stilling basin to dissipate energy safely.
A stepped spillway interrupts the water free fall, forcing part of the potential energy to be dissipated through re-circulation zones in step cavities, which are capable to form local turbulence. Shear stresses between steps and re-circulation zones provide impact in turbulence production and further the steps reduce the downstream kinetic energy peak.



a) Stepped model b) Labyrinth model

Fig. 1. The 3D model of stepped water spillway constructive versions

Energy dissipation within the structure reduces the needs for a massive stilling basin downstream and ensuring a safer discharge conditions with less erosion.
Hydraulic safety conditions with smoother pressure gradients comparative to a smooth version.
A flat step version is simple to build, good for low to moderate discharges, while the labyrinth version is expected to provide improved fluid flow entrainment, smoother water flow transition regimes, reducing the negative pressures, mitigate cavitations and increase dissipation efficiency.
Both constructive versions show a compact design, economical compared to large stilling basins.

3. Numerical analysis for water flow on construction models

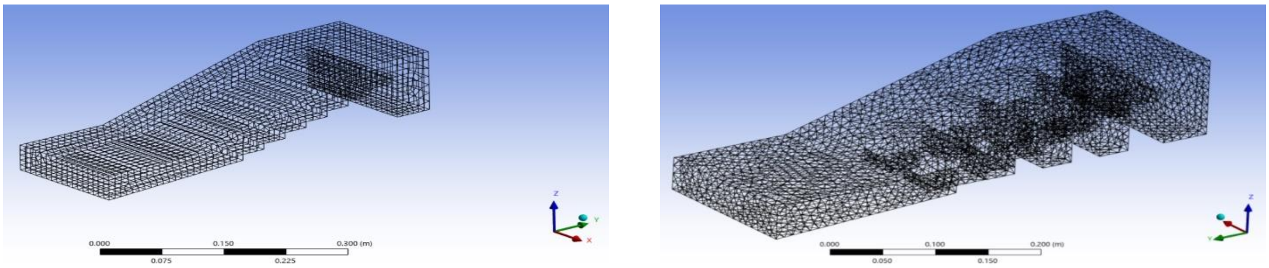
The flow analysis is made with ANSYS CFX software, considering the two model versions, in order to establish the flow regimes for each constructive solution based on special parameters involved.
The flow simulation is aimed to reproduce the hydraulic behaviour of the stepped spillway under controlled conditions, with specific expectations related to flow hydraulics representation where it can be captured the velocity field along the constructive versions geometry, showing acceleration zones from the crest to the base, identify recirculation zones inside step cavities where vortices form and quantify the maximum velocities and flow attachment on step crests.
The main details for analysis are presented in table 1, while the mesh and special domain configuration on constructive models are showed in figure 2.

Table 1: The details of numerical flow analysis

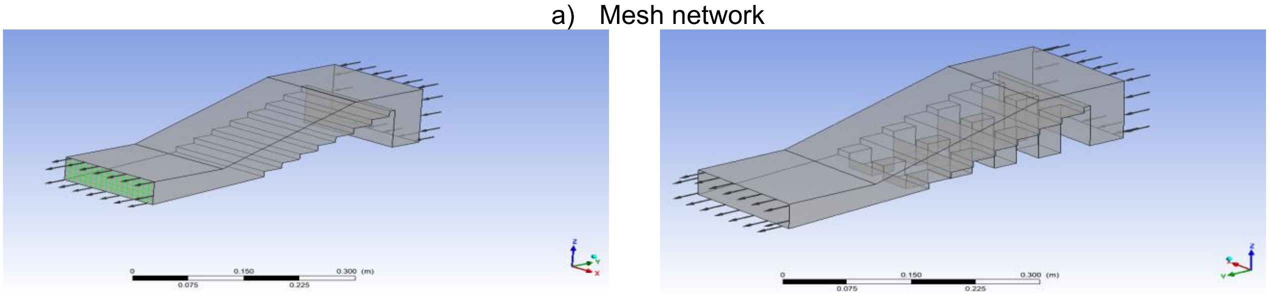
Parameter	Value
Solver	ANSYS CFX 2025 R2
Flow regime	Incompressible, isothermal
Fluid	Water (ρ=1000 kg/m³, μ=0.001 Pa·s)
Inlet boundary	Velocity = 1.0 m/s
Outlet boundary	Pressure = 0 Pa (gauge)
Walls	No-slip
Top boundary	Opening (atmospheric)
Gravity	9.81 m/s² (−Z)
Turbulence model	SST k–ω
Free surface model	VOF
Time step	0.001–0.005 s
Convergence criteria	RMS residuals < 1×10^{-4}
Mesh size	0.005–0.01 m avg.

For pressure distribution will be visual the total and static pressure fields to assess regions of high and negative pressure, evaluate the potential cavitation-prone zones in the step cavities and compare the pressure gradients between different geometries (stepped and labyrinth).

Regarding the energy dissipation efficiency it is possible to estimate the head loss between inlet and outlet using pressure–velocity data, determine the proportion of potential energy converted into turbulence and dissipated and compare dissipation efficiency across step geometries. The obtained results make possible a design evaluation of the models and verify whether the stepped geometry and labyrinth model effectively reduces downstream kinetic energy, which will provide insights into optimal geometry for maximizing energy dissipation while minimizing cavitation risk.
The expectation from the ANSYS CFX simulations is a clear understanding of how potential energy is partially dissipated via turbulence and step geometry interaction, thus validating the role of stepped spillways as efficient flow energy dissipators.



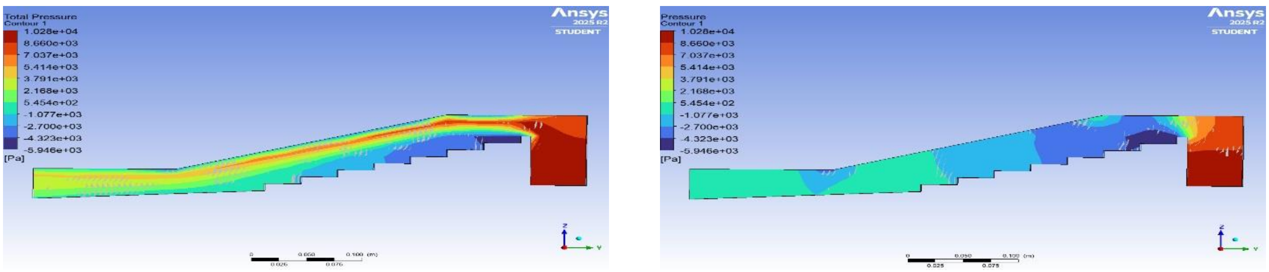
a) Mesh network



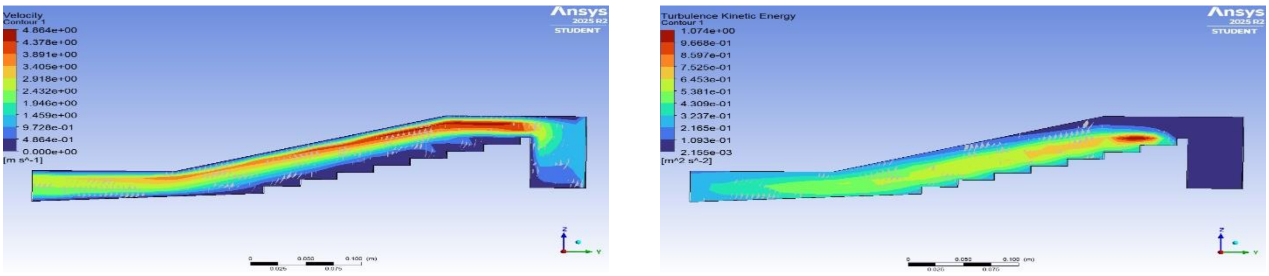
b) Stepped version a) Labyrinth version

Fig. 2. Mesh network and domain flow analysis details

The obtained results for the two cases corresponding to the constructive versions analyzed are presented in figures 3 and 4.

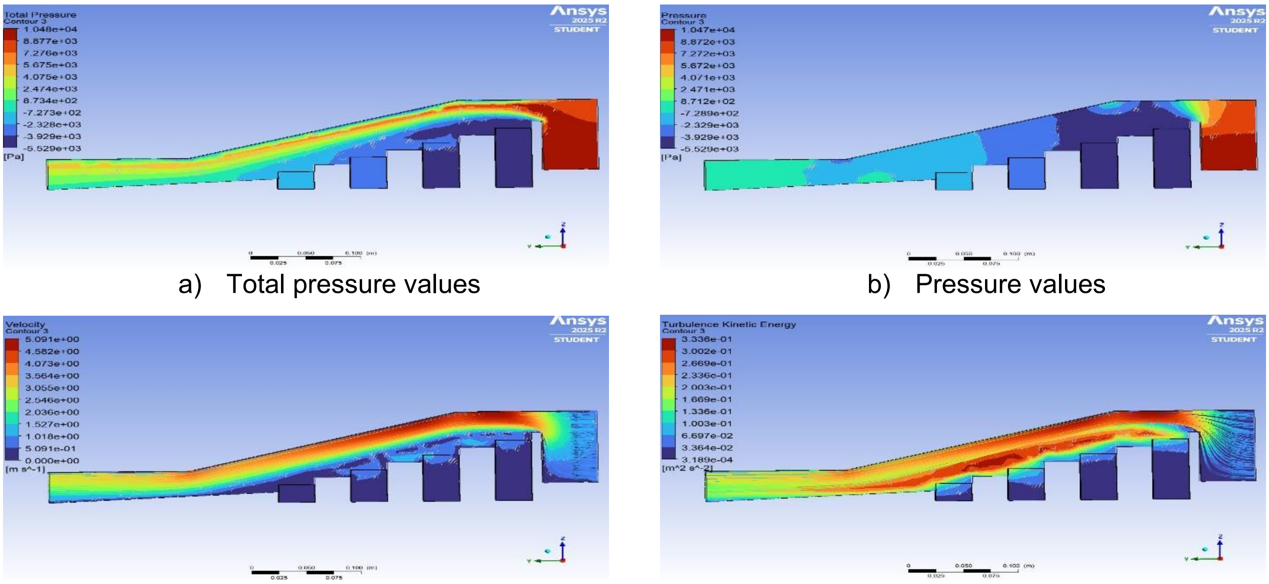


a) Total pressure values b) Pressure values



c) Velocity values d) Turbulence kinetic energy values

Fig. 3. Results for stepped spillway model version



a) Total pressure values
b) Pressure values
c) Velocity values
d) Turbulence kinetic energy values

Fig. 4. Results for labyrinth stepped spillway model version

The obtained results show the velocity values contour in a range of 1-4.8 m/s, while this velocity rise corresponds to a pressure drop described by Bernoulli principle, while the spillway model converts potential energy into kinetic energy, which is then partly dissipated at steps.
For step cavities as recirculation zones, the velocity contour show values in range of 0–0.5 m/s, indicating near-stagnant recirculation vortices inside step cavities.
The fluid recirculation enhances turbulence and energy dissipation but increases cavitations risk. Energy dissipation efficiency for high velocities and alternating pressure fluctuations ensure step-induced turbulent kinetic energy production.
Compared to a smooth spillway, the stepped profile reduces downstream jet momentum, lowering scour potential.
The pressure distribution results show values ranged from about −6000 Pa to +10,280 Pa with high total pressure concentrated at the upstream inlet region, where water impinges and accelerates over the crest.
Lower pressures values appear in the circulation cavities behind the steps which is typical for water flow on stepped spillways.
The flow structure indicate that energy loss is enhanced along the model geometry as water passes step by step to the outlet region, where pressure decreases as the flow accelerates downstream.
The alternating zones along the free surface and negative values in the step cavities indicate zones of flow separation and reattachment.
Energy dissipation is provided when negative or low pressure values behind steps are registered where turbulent eddies form, as main mechanism of energy loss within stepped spillways.
Regarding the hydraulic safety aspect the most negative pressures (−6000 Pa) are relatively close to vapor pressure (depending on water temperature), while these zones meet the cavitations conditions.

4. Conclusions

The numerical simulations carried out in ANSYS CFX demonstrated that both stepped and labyrinth spillway geometries are effective in dissipating flow energy within the chute. The stepped model dissipates energy primarily through localized recirculation in step cavities, producing predictable pressure fluctuations and strong but confined shear layers. In contrast, the labyrinth geometry generated larger recirculation zones and stronger turbulence, which enhanced overall energy dissipation but also broadened the regions of negative pressure, increasing cavitations risk.

Velocity fields confirmed that the labyrinth configuration reduced the mean downstream jet momentum more effectively, while the stepped model maintained higher outlet velocities but with greater aeration at each cavity. Pressure contours indicated that both step variants can reduce localized suction, making the stepped chute a safer choice in terms of cavitations.
In summary, the labyrinth design achieved higher energy dissipation efficiency, but the stepped spillway provided more stable hydraulic performance and lower structural risk.
The choice between the two constructive versions should be guided by site conditions and design priorities, balancing maximum dissipation with cavitations safety.

Acknowledgments

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References

[1] Jahad, Udai A., Ali Chabuk, Riyadh Al-Ameri, Hasan Sh. Majdi, Ali Majdi, Nadhir Al-Ansari, and Salwan Ali Abed. "Flow characteristics and energy dissipation over stepped spillway with various step geometries: case study (steps with curve end sill)." *Applied Water Science* 14 (2024): 60.
[2] Farooq, U., S. Li, and J. Yang. "Numerical Analysis of Flow Characteristics and Energy Dissipation on Flat and Pooled Stepped Spillways." *Water* 16, no. 18 (2024): 2600.
[3] İkinciogullari, E. "Energy dissipation performance of the trapezoidal stepped spillway." *Journal of Engineering Research* 11, no. 2A (2021): 131-142.
[4] İkinciogullari, E. "Stepped spillway design for energy dissipation." *Water Supply* 23, no. 2 (2023): 749–763.
[5] Gubashi, K. R., S. Mulahasan, Z. A. Hacheem, and A. Q. Rdhaiwi. "Effect of the stepped spillway geometry on the flow energy dissipation." *Civil Engineering Journal* 10, no. 1 (2024): 145–158.
[6] Saleh, Shawnm Mudhafar, Sarkawt Hamarahim Muhammad, and Abdulla Abdulwahid Abo. "Effect of pooled and flat stepped spillway on energy dissipation using computational fluid dynamics." *Tikrit Journal of Engineering Sciences* 29, no. 2 (2022): 75-79.
[7] Bekheet, A. A., N. M. Aboul Atta, N. Y. Saad, and D. A. El-Molla. "Energy dissipation in stepped spillways: a comprehensive review of the recent research." *Innovative Infrastructure Solutions* 10 (2025): 253.
[8] Matos, Jorge, Carolina Kuhn Novakoski, Rute Ferla, Marcelo Giulian Marques, Mauricio Dai Prá, Alba Valéria Brandão Canellas, and Eder Daniel Teixeira. "Extreme Pressures and Risk of Cavitation in Steeply Sloping Stepped Spillways of Large Dams." *Water* 14, no. 3 (2022): 306.
[9] Saleh, S. M., and S. M. Husain. "Numerical Study to Evaluate the Performance of Non-uniform Stepped Spillway Using ANSYS-CFX." *Polytechnic Journal* 10, no. 2 (2020): 1-9.