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Lessons Learned from Recently Constructed Stepped Spillways: A Review

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Abstract

Stepped spillways are a practical widely used hydraulic solution for energy dissipation in dams. Their significance lies in their ability to reduce the kinetic energy reaching the toe while decreasing the required size of downstream stilling basin. This review synthesizes some recent prototype-sized and real case studies of stepped spillways, with emphasis on the lessons learned from their design. The selected literature shows that stepped spillways can achieve high energy dissipation, but their performance depends on the slope, discharge, aeration, step geometry, and the presence of 3D flow effects. The review also confirms that the risk of cavitation, especially at higher discharges, remains the main design constraint and that prototype-sized verification is still essential for non-standard stepped spillway geometries. Overall, the literature review supports that stepped spillways are efficient and adaptable structures, provided they are designed within realistic hydraulic limits and checked against field or large-scale modeling data.

Keywords: *stepped spillway; energy dissipation; prototype-size models; real case studies; cavitation; inception point; lessons learned*

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I. Introduction

Stepped spillways are among the oldest hydraulic structures, but their modern engineering use expanded strongly with roller compacted concrete (RCC) dam construction (Chanson 2022a). In practice, the stepped geometry offers a major hydraulic advantage because it dissipates flow energy along the spillway and reduces the residual velocity at the toe (Chanson 2022b). This often reduces the required downstream stilling basin and can simplify the spillway's maintenance and rehabilitation (Boes and Hager 2003).

The recent literature shows that the usage of stepped spillways is not limited to a single dam type. They have been used with gravity dams, embankment dams, check dams, and rehabilitation projects (Salmasi and Abraham 2023; Chanson and Gonzalez 2024; Chanson and Hu 2024a). At the same time, the studies also show that stepped spillways are not automatically suitable for every site, especially where the discharge is very high, aeration is limited, or the geometry is non-prismatic (Zindovic et al. 2014; Wahl and Falvey 2022). For this reason, the current review focuses on the most reliable prototype and large-scale constructed stepped spillways.

This review discusses some journal papers and essential technical books and manuals that include cases of prototype-size experiments, large-scale physical models, and real cases. A few numerical studies that are widely cited are also discussed for further interpretation. The selected examples were chosen to cover the main hydraulic and practical themes: energy dissipation, cavitation risk, alternative geometries, and low-cost materials. Thus, this review presents some key lessons needed by the designers and researchers interested in stepped spillways.

II. Background: Hydraulic Characteristics of Stepped Spillways

2.1 Flow Regimes

Flow over a stepped spillway is commonly divided into nappe, transition, and skimming regimes (Boes and Hager 2003). At low discharge, nappe flow occurs and each step behaves like a free-falling drop. At intermediate discharge, the flow becomes unstable and mixed. At higher discharge, skimming flow dominates, with the main current moving over the step edges while recirculating vortices occupy the cavities below (Boes and Hager 2003; Chanson 2022b). Figure 1 shows the different flow regimes of stepped spillways (a) nappe flow regime, (b) transition flow regime, and (c) skimming flow regime.

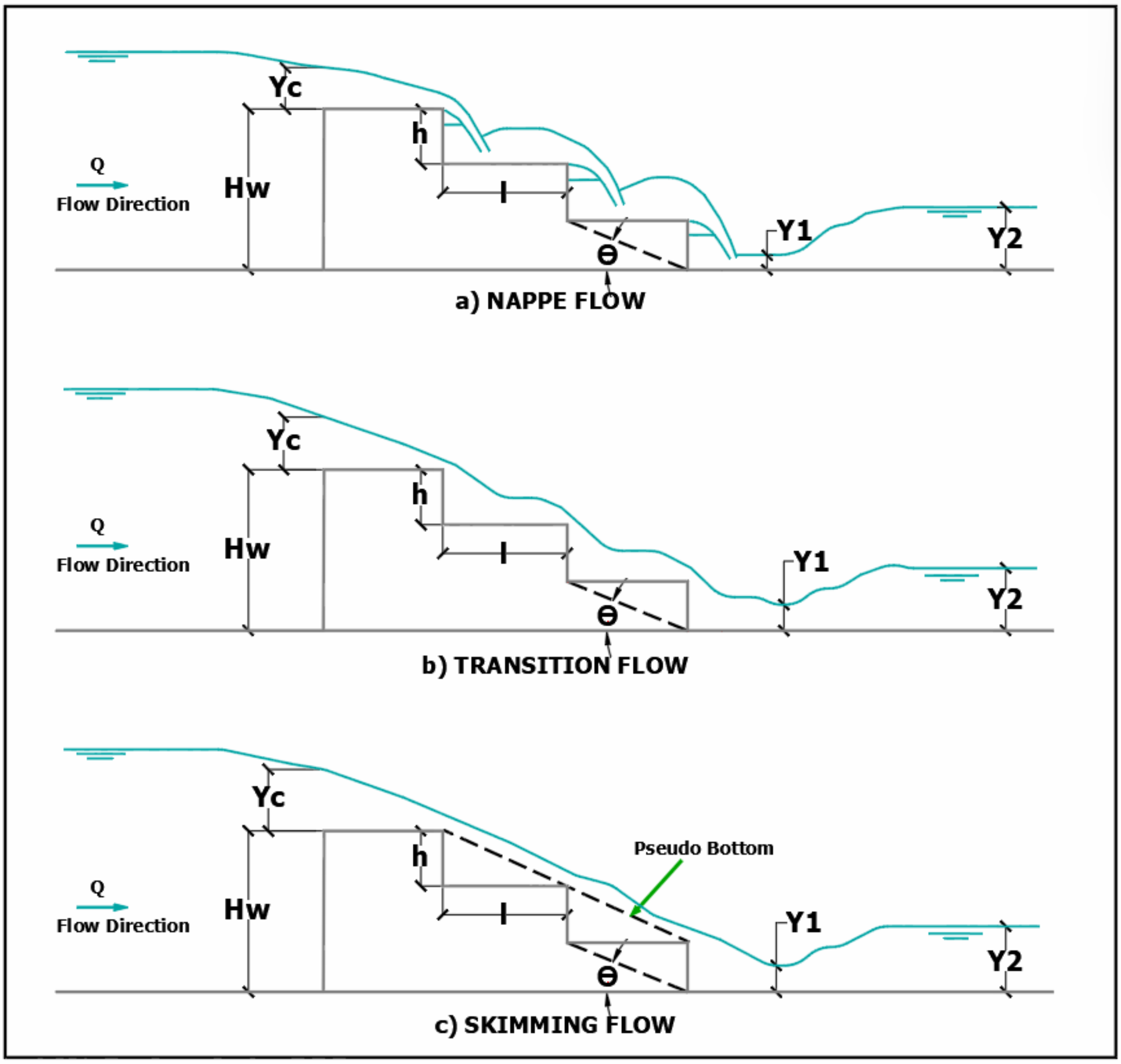

Figure 1: The different flow regimes of stepped spillways (a) nappe flow regime, (b) transition flow regime, and (c) skimming flow regime (Adapted from (Salmasi and Özger 2014)).

For modern stepped spillways, the skimming regime is the most operationally relevant. Within this regime, the turbulent boundary layer expands progressively from the crest until it breaks the free surface, this location is referred to as the inception point. Downstream of that location, the flow becomes aerated and more resistant to cavitation. This is why the inception point is one of the most important design indicators in stepped spillway analysis (Wahl and Falvey 2022; Chanson and Gonzalez 2024).

2.2 Energy Dissipation

The principal hydraulic benefit of a stepped profile is the progressive conversion of kinetic energy to turbulence and heat (friction) along the spillway (Chanson 2015, 2022a). Classical design relations for residual toe energy were developed by Chanson (2015) and Boes and Hager (2003) and they remain the primary sizing tools. Experimental prototype data confirm that stepped spillways dissipate approximately twice the energy of smooth spillways with equivalent slope and length (Chanson and Hu 2024b; Bekheet et al. 2025). Beyond the standard flat-step geometry, modified configurations offer further performance enhancements. Pooled steps can increase energy dissipation relative to flat steps (Felder, et al.2012), while circular step profiles have been shown to yield up to 18% additional dissipation compared with conventional stepped spillways in skimming flow (Ghaderi, et al. 2024). Evidence from experimental studies supports this conclusion. Field measurements at real structures such as Hinze Dam and Paradise Dam show that the measured behavior can be consistent with large-scale model predictions when similarity is respected (Chanson 2022a; Chanson and Gonzalez 2024;Chanson and Hu 2024b). However, performance still depends strongly on the step's shape, slope, and air entrainment. Hence, energy dissipation should never be assumed from the spillway's geometry alone (Chanson and Hu 2024a).

2.3 Cavitation Risk

Cavitation is the most important hydraulic risk for stepped spillways operating at high discharges (Wahl and Falvey 2022). The non-aerated region upstream of the inception point is the most vulnerable part of the spillway (Wahl and Falvey 2022; Chanson and Gonzalez 2024). For this reason, design practice often treats about 30 m^2/s as a practical upper limit unless additional aeration measures are used (Terrier et al. 2022).

The recent literature also shows that this limit is not absolute. Geometry, slope, and local pressure distribution all matter, and step-face pressure measurements indicate that critical cavitation conditions may appear even below the nominal discharge threshold in some configurations (Wahl and Falvey 2022). This is why modern design is moving toward geometry-specific cavitation checks rather than relying only on broad discharge rules (Wahl and Falvey 2022).

III. Case Studies of Recently Constructed Real or Prototype-Sized Stepped Spillways

Table 1 summarizes some case studies of recently constructed real or prototype-sized stepped spillways

Table 1. Summary of Case Studies of Recently Constructed Real or Prototype-Sized Stepped Spillways

#	Dam / Project	Country	Type	Key Findings & Lessons Learned
1	Hinze Dam (Chanson 2022a; Chanson and Hu 2024a)	Australia	Rock and earth-fill embankment dam with a concrete stepped spillway	Skimming flow dominated at the design discharge. Self-aeration was well-predicted by Froude similarity. $\Delta E/E$ = 43–46% and agrees with the lab values at same slope (1V:0.8H). **Lesson learned:** Froude similarity scaled models reliably predict air-water skimming flow for the same slope.
2	Paradise Dam (Chanson and Gonzalez 2024)	Australia	RCC Gravity	Two flood events were documented. Studying the fish passage showed low fish mortality over the stepped spillway during the skimming flow regime. **Lesson learned:** Stepped spillways are compatible with environmental fish-passages if skimming flow is maintained.
3	Zirdan Dam (Salmasi and Abraham 2023)	Iran	RCC Gravity	Steps shorten the boundary-layer length. Faster aeration and inception point is nearer to crest than smooth spillway. Energy dissipation was 47% greater than the smooth alternative. **Lesson learned:** RNG k-ε model is reliable for skimming-flow prototype validation when field calibration data are available.
4	Bogovina Dam (Zindovic et al. 2014)	Serbia	RCC Gravity	The presence of steps is effective in the energy dissipation. Scaled experimental model + empirical equations + Ansys Fluent numerical model used concurrently and led to an acceptable three-way agreement. Location of the inception point was matching for all three approaches. **Lesson learned:** Multi-method approach (experimental + empirical + numerical) reduces design uncertainty.
5	Bastora Dam (Husain and Ahmed 2017)	Iraq	RCC Gravity	A physical model of scale 1:40 Inception-point location, sidewalls freeboard, and stilling basin depth were compared with empirical equations; and minor discrepancies were found. **Lesson learned:** Physical models are essential for design reports in data-scarce regions.

6	Geobag Check Dam, Shaanxi Province (Yu et al. 2022)	China	Geobag Stepped	A prototype pilot dam model of 10 m was constructed. More than 30 overflow tests were performed. No geobag deformation occurred at the maximum toe velocity (6.7 m/s). ΔE/E was highly sensitive to the total drop height. **Lesson learned:** Geobag stepped spillways are viable and cost effective for small check dams in developing regions.
7	Trapezoidal Labyrinth Stepped Spillway (Ghaderi et al. 2020)	Lab Experiment	Trapezoidal Labyrinth Step	Trapezoidal labyrinth stepped spillway yields up to17% more dissipation than traditional steps in skimming flow. **Lesson learned:**: Labyrinth geometry is promising but the cavitation risk at high q must be also studied before its implementation.
8	Pooled Stepped Spillways (Felder, et al..2012)	Lab Experiment	Flat stepped, pooled step, and alternation of flat and pooled steps	Pooled steps consistently cause more turbulence than flat steps. A combination of flat and pooled steps led to the biggest energy dissipation. **Lesson learned:** While the combination of flat and pooled steps caused the largest energy dissipation, this may not be the optimum design due to its strong flow instabilities and unsteady flow, which can affect its safe operation.
9	Circular Stepped Spillway (CSS) (Ghaderi, et al. 2024)	CFD study	CFD modeling	The circular labyrinth spillway with three cycles led to 18.3% more dissipation than traditional stepped spillway. It also led to less negative pressure in the upper half of the vertical face of the steps. **Lesson learned:** CSS is a promising next-generation geometry; yet scale effects and cavitation data must be characterized before field adoption.
10	SpillwayPro (Design Tool Validation) (Wahl and Falvey 2022)	CFD study	Digital	Integrated water-surface profile, cavitation analysis, and aerated-flow module for both smooth and stepped spillways. It was validated against multiple constructed prototypes. **Lesson learned:** Dedicated stepped-spillway design software significantly reduces trial-and-error and the cavitation module is a critical component.

IV. Discussion and Key Findings

4.1 Energy Dissipation Performance

Across the presented literature, the main finding is clear and consistent: stepped spillways dissipate much more energy than smooth spillways of comparable slope (Boes and Hager 2003; Chanson 2015, 2022b). This energy dissipation level is often big enough to reduce the stilling-basin requirements. The exact benefit depends on slope, step geometry, discharge, and the flow regime (Rajaratnam 1990; Chanson 2022a).

Pooled and modified geometries can further improve dissipation, but most of those results are still laboratory studies than full prototype experiments (Felder et al. 2012; Ghaderi et al. 2020, 2024). For that reason, they should be viewed as promising rather than fully mature design options. The best-supported practical conclusion remains that standard stepped spillways already provide major hydraulic benefits in terms of energy dissipation when designed properly (Boes and Hager 2003; Chanson 2015, 2022b)

4.2 Prototype–Laboratory Agreement

Strong agreement between laboratory predictions and field behavior is documented at Hinze Dam and Paradise Dam (Chanson 2022a; Chanson and Gonzalez 2024;Chanson and Hu 2024a). Those cases demonstrate that hydraulic performance observed in the laboratory can be reproduced in a real structure when Froude scaling is applied appropriately and when the physical model is large enough to limit viscous and surface tension effects. Continued prototype monitoring at such sites is valuable because it provides independent confirmation that the design assumptions are reliable under actual flood conditions (Chanson 2022a;Chanson and Hu 2024a).

At the same time, the transfer is not perfect for every case. Scale effects can influence air concentration and bubble count rate measurements, especially in smaller laboratory models (Chanson and Hu 2024a). This means that physical models remain useful, but they should be interpreted cautiously and complemented with prototype observations where possible.

The Bogovina Dam study (Zindovic et al. 2014) used a three-way comparison of physical model, empirical equations, and numerical model. The empirical and numerical results reached acceptable agreement, but considerable differences were reported between the physical model and the other two approaches; the physical model should therefore not be treated as the definitive calibration benchmark in that case.

4.3 Cavitation Risk and the Discharge Threshold

The literature supports the conservative approach in determining cavitation (Boes and Hager 2003; Wahl and Falvey 2022). High discharge, steep slopes, and insufficient aeration all increase the risk in the upstream non-aerated zone (Wahl and Falvey 2022; Chanson and Gonzalez 2024). In practice, this is why stepped spillways above roughly 30 m²/s should be treated carefully and checked case by case, not by a single rule (Terrier et al. 2022).

A useful practical point is that cavitation concern does not mean that stepped spillways are unsafe. It means that the design must be matched to the hydraulic conditions, and that aeration or an alternative spillway type may be needed when the discharge is too high (Wahl and Falvey 2022). This is the constraint that should determine the stepped spillway's applicability.

V. Identified Problems and Challenges

5.1 Cavitation in the Non-Aerated Zone

The main recurring problem is cavitation risk near the spillway's crest and in the zone before aeration begins (Wahl and Falvey 2022; Chanson and Gonzalez 2024). This is where pressures can become highly negative and where the step edges are most vulnerable. The literature does not show widespread prototype cavitation damage, but it shows enough risk to justify a conservative design (Wahl and Falvey 2022).

5.2 Scale Effects in Physical Modelling

Scale effects remain an issue in laboratory work (Chanson and Hu 2024a). The problem is not that physical models are unreliable, but that small models can under-represent aeration and pressure behavior. This is why larger physical models and prototype checking remain valuable, especially for high-head dams and complex step shapes (Zindovic et al. 2014; Chanson and Hu 2024a).

5.3 Stilling Basin Sizing Under Extreme Events

Several cases show that the toe still needs careful design even when a stepped spillway is used (Husain and Ahmed 2017). The stepped spillway reduces residual energy, but it does not always remove the need for a hydraulic-jump stilling basin. Underestimating the toe velocity can cause the basin to be too small or too weak for extreme events (Chanson 2015; Husain and Ahmed 2017).

5.4 Long-Term Durability and Maintenance

Low-cost alternatives such as geobags and gabions are useful, but their long-term durability remains less certain compared to RCC (Peyras et al. 1992; Yu et al. 2023). Gabion corrosion and geobag aging are the main concerns. RCC remains the most proven material for long-life stepped spillways (Chanson 2022b).

VI. Conclusions

Stepped spillways remain one of the most effective hydraulic solutions for dissipating energy in dams and related overflow structures (Chanson 2015, 2022b). The strongest evidence comes from prototype and large-scale studies showing that these spillways can work very well when slope, discharge, and aeration are properly matched (Chanson 2022b; Chanson and Gonzalez 2024; Chanson and Hu 2024b). Stepped spillways are especially attractive because they can reduce downstream stilling-basin demands while remaining easy to construct and durable (Boes and Hager 2003).

The main limitation is still cavitation risk at high unit discharges, especially before the flow becomes fully aerated (Chanson and Gonzalez 2024;Wahl and Falvey 2022). For that reason, stepped spillways should be designed conservatively and verified using reliable model or field data. The literature also shows that novel geometries and low-cost materials are promising, but they need more prototype evidence before they can replace the established traditional stepped spillways (Peyras et al. 1992; Wahl and Falvey 2022; Yu et al. 2023; Ghaderi et al. 2024).

VII. Recommendations for Practice and Future Research

7.1 Design Practice Recommendations

1. Limit stepped spillways without special aeration to approximately $q \leq 30$ m²/s unless geometry-specific verification shows acceptable cavitation risk (Boes and Hager 2003; Wahl and Falvey 2022).
2. Use large-scale physical models or prototype-backed verification for high-head spillways and non-standard geometries (Zindovic et al. 2014; Chanson 2022b; Chanson and Hu 2024b).
3. Use pooled or modified geometries only after confirming that their prototype doesn't create any unaccepted flow behavior (Peyras et al. 1992; Matos and Meireles 2014; Ghaderi et al. 2020, 2024).
4. Validate stilling-basin dimensions against physical model or high-fidelity CFD results before final design approval (Zindovic et al. 2014; Husain and Ahmed 2017)

7.2 Recommendations for Future Research

Future research should focus on the following points:

1. Expanding prototype monitoring for stepped spillways in regions where modern RCC dam construction is active but field data remain limited.
2. Testing promising novel geometries at larger scale before treating them as a standard practice.
3. Developing stronger long-term durability records for geobag and gabion stepped spillways.
4. Investigating the implementation of aeration devices for stepped spillways operating near or above the high-discharge limit.
5. Improving prediction tools using combined experimental, prototype, and numerical datasets.

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Competing interests

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