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Editorial

Advances in Spillway Hydraulics: From Theory to Practice

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Abstract: Over the past decades, significant advances have been achieved in hydraulic structures for dams, namely in water release structures such as spillway weirs, chutes, and energy dissipators. This editorial presents a brief overview of the eleven papers in this Special Issue, *Advances in Spillway Hydraulics: From Theory to Practice*, and frames them in current research trends. This Special Issue explores the following topics: spillway inlet structures, spillway transport structures, and spillway outlet structures. For the first topic of spillway inlet structures, this collection includes one paper on the hydrodynamics and free-flow characteristics of piano key weirs with different plan shapes and another that presents a theoretical model for the flow at an ogee crest axis for a wide range of head ratios. Most of the contributions address the second topic of spillway transport structures as follows: a physical modeling of a beveled-face stepped chute; the description and recent developments of the generalized, energy-based, water surface profile calculation tool SpillwayPro; an application of the SPH method on non-aerated flow over smooth and stepped converging spillways; a physical model study of the effect of stepped chute slope reduction on the bottom-pressure development; an assessment of a spillway offset aerator with a comparison of the two-phase volume of fluid and complete two-phase Euler models included in the OpenFOAM® toolbox; an evaluation of the performance and design of a stepped spillway aerator based on a physical model study. For the third topic of spillway outlet structures, physical model studies are presented on air–water flow in rectangular free-falling jets, the performance of a plain stilling basin downstream of 30° and 50° inclined smooth and stepped chutes, and scour protection for piano key weirs with apron and cutoff wall. Finally, we include a brief discussion about some research challenges and practice-oriented questions.

Keywords: hydraulic structures; spillways; weirs; energy dissipators; experimental modeling; CFD modeling

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1. Introduction

From a safety point of view, spillways are vital water release structures that avoid uncontrolled overtopping and possibly dam failure. The spillway protects the dam and the population downstream against failures, as uncontrolled water release from the reservoir may result in catastrophic damage. Almost 59,000 large dams higher than 15 m satisfy the worldwide vital need for water, energy, food, and flood protection [1]. Spillway design and hydraulics are highly relevant since floods exceeding spillway capacity have caused many past dam incidents and failures, namely 25 to 35% [2].

Spillways can be characterized by the three main elements forming them: inlet structures, transport or conveyance structures, and outlet or energy dissipation structures [3]. A further criterion is whether the spillway is controlled or not by gates or fuse elements such as plugs or gates. As inlet structure linear weirs, nonlinear weirs, side weirs, circular weirs, syphons, or orifices may be used. The transport structure may be absent in the case of a free-falling jet from the inlet structure. Options for the transport structure comprise cascades or stepped chutes, smooth chutes, free surface tunnels, and pressurized tunnels or shafts. For the outlet structure, stilling basins or ski jumps are applied to ensure the safe energy dissipation. Combinations of all these options forming a spillway are numerous; nevertheless, the best option must be chosen from a safety and economical point of view and depending on the dam type. Thus, selecting the dam and spillway type is highly interrelated and challenging, rather a design art than a simple engineering task [3]. In the case of concrete dams, the spillway structure can often be combined directly with the dam itself. However, in the case of embankment dams, the spillway must generally be located on the side of the dam in the rock abutment. Chutes can be easily placed, though generally only in the case of gravity dams directly on the downstream face of the dam, which is more difficult for buttress dams. Stepped chutes have been developed mainly combined with RCC gravity dams or as overtopping protection of embankment dams. However, they are increasingly used in rock abutments for primarily embankment dams. Orifice and crest spillways can be combined directly with arch dams managing the free-falling jets into a plunge pool downstream of the dam toe. For embankment dams, chute spillways must be located for arch dams on the side of the rock abutment. Other spillways completely independent of the dam comprise morning glory and tunnel, shaft, and vortex spillways. However, each dam project has individual characteristics which require finding the most suitable dam type in combination with the spillway type composed of the above-mentioned elements of inlet, transport, and outlet structures.

Given potential catastrophic downstream consequences, the safety requirements for spillways are high. The safe passage of the design flood, typically a 1000 years flood, must be guaranteed with sufficient freeboard and typically under the assumption that one gate of the spillway or outlet with the largest discharge capacity is blocked («n − 1 rule»). Furthermore, a safety check flood, normally the Probable Maximum Flood (PMF), must safely pass the dam for all gates in operation without surpassing its critical water level resulting in catastrophic damages. For embankment dams having a high risk of failure when overtopped, the «n − 1 rule» often still applies for the safety check flood [3].

The state of the art of design of spillways and the related hydraulics with calculation methods are outlined in detail in the recent book *Hydraulic Engineering of Dams* [3], addressing researchers and practitioners. Among the intake structures of spillways, the frontal and spatial crest overflows, including side channels, morning glory overfalls, labyrinth weirs, piano key weirs, and syphons are treated. The transport structures comprise smooth and stepped chutes and related aeration devices. The dissipation structures include a detailed presentation of stilling basins, drop structures, free-fall outlets, ski jumps, flip buckets, and plunge pools with related scour issues.

Recent developments of spillways confirmed in practice have also been presented in the latest dam hydraulics Bulletin of the International Commission on Large Dams (ICOLD) [4]. The focus is on stepped spillways, labyrinths, piano key weirs, and tunnel spillways. The conventional types of structures are analyzed in view of operating under special conditions such as very large flows, very high heads including scour challenges, and very cold climates. Finally, economic and cost issues are also addressed. The blockage of reservoir outlet structures by floating debris has become a more current concern, and an overview has been presented in a recent Bulletin of ICOLD [5].

Most spillway design methods are based on empirical and semi-empirical relationships from systematic physical laboratory experiments. Complex spillway arrangements involving three-dimensional flow features are still analyzed and optimized with comprehensive hydraulic model tests, which are also precious tools for convincing decision-makers in controversial situations. With the advancement in numerical modeling, using both a physical and a numerical model together as a composite or hybrid model has proven to improve modeling accuracy and reduce modeling uncertainty, besides reducing time and costs. Composite modeling is an effective tool for hydraulic structure design [4]. Furthermore, composite or hybrid modeling provides a unique opportunity for researchers and engineers to understand the uncertainties and limitations of both the physical model and the numerical model since their parallel operation allows for direct comparison and calibration as well as validation. When complex three-dimensional and multi-phase flow conditions are involved, numerical models are often limited in their ability to simulate the flow features, including air entrainment and sediment transport, compared with a physical model [4].

2. Overview of This Special Issue

This Special Issue was established to highlight recent advances in spillway hydraulics with a focus not only on theoretical but also on practical issues. In total, eleven collected papers are grouped in the following subsections according to the three main elements forming a spillway: inlet structures, transport or conveyance structures, and outlet or energy dissipation structures.

2.1. Spillway Inlet Structures

The inlet structure controls the upstream reservoir level and the discharge released through the spillway. Today, several reasons tend to increase the design discharge of spillways, which, in turn, favor the development of new types of weirs or the operation of existing solutions above their design value. The two contributions related to spillway inlet structures focus on these aspects.

Sangsefidi et al. [6] complement the rich literature, e.g., [7–11], on the innovative piano key weir, an improved type of nonlinear weir with high discharge capacity which can be placed atop gravity dams, first proposed by Lempérière and Ouamane in 2003 [12]. Based on physical model tests, they analyze discharge efficiency and detail flow conditions for triangular, trapezoidal, and classical rectangular piano key weirs considering a large range of parameter values. They confirm that thanks to its numerous geometric parameters, the piano key weir is a very versatile structure, always more hydraulically efficient than the corresponding linear weir of the same width on the dam crest [13]. A single optimal piano key weir geometry does not exist. However, shape optimization can lead to a substantial gain in hydraulic efficiency, required volume of concrete or formworks complexity, for instance. Consequently, optimum is closely related to specific project constraints and objectives.

Moreover, Stilmant et al. [14] focus on a traditional linear weir with an ogee crest. They derive a purely theoretical model for computing the weir discharge coefficient depending on the upstream head ratio. The model provides water depth, flow velocity, and pressure distribution at the weir crest and is validated against experimental data for the upstream head up to five times the crest design head. In addition to being free of any empiricism, the model enables us to better understand flow conditions at ogee crests and then contributes to a better assessment of flow detachment and cavitation risk when operating standard linear weirs above the design head [15].

2.2. Spillway Transport Structures

Appropriately assessing the chute flow behavior, including aeration and cavitation risk, is still a challenge for researchers and designers, as confirmed by the six contributions received. Besides the already quite well-known flow features on smooth spillway chutes more focus is given to actual research on stepped chutes with both numerical and experimental approaches.

Wahl and Falvey [16] present the computation tool SpillwayPro for the analysis of integrated water surface profiles, including the effect of aeration and the risk of cavitation on smooth and stepped chutes. SpillwayPro [17] is based on fundamental energy and momentum equations supplemented by empirical relations developed from laboratory and prototype measurements. As an interactive tool, it was developed on an Excel workbook featuring multiple worksheet tabs and takes advantage of developments over several decades at the Bureau of Reclamation. Interestingly, for practitioners, the simultaneous calculation of smooth and stepped chutes allows an efficient selection of the appropriate chute type regarding energy dissipation and cavitation risk for a certain dam arrangement. For both smooth and stepped chutes, the technical and scientific basis used in the calculation tool is presented and discussed in detail, including the aeration inception point, the fully developed and developing aerated flow zone, the bottom air concentration, the friction factor, the flow bulking, and the cavitation potential. Furthermore, based on the specific energy values obtained at the bottom of the chute, SpillwayPro allows estimating the length of four USBR types of possible stilling basins. The performance of SpillwayPro is finally illustrated with three practical case studies.

Nóbrega et al. [18] present three-dimensional (3D) simulations for smooth and stepped spillway chutes with converging walls using the smoothed particle hydrodynamics (SPH) method to evaluate the influence of the wall deflection and the step macro-roughness on the main non-aerated flow properties. The studied case corresponds to a broad crested weir followed by a 1 V/2 H sloping smooth or stepped chute having a wall convergence angle of 9.9° or 19.3°. Such a layout may be used as a concrete overlay structure on small embankment dams. The same configuration was investigated with a physical model having a scale of 1:10 compared to the simulated prototype. Overall, the numerical results of the SPH simulations agreed generally well with the experimental data on the broad crested weir and the spillway chute, namely flow depths, velocity profiles, and the development of the standing wave width on the chute. As expected, the standing waves were attenuated on the stepped chute due to the significant macro-roughness effect of the steps compared to the smooth chute. Moreover, the authors obtained some differences in the stepped chute configuration for flow depth and velocities compared to the experimental data. The numerical results slightly overestimated the flow depths at the chute centerline or pseudo-centerline, mainly near its downstream end. The flow velocities mostly deviated close to the pseudo-bottom of the stepped invert. According to Nóbrega et al. [18], this could be overcome by using the modified dynamic boundary conditions (mDBC) implemented in the current version of DualSPHysics [19].

For construction reasons to avoid formworks, there may be an interest in building RCC overlays for embankment dam rehabilitation or even new dams with beveled-face steps. Hunt et al. [20] describe a large-scale experimental study with a 1.8 m wide flume having a total drop height of 5.6 m and a chute slope of 18.4° (e.g., 3 H/1 V) using step heights of 152 mm. The results comprise the inception point of free-surface aeration, relative flow depths, the mean air concentration, and energy losses. The authors found that for beveled-face steps, the distance to the inception point of free-surface aeration normalized by the surface roughness is reduced by approximately 25% for the same Froude number defined in terms of roughness height compared to vertical face steps. A fitted correction factor was developed to adjust the vertical face step inception point relationship for applications with beveled face steps. The flow depths and air concentrations for beveled face steps were slightly higher for equal values of relative free-surface inception point and relative step height. It seems that towards the end of the chute, the relative energy loss becomes slightly smaller for beveled face steps compared to vertical steps.

Stepped spillways have been built for several decades in combination with roller-compacted concrete dams. Recently, stepped spillways are also excavated into the rock along the abutments of embankment dams [21]. According to the prevailing topography, these stepped spillways are designed with variable step heights and slope changes along the channel. Ostad Mirza Tehrani et al. [22] present systematic laboratory tests studying the influence of abrupt slope changes on the flow characteristics of stepped spillways. A relatively large-scale physical model, including abrupt slope reductions from 50° to 18.6° and from 50° to 30° was used, operated with skimming flow. The contribution focuses on dynamic pressures measured on both vertical and horizontal faces at several steps in the vicinity and far downstream of the slope change. A substantial influence of the tested slope reductions on the bottom-pressure development was observed. In the vicinity of the slope reduction, the mean pressure head near the edge of the horizontal step face reached 0.4 to 0.6 times the velocity head upstream of the slope reduction for critical flow depths normalized by the step height ranging between 2.6 and 4.6. This global increase in the bottom pressure should be considered to estimate the total thrust and bending moment on the chute walls.

High-velocity flow on spillway chutes may result in low bottom pressure with a high risk of cavitation damage. Chute aerators have been proven, for a long time, as an efficient mitigation measure against cavitation damage on smooth chutes. Design guidelines for aerators have been developed mainly via systematic laboratory experiments on large-scale models [3,23–25]. Numerical modeling of two-phase air–water highly turbulent flows with aeration on chutes is still a challenge. Mendes et al. [26] compare the performance of a spillway offset aerator using the two-phase volume-of-fluid (TPVoF) and the complete two-phase Euler (CTPE) method. They conclude that the complete two-phase Euler surpasses the two-phase volume-of-fluid model, evidencing an efficient cost–benefit performance and significant value in hydraulic engineering applications of spillway aerated flows. Nevertheless, not all aspects of the flow are reproduced with acceptable accuracy. Further developments are expected to enhance the tool's efficiency and stability. However, the two-phase volume-of-fluid (TPVoF) was considered appropriate to model the spillway intake structure and possibly the outlet structure.

As already mentioned, stepped spillways are also excavated into the rock along the abutments of embankment dams [21]. Over the last years, the specific design discharge over stepped spillways has increased significantly. Specific discharges higher than 30 $m^3/s/m$ for skimming flow regimes are not rare anymore. For such high specific discharges, the risk of cavitation damage may occur in the clear water flow region of the stepped chute. This risk can be mitigated by implementing a specially designed aerator in the upstream reach of the stepped chute. Based on systematic laboratory experiments on a large-scale model, Terrier et al. [27] present the performance and design of a spillway aerator arranged at the beginning of a stepped chute. They systematically analyzed the lower and upper surfaces of the jet issued by the deflector and could derive empirical equations for the lower and upper effective takeoff angles. With the takeoff velocity, the lower and upper jet surfaces can be described with ballistic equations to obtain the maximum jet elevation, the jet length, and the jet impact angle on the pseudo-bottom, which are the most important parameters to predict aerator performance. The authors demonstrate that the air entrainment coefficient of the aerator could be derived from the relative jet length and propose an empirical relationship, thus able to obtain the air entrainment coefficient as a function of the Froude number and the deflector geometry. Finally, Terrier et al. [27] give relations for estimating the average and bottom air concentrations at relevant locations along the flow, which provide a sufficient value to counter cavitation damages. The design procedure for a stepped spillway aerator is illustrated with a practical example.

2.3. Spillway Outlet Structures

Three contributions focus on outlet structures. They relate to free-falling jets from linear weirs [28], to stilling basin performance downstream of smooth and stepped spillway chutes [29], and to specific arrangements to prevent erosion at the toe of nonlinear weirs used in low-head projects [30], i.e., without spillway channel and with energy dissipation directly at the weir toe. As such, these contributions highlight the wide variety of problems associated with outlet structure design depending on project configuration and requirements.

Carrillo et al. [28] improve the current knowledge of turbulent rectangular jets by analyzing experimental data gained on a 2.0 m high fall facility with a conductivity phase-detection probe and a back-flushing Pitot–Prandtl tube. In particular, they characterize the evolution of air content along the jet length and show that the whole jet cross-section starts to be affected by aeration for a falling distance higher than 15 times the total energy head over the weir crest. While these new results are in good agreement with formerly published relations for free-falling jets of other kinds of air–water flows, we still need further analysis to better characterize the energy dissipation in the region near the break-up length. Scale effects affecting air–water flow experimental modeling and the nappe oscillation phenomenon are other topics of current interest in this field.

Stilling basins are a solution to dissipate residual energy at the toe of spillway chutes. However, while stepped spillway chutes have been extensively studied, only limited knowledge is available on stilling basin performance downstream of such chutes. Stojnic et al. [29] fill in this gap in knowledge by conducting an experimental analysis of stilling basin performance downstream of a 30° or 50° inclined stepped chute in comparison to the same smooth chute. While their study shows that chute slope has little effect on surface characteristics as well as on the roller and hydraulic jump lengths, it confirms that stepped chutes require longer dimensionless stilling basins compared to smooth chutes. Stepped chutes also increase extreme and fluctuating pressure characteristics at a stilling basin entrance area, the magnitude of which is magnified by the chute slope. However, high bottom aeration induced via stepped chute inflow should prevent cavitation damage from occurring in such entrance areas. Empirical equations to predict flow features are proposed to ease the practical structural design of stilling basin bottom slabs and side walls, which is still a challenging task.

Lantz et al. [30] present a comprehensive study of scour at the toe of piano key weirs used in channel applications and propose guidance to design a horizontal apron with a cutoff wall to mitigate this scour risk. While most of the research published to date about piano key weirs focused mainly on their design and hydraulic behavior, e.g., [7–11], flow conditions downstream of this new type of spillway inlet structure but also design guidelines must be further documented to ease their implementation on prototypes. In addition to [30], some publications [31,32] paved the way for future research on scour development downstream of piano key weirs, but all the other aspects of flow in spillway conveyance structures must also be analyzed, such as air entrainment and energy dissipation.

3. Discussion

The following discussion completes the advances in spillway hydraulics, as presented in this Special Issue, with some other challenges addressed in recent research and practical questions.

Floating debris may significantly reduce spillway discharge capacity and result in a dangerous rise in the reservoir level [5]. With climate change, the flood risk and the quantity of floating debris in reservoirs are expected to increase. A comprehensive state of the art on floating debris issues at dam spillways can be found in [33]. Recommendations regarding risk and mitigation measures are given in [5]. Recent research on floating debris focuses on the blocking probability of different types of spillway intake structures [34–38], as well as the potential rise of the reservoir level [39,40]. Floating debris accumulation at PK weirs creates less reservoir level raise compared to traditional linear weirs [38].

The behavior of the flow on spillway chutes is well known on both smooth and stepped spillways thanks to many research studies in laboratories and advanced numerical modeling. However, the catastrophic failure of the spillway chute at Oroville Dam in the USA in February 2017 [41] and at Toddbrook Dam in the UK in August 2019 [42,43] revealed some lack of knowledge regarding dynamic flow pressure transfer below the concrete chute slabs for spillways arranged on rock abutments of dams. Following Oroville and based on previous laboratory testing incidents, Wahl et al. [44] developed relations between chute velocity, joint geometry, and uplift pressure transmitted into a joint. They concluded that additional research is still needed to quantify rates of flow through open joints of chute slabs and to confirm relations between uplift pressure and boundary layer velocities also considering the effects of aerated flow. Another still quite unknown challenge is the fluid–structure interaction effect, which is the interaction between the dynamic fluid pressure on the chute bottom and the induced vibration and response of the concrete slab. In the case of smooth chutes, the dynamic bottom pressures are quite well known, which are triggered by the turbulent boundary layer and the air entrainment [3]. In the case of stepped chutes, the hydrodynamic pressure field from a structural point of view is an important issue to help identify the reaches of cavitation risk. Several researchers have described in detail the development and fluctuations of the pressure field on both the horizontal and vertical step faces in stepped chutes [45–49]. Nevertheless, for the full spectrum of pressure fluctuations, prototype measurements would be needed, which are still difficult to execute.

The observation of the behavior of prototype chute aerators during significant floods, for example, in Iran, revealed that much more air is entrained in the flow than predicted via the empirical approaches used for the design of the aerators. Yang et al. [50] tried to explain the differences between the laboratory and prototype behaviors of spillway aerator flows. They found that a direct conversion of air flow from the model to the prototype is justified only if the approach flow velocity in the model exceeds 7.0–7.5 m/s. Otherwise, there would be errors in prototype predictions depending on both the model scale and flow magnitude. Furthermore, they concluded that the air concentration decay in the prototype is much slower, and a higher level is maintained over a longer distance downstream of the impact location compared to the hydraulic model.

These latter comments remind us that, to date, most of the research about spillway flows has been conducted based on observations and measurements of flow on scale physical models [51]. Because the fluid properties are not scaled, scale models suffer scale effects, whose impact on flow properties may be important but depends on which specific parameter is considered [52–56]. Experimental studies using large-scale models [57–59] or even on prototypes [60–62] need to be performed to complement traditional research and enable the validation of the current knowledge at the scale to which it is applied.

4. Conclusions

A collection of eleven papers were included in this Special Issue addressing spillway hydraulics, embracing the following main elements: spillway inlet structures, spillway transport structures, and spillway outlet structures. For the first topic, spillway inlet structures, discharge efficiency, and flow conditions are experimentally studied for PK weir with different plan shapes (i.e., triangular, trapezoidal, and rectangular), considering a large range of parameter values (Sangsefidi et al. [6]). In turn, Stilmant et al. [14] derive a purely theoretical model, validated against experimental data for a broad range of upstream heads, to compute the discharge coefficient with an ogee crest, which does not depend on empirical coefficients. Regarding the second topic, spillway transport structures, a diversity of subjects are analyzed, such as examining the physical effects of beveled face steps on various hydraulic design parameters, of relevance to contemporary design and construction practices for stepped chutes (Hunt et al. [20]); computing the flow parameters of engineering interest for smooth and stepped spillway chutes using the SpillwayPro program (Wahl et al. [17]); evaluating the performance of 3D SPH simulations for nonaerated flow over smooth and stepped spillways with converging walls (Nóbrega et al. [18]); estimating bottom-pressure development on stepped chutes caused by an abrupt slope reduction (Ostad Mirza Tehrani et al. [22]); CFD modeling of a spillway offset aerator, using the two-phase volume of fluid versus the complete two-phase Euler models included in the OpenFOAM® toolbox (Mendes et al. [26]); and investigating the performance of a deflector aerator at the upstream reach of stepped chutes to prevent cavitation damage, and, therefore, allow high specific discharges (Terrier et al. [27]). For the third topic, spillway outlet structures, the contributions include reasonably large-scale physical model studies of the air–water flow properties in rectangular free-falling jets (Carrillo et al. [28]), stilling basin performance below 30° and 50° inclined smooth and stepped chutes (Stojnic et al. [29]), and scour process occurring downstream of a PK weir in the presence of downstream apron (Lantz et al. [30]). These papers are novel contributions to the research on spillway hydraulics and constitute a stimulus for further developments on this fascinating subject.

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