Hydraulic Properties of Flow Over Different Types of Spillways: A Review

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Abstract A review of hydraulic properties of flow over the spillway via physical experiment and computational approaches is presented in this paper. The hydrodynamic analysis of flow via the computational fluid dynamics (CFD) approach is vital in solving complex flow problems where the field and experimental assessments are limited. The most selected and efficient turbulence model is the RNG k-ε model. Free water surface profile, Froude number, flow regime, velocity, and pressure distribution were identified as the most studied parameters of flow over the spillway structure. These hydraulic characteristics of flow were affected by the geometrical configuration such as the type and arrangement of the spillway. The skimming flow was recognized as the most frequent type of flow in the actual field. The stepped and hybrid types were identified as the most studied concerning functionality in controlling the velocity and dealing with rapidly varied flow types as compared to the ogee-type. Understanding the hydraulic properties of flow is mandatory and

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important to ensure the serviceability of the spillway structure to safely transfer the water to the downstream section and to minimize the massive impacts of hydraulic jump together with the presence of air–water interface, cavitation, and downstream scour problem. The potential future research work includes an in-depth relationship between the hydraulic characteristic of flow between the efficient spillway structure and the baffle block structure in controlling the hydraulic jump in the stilling basin area.

Keywords Spillway · Hydraulic characteristics · Clean water and sanitation · RNG k-ε model · Velocity · Pressure · Skimming flow · Energy dissipation

1 Introduction

Over a few decades, a dam has been identified as one of the main hydroelectric power generation, flood control facilities, and water storage infrastructures to cater to a continuous water supply demand. In addition, the dam itself should be properly built (new dam infrastructure) with effective and efficient management for a sustainable operation (available constructed dam). This promising effort is in line with the Sustainable Development Goals (SDGs) No. 6 and No. 7, namely clean water and sanitation, and clean energy, respectively [1]. This effort was frequently and critically considered due to the current and future sustainability concerns and operability of the infrastructure and its resources. In-depth, a proper policy together with the list of scheduling efforts should be in line for both short- and long-term planning. Thus, this effort requires continuous support from both top to bottom and vice versa including policy implementation (technical design code and guidelines), pre-construction (planning and site survey), during construction (construction method and materials as well as identified problem and limitation), and post-construction (maintenance, operationality, and monitoring aspects including preparedness towards hazard and related system for vibration and cracking detection due internal and external factors).

The functionality and safety related to the structural stability of a dam mainly in an aging condition should be a priority due to its current and future positive and negative impacts on human and environmental factors. Historical and current rainfall input data, actual and predicted flow determination and simulation, and reliable technical design on dam structures (reservoir/water intake, radial gate, spillway, stilling basin, orifice, tailrace, etc.) should be considered in ensuring the functionality and safety of the infrastructure. For instance, the validated data on the hydrostatic force on the dam structure should be identified and estimated correctly by conducting the stability analysis at the technical design stage [2]. Other important factors including maintenance and monitoring (seismic and structural monitoring) efforts [3, 4] are vital with regards to hazard preparedness due to unpredictable global situations concerning climate changes impacts (rainfall patterns imbalanced and dam overtopping due to severe flooding effect) [5–9] and natural disaster problems (earthquake-induced strong ground vibration or shaking) [10, 11].

The spillway is known as one of the dam structural components to provide excess water transfer from the reservoir via inlet to the stilling basin structure and downstream section [12]. Thus, understanding the hydraulic characteristic of flow behavior is crucial to avoid any shortcomings in either short-term or long-term periods. Furthermore, the characteristic of flow result from different spillway types and the installation of an energy dissipation structure at the end of the spillway toe are added to these. Several spillway structures are considered and studied by previous researchers in terms of traditional and innovative design types. The type of traditional spillway structure was ogee-crested, stepped, and siphon spillways [2, 13–17] while the innovative spillway structure includes flat, pooled type, hydraulic-jump-step-spillway, and quarter-circular crested stepped spillway [13, 18–21].

Conventionally, flow characteristics on the hydraulic structure can be measured via field measurement. However, this option is time-consuming and provides limited site access. Therefore, a hydraulic physical model study based on laboratory pilot testing has been introduced to cope with this limitation. The physical experimental model is beneficial as it was studied at an early stage even before the development of the numerical model to understand the actual causal impact situation and be as an actual reference together with actual data acquisition [14, 19–21]. However, this selection is costly and required a longer time due to structural design and construction as well as regular system maintenance in terms of pumps and water tanks together with other related systems to ensure efficient water flow. Thus, numerical simulation provides inexpensive, accurate, and shorter time as it considers computer simulation and offers validation of flow conditions observed during field or physical model experiments [2, 22]. Recently, most researchers consider numerical simulation in dealing with the more complex fluid flow analysis on the spillway [2, 13, 15–18, 20, 22–25].

This paper aims to provide a short review of the hydraulic characteristics of flow (such as flow pattern, Froude number, velocity, and pressure distribution) over a spillway via both physical model experiments and numerical simulation works. The paper is organized as follows: First, an overview of the literature on traditional and modified spillway structures is presented. Second, the hydraulic characteristic of flow is studied based on the experimental and numerical set-up afterward with a conclusion of the reviewed study. The article ends with a future direction of research.

2 Traditional and Modified Spillway Structures

The spillway structure is divided into traditional and hybrid types. Table 1 shows summaries of the different types of spillway design based on the specific purpose and contribution.

Practically, the spillway is designed and constructed either freely or controlled by gated- and ungated-type structures. These gated or ungated types may function

Table 1 Overview of the different types of spillway design, purposes, and contributions

Author(s)	Categories/Type of spillway	Purpose	Contribution
Ghaderi et. al. [18]	Pooled stepped spillways • Flat steps, reference pooled steps (RPS), and notch pooled steps (NFS) • Fully pooled steps (FPS) • Zig-zag pooled steps (ZPS) • Central pooled steps (CPS) • Two-sided pooled steps (TPS)	Impacts of the geometrical characteristics of the flat and pooled step on the: • Energy dissipation • Hydraulic characteristics of flow (flow patterns' properties, velocity rates, and pressure distribution), • Inception point of air entrainment • Turbulent kinetic energy	• Best energy dissipation performance (flat step configuration) • Improved 5.8% of the efficiency performance (notch pooled step configuration) • Smaller interfacial velocities (flat step configuration) • The pressure rate is higher at the entrance of pooled configuration compared to the flat step configuration • The maximum pressure in the notch pooled configuration is decreasing near the step pooled configuration
Zhou et. al. [13]	Hydraulic-jump-stepped spillway (HJSS) Traditional stepped spillway	Performance of the HJSS on the: • Flow pattern • Energy dissipation • Air entrainment characteristics • Time-averaged pressure (horizontal and vertical condition)	• Reduction of cavitation damage • Higher energy dissipation • Better air entrainment performance • Reasonable pressure distribution • 69% increment of unit discharge capacity (traditional step spillway)
Karim and Mohammed [14]	Ogee-crested spillway (OS)	Performance of the OS on the: • Mean velocity • Vertical velocity distribution • Locations of the maximum velocity, d_m	• Understanding of flow over the ogee-crested spillway in a controlled environment for heads higher than the design head and selection of the vertical location for maximum velocity

(continued)

Table 1 (continued)

Author(s)	Categories/Type of spillway	Purpose	Contribution
Imanian and Mohammadian [15]	Ogee-crested spillway (OS)	Performance of the OS on the: • Flow separation • Discharge coefficient	• Understanding of the hydrodynamic field (flow separation or significant streamline curvature) • Flow separation zone grows linearly (increasing hydraulic head) • Discharge coefficient is increased due to decreasing pressure on the ogee crest (increasing of head ratio)
Li and Zhang, 2018 [22]	Pooled stepped spillway	• Understanding	• Understanding of the hydrodynamic field (flow regime, pressure distribution, and vortex detection)
Daneshfaraz and Ghaderi [25]	Inverse curvature ogee spillway	Performance of the inverse curvature OS on the: • Pressure profile	• Understanding the flow behavior on the ogee spillway • Understanding the relationships between pressure with inverse curvature • Maximum pressure on the inverse curve is reduced by increasing the radius of curvature (economical cost related to radius curvature construction)
Felder and Chanson 2016 [20]	Stepped spillway • Flat uniform and non-uniform configuration • Flat, pooled, and porous pooled steps • Combination of flat and pooled steps	Impacts of the geometrical characteristics of the flat, pooled, porous pooled, and combination of flat and pooled step on the: • Energy dissipation • Hydraulic characteristics of flow (flow patterns properties, velocity rates) • Inception point of air entrainment	• Understanding the flow behavior on the different configurations of flat uniform and non-uniform as well as flat, pooled, porous pooled, and combination of flat and pooled steps

(continued)

Table 1 (continued)

Author(s)	Categories/Type of spillway	Purpose	Contribution
Krisnayanti et al. 2016 [21]	Stepped spillway • Flat uniform • Pooled steps	Impacts of the geometrical characteristics of the flat and pooled step on the: • Energy dissipation • Hydraulic characteristics of flow (flow patterns properties, velocity rates)	• Understanding the flow regime on the different configurations of flat and pooled steps as well as energy dissipation
Johnson and Savage 2006 [2]	Ogee spillway	Performance of the OS (with the presence of tailwater) on the: • Discharge • Pressure	• Understanding the flow behavior, velocity, and pressure distribution on the ogee spillway with the submergence spillway
Savage and Johnson 2001 [17]	Ogee spillway	Performance of the OS (without the presence of tailwater) on the: • Discharge • Pressure	• Understanding the flow behavior, velocity, and pressure distribution on the ogee spillway without the submergence of the spillway

as an overflow structure mainly during the full capacity of the reservoir. The difference between these two types is that the ungated type may allow water to freely overflow from the fully occupied reservoir, while the gated one is operated based on the full capacity level and follow the water release schedule [12]. Conventionally, the ogee-crested spillway is the most frequently selected and designed type chosen by the engineer due to its broad functionality (higher amount of water being released), serviceability, and economical factors [2, 13, 15–19, 23–25]. Most of the conducted studies were done experimentally and numerically by referring to the standard guidelines and previous literature for results comparison and validation. The problem with ogee-type spillways is both uncontrolled and controlled gate structures may contribute to the energy dissipation problem and scour effect at the downstream section of the spillway. This problem is getting worsened with the presence of fluid jet impacts from upstream to the transfer section or downstream section due to the sloping condition of the ogee-crest spillway [12]. Thus, a focused study related to this matter is done by Daneshfaraz and Ghaderi [25] on the inverse curvature curve ogee spillway to study the relationship between the effects of pressure distribution with the modification of the radius of curvature concerning the economic aspects.

The introduction of a steps spillway provides an improvement on the flow characteristic distribution (three-dimensional) and is suitable for the skimming flow regime [18, 20]. In addition, an effort has been conducted to improve the energy dissipation capacity by designing a more reliable and efficient stepped spillway either single or hybrid concepts. Thus, this innovative spillway design provides a higher ability to convey the massive and high-speed flood flow from the upper section to the end of the spillway section by protecting the respected section from scour and cavitation problems as well as reducing the hydraulic jumps or fluid turbulent impacts [18, 22]. Interestingly, the cavitation problem is eliminated or reduced concerning the hydraulic jump reduction (length).

The innovative stepped spillway, for instance, pooled steps with several configurations (fully, zig-zag, double, etc.), and hydraulic-jump-stepped spillway (HJSS) are designed with the novel steps, and the system has given further attention to global researchers based on the resulting energy dissipation improvement. Thus, the focus on the traditional and innovative step spillway via experimental and numerical study is significantly increased due to the complicated fluid flow problem such as the air–water interface, the flow regime, and the energy loss process due to the hydraulic jump problem [20, 22]. The design of stepped spillways of both traditional and innovative has stressed the geometrical step and configuration. This is the main key factor for the high energy dissipation rate. The energy dissipation may be improved by the improvement of the amount of entrained air. The higher energy dissipation leads to a reasonable and appropriate downstream stilling structure concerning the construction cost.

In conclusion to this point, the most effective and gain interesting spillway structure among the researcher for energy dissipation improvement is the stepped spillway. This interest has been driven by the higher energy dissipation rate condition with the presence of several steps on the structure. The stepped spillway is more robust as compared to the ogee-type (free fall flow) where it could control the velocity jet and deal with the rapidly varied flow type. In addition, the stepped type is better in handling skimming flow problems, which is the actual condition of flow on-site. Furthermore, the innovation of single and hybrid stepped may enhance the better understanding of flow especially related to the three-dimensional complex hydrodynamic problem. In addition, the problem related to an air–water interface may be reduced or solved depending on the situation and condition. Thus, a proper investigation of the geometrical configuration of the stepped spillway should be conducted to differentiate the effect between them. The focus also may be extended to connect the ogee type with the stepped type (hybrid type), and the relationship between these combinations may be studied to evaluate the performance of these hybrid spillway types in terms of energy dissipation rate and air–water interface problem.

3 Remarked Hydraulic Properties of Flow Over Spillway Structures

The hydraulic characteristics of flow over a spillway structure were summarized in Table 2.

Table 2 Hydraulic properties of flow studied by different researchers

Author(s)	Type of study/Model	Q (m^3/s)/ Unit Q (m^2/s)	V (m/s)	Fr. No	Re. No	Flow regime	Free water surface profile and streamlines	P (KPa)	Turbulent kinetic energy, (J/kg)	C_d
Ghaderi et. al [18]	Numerical models—CFD: FLOW-3D® model—volume of fluid (VOF) Hydrodynamic model—three-dimensional Navier–stokes equations [Reynolds-averaged Navier–Stokes (RANS)] and the continuity equation Turbulence model—RNG k-ε	√	√	√	√	√	√	√	√	NA
Zhou et. al. [13]	Hydraulic physical model (inflow channel, weir, aeration basic, stepped spillway, outflow channel) Scale: 1:40	√	√	√	NA	√	√	√	NA	NA
Karim and Mohammed [14]	Physical model and numerical model	√	√	NA	NA	√	√	√	NA	√
Imanian and Mohammadian [15]	Numerical models—CFD: OpenFOAM—volume of fluid (VOF) Turbulence model—standard k-ε, realizable k-ε, k-ω SST and LRR (Launder–Reece–Rodi) RNG k-ε	√	√	NA	NA	√	√	√	NA	√

(continued)

Table 2 (continued)

Author(s)	Type of study/Model	Q (m^3/s)/ Unit Q (m^2/s)	V (m/s)	Fr. No	Re. No	Flow regime	Free water surface profile and streamlines	P (KPa)	Turbulent kinetic energy, (J/kg)	C_d
Li and Zhang [22]	Numerical models—CFD: ANSYS 16.0—volume of fluid (VOF) Turbulence model—RNG k-ε	✓	✓	✓	NA	✓	✓	✓	NA	NA
Daneshfaraz and Ghaderi [25]	Numerical models—CFD: fluent—volume of fluid (VOF) Turbulence model—RNG k-ε	✓	✓	NA	NA	NA	✓	✓	NA	NA
Krisnayanti et al. [21]	Physical experimental model	✓	✓	✓	NA	✓	✓	NA	NA	NA
Felder and Chanson [20]	Physical experimental model	✓	✓	✓	✓	✓	✓	NA	NA	NA
Johnson and Savage [2]	Numerical models—CFD: FLOW-3D® model—volume of fluid (VOF) Existing literature	✓	✓	NA	NA	✓	✓	✓	NA	NA
Savage and Johnson [17]	Physical model, numerical model, and existing literature	✓	✓	NA	NA	✓	✓	✓	NA	NA

The understanding of the hydraulic characteristic of flow is vital, especially for design purposes. The previous design of hydraulic structures especially spillways only depended on the technical guidelines and design handbook. However, the sustainability of the hydraulic structure (ability to function and serve within its operational and design life) provides an interest among the researchers to focus on the area. In addition, natural disasters including climate change impacts show an alert to the post-construction (maintenance and monitoring purposes) activity. The presence of hydraulic jump phenomena may contribute to the scour and cavitation problem in the downstream section [18, 21].

Conventionally, the actual site assessment is conducted together with the experimental work. However, in dealing with the complex flow problem and on-site limitation (safety purposes) plus limited experimental work related to complex flow problems, a numerical simulation may be a good and alternative option. Numerical analysis is a robust technique with a complex flow solution (hydrodynamic analysis especially for 3D flow). An arrangement or configuration has been done numerically without any doubt via the specific model. Based on the review data, most of the researchers used several types of computational fluid dynamics models either 1D, 2D, or 3D flow models based on the basic equation of three-dimensional Navier–Stokes equations: Reynolds-averaged Navier–Stokes (RANS) and continuity equation for the hydrodynamic model analysis. The type of most applicable turbulence model is the RNG k-ε model [1, 13, 25]. Furthermore, another researcher also applies other types of models, namely standard k-ε, realizable k-ε, k-ω SST, and Launder–Reece–Rodi (LRR) in addition to the RNG k-ε [15].

The most studied hydraulics parameters are velocity and pressure distribution as shown in Table 2. Based on these parameters, it can be said that there is the main impact of velocity and pressure in the formation of several types of hydraulic jumps. In addition, the most influential point for hydraulic failure is located at the stilling basin section where the water is being transferred from the inlet via spillway structure to the stilling basin. Here the formation of a hydraulic jump occurs (the intensity is dependent on the velocity, pressure, and sloping condition). In this section, it is vital to provide additional structures for energy dissipating purposes. Normally, the type of flow over the spillway can be divided into nappe, transition, and skimming flow. Interestingly, the actual flow condition on the field is the skimming-type flow which is affected by the site condition.

Daneshfaraz and Ghaderi [25] conducted a study related to the impact of inverse curvature on the pressure rate and found that the maximum pressure is achieved by increasing the inverse linear curvature. This study was less investigated by the researcher and provided a long-term value as it would be an economical option. Other studies are related to the hydraulic characteristic (discharge characteristics and pressure distribution) of flow over submerged ogee with the effect of tailwater, via physical mean and numerical simulation in comparison with the previously established standard guidelines and literature. In addition, the usage of a numerical model for hydrodynamics analysis accurately simulates the flow and pressure distribution and gives significant findings especially related to the understanding of pressure distribution related to a submergence case study [2]. The pressure distribution and discharge rate are affected by the crest and spillway geometry, upstream flow depth, together with the downstream depth. The analysis of pressure on the submerged spillway is important due to the resisting force to overturn or slide at the end of the spillway section [2].

Zhou et al. [13] study on the effect of time-averaged pressure on the face of a stepped spillway: horizontal and vertical conditions via physical model experimental. The obtained result shows the pressure distributions on the horizontal step surfaces exhibited S-shaped variations with the maximum and minimum values occurring at the downstream end and upstream start, respectively. The study on this variation is good since the whole direction of pressure on the spillway was analyzed and identified. Some studies and experiments were also performed on flat and pooled stepped spillways, providing information on flow patterns and dissipation performance [18, 20, 21].

Ghaderi et al. [18] investigated the simulated velocity, pressure, and total kinetic energy distributions agreed with the previous literature and within the consistency of the experimental data. The free water surface of flow was identified horizontally on flat and FSP steps while unstable in other configurations. The appearance of streamlines is decreasing on notch pooled steps due to the presence of vortex conditions. The maximum velocity was detected on the surface of the pool steps, while the minimum velocity value occurred in the bottom section of each of the steps. Maximum pressure was found to be higher in the beginning section of the pooled step compared to the flat step, while no negative pressure was found throughout the horizontal step section of flat and pooled types. The lowest pressure is also improved on the horizontal and vertical sections of the notched pool step surface compared to the flat and simple pooled. Thus, the cavitation risk due to the water pressure is mitigated. The excellent energy dissipation was founded on notched pool steps as compared to others. Thus, making this type of geometry can be one of the great options for energy dissipating structures.

In conclusion, most of the changes in the hydraulics characteristics of flow were contributed by the different types of the spillway, geometrical configuration, and flow characteristics including discharge and Froude number, length of the steps (for the stepped spillway). The skimming flow type is said to be the real type of flow regime on the actual engineering site compared to other types of flow (nappe and transition). Furthermore, the rapidly varied flow was found to be experienced in the flow over the spillway due to the sloping condition from the inlet to the end of the spillway connected to the stilling basin section. The understanding of the hydraulic characteristic of flow over the spillway is crucial mainly related to the complex flow problem. Furthermore, the application of numerical analysis for hydrodynamic flow provides an alternative to solving fluid flow problems (from simple to complicated case studies) other than experimental and actual site determination. Furthermore, it is of utmost importance in choosing the energy dissipation structure for the industrial application within the scope (problem-solving strategies), time, and cost. The stepped spillway and hybrid spillway is found to be the best option in terms of energy dissipation structure as compared to the ogee type. This is said to be the best option for the industrial practitioner if there are no issues related to the budget. However, the appropriate option such as the beneficial contribution of the inverse curvature ogee-type study is found to be economically feasible and reasonable to be applied as the industrial application or dam authority is facing constraints with the budget.

4 Conclusion

In conclusion, the understanding of the characteristic of flow over the spillway is a crucial part before the design (new dam infrastructure), repairing of the available structure, and implementation stage (construction and post-construction). The structural functionality for a maximum and optimum safe water transfer in a hydraulic structure (from the reservoir via spillway to the downstream section) is of utmost importance due to the risky condition. The connection between the fluid and structural aspects is crucial in dealing with the cavitation and scour effect due to the hydraulic jumps problem at the end of the spillway toe. This knowledge is essential when planning and dealing with natural disasters and hazard preparedness mitigation strategies (short- and long-term periods). Furthermore, the hydraulic characteristic of flow is useful as a guideline to choose the most applicable energy dissipation structure at the optimum function within the quality, scope, and budget. The arrangement of geometrical configuration is important to achieve the best option for energy dissipation structure. The numerical modeling of flow mainly the hydrodynamic simulation and analysis is vital before the current and future practices to overcome the field and hydraulic model limitation. In addition, the frequent changes in flow conditions due to environmental changes may affect the important parameters including Froude number, velocity, and pressure distribution.

5 Future Direction of Research

The future direction of the study is listed and explained based on the review conclusion and potential research gap based on the influence factor, variables as well as case study, and method. The potential research work includes an in-depth relationship between the hydraulic characteristic of flow between the efficient spillway structure and the baffle block structure in the stilling basin area. Other is the critical review of the hydraulic jump types and efficient energy dissipating structure.

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