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REVIEW PAPER

Advancements in Flow Behavior Investigation and Performance Enhancement of Morning Glory Spillways: A Systematic Review of Numerical and Physical Models

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Abstract
Conducting numerical and physical models to investigate the flow behavior through morning glory spillways (MGSs) are the only two methods usually used in the design phase of such spillways. The numerical models are the newest trend applied in the last two decades. In this regard, recently, significant efforts have been made to improve the flow behaviors of MGS by establishing numerical simulations and experimental works. Following the PRISMA checklist procedure, the current investigation employed a systematic review to carefully select and review the pertinent literature. Sixty-six articles from academic journals and conference proceedings were included, focusing specifically on the utilization of numerical and physical models for studying the flow characteristics of MGS. The current trend of the studies includes; modified inlet, vertical bend modifications, placing anti-vortex devices on the spillway crest, and readapting the boundaries of the spillway entrance. The performed techniques to examine various aspects of flow in MGS were reviewed, classified, analyzed, and discussed in detail. In addition, the modifications' effects on improving the spillway's hydraulic performances were demonstrated, and the operative ones were highlighted. Finally, after analyzing and comparing several empirical relations proposed in past studies to predict the discharge coefficient (Cd), an artificial neural network model was developed to estimate the Cd value. So far, few studies have focused on investigating the air entrainment process and slug flow regime in this type of spillway due to the lack of information and measurement difficulties; thus, further studies in this path will be considered valuable.

Keywords Morning glory spillway · Systematic review · Hydraulic characteristics · Numerical model · Physical model

1 Introduction

The spillway is a crucial component of a dam, playing a vital role in safely directing the overflow discharge from the upstream to the downstream side. Designing the spillway correctly is of utmost importance to ensure its effectiveness. During the design phase, thorough analysis and testing of the spillway are necessary to prevent any abnormal flow conditions. Furthermore, it is essential to reassess and verify the design and construction of various hydraulic structures that were built in the past, as they may have been based on limited hydrological data. This revision and examination are crucial to guarantee the safety and reliability of their operations (Nohani 2015c). The optimal design of spillways holds significant importance in dam construction due to their high cost, which constitutes a major portion of the overall construction expenses. The construction cost of spillways typically accounts for approximately 20 and 80% of the total dam construction cost for large and small dams, respectively (Haddad et al. 2010).

The morning glory spillway (MGS) is a unique hydraulic structure that operates independently from the main dam body. It is characterized by a funnel-shaped entrance, along with vertical and horizontal shafts. The MGS is specifically utilized in situations where alternative spillway options are impractical or infeasible. The performance and behavior of the MGS are influenced by several factors, including the

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topography of the surrounding boundaries, the size and shape of the inlet, and the dimensions of the outlet tunnel (Sabeti et al. 2019).

The flow characteristics across the spillway crest can be classified into three distinct types depending on the water level above the spillway: crest control, orifice control, and pipe control. MGSs are typically engineered to operate efficiently under crest control conditions. This is because their discharge efficiency is significantly reduced in both orifice and pipe control scenarios (Alkhamis 2021).

Various studies have been conducted to enhance the hydraulic performance of MGS. These investigations have involved the use of numerical and physical modeling to explore the effects of different techniques aimed at improving spillway efficiency. These techniques include modifying the geometries of the spillway crest and vertical bend, installing vortex breakers (VB) over the spillway crest, and making adjustments to the spillway boundaries.

One of the most common approaches to increasing spillway efficiency is examining the spillway's discharge capacity for various inlet shapes (Aghamajidi 2013; Aghamajidi et al. 2013; Alkhamis 2021; Asadsangabi et al. 2014; Bagheri et al. 2010; Bagheri and Nohani 2014; Banejad et al. 2016; Bordbar et al. 2010; Brakeni and Guryev 2020; Cicero et al. 2011; Djillali et al. 2021; Gur'yev et al. 2021; Kabiri-Samani and Keihanpour 2021; Kamanbedast and Mousavi 2017; Kashkaki et al. 2019; Keihanpour and Kabiri-Samani 2021; Liu et al. 2018; Naderi et al. 2013; Nan et al. 2017; Nasiri et al. 2021, 2022; Rouzegar et al. 2019; Sabeti et al. 2019; Shemshi and Kabiri-Samani 2017; Aydin and Ulu 2023b; Talebi et al. 2022). The circular piano key (CPK) inlet is one of the newest reformed shapes of traditional MGS studied (Kashkaki et al. 2019; Nasiri et al. 2021; Shemshi and Kabiri-Samani 2017). Also, different entrance polygonal shapes were investigated (Brakeni and Guryev 2020; Djillali et al. 2021; Gur'yev et al. 2021; Nan et al. 2017) and examined stepped MGS (Aghamajidi 2013; Aghamajidi et al. 2013; Alkhamis 2021; Bordbar et al. 2010; Haghbin et al. 2022; Parsaie and Haghiabi 2019).

Vortex formation above the spillway crest is one of the problems that cause a decrease in the spillway capacity, so many researchers tested various anti-vortex devices to overcome it. During the vortex phenomenon, the tangential velocity increases due to changes in the flow path of the direct mode. Then, more flow energy will dissipate, reducing the spillway discharge capacity (Rahimi and Razavi 2018). One effective solution for mitigating the adverse effects of the vortex phenomenon is the implementation of inserted piers on the spillway crest (Christodoulou et al. 2010). Accordingly, various types and numbers of VB on the crest of MGS have been used to effectively reduce and eliminate this problem (Aghamajidi 2013, 2022; Aghamajidi et al. 2013; Akbari et al. 2015; Broucek et al. 2021; Christodoulou et al. 2010; Emami and Schleiss 2016; Fattor and Bacchiega 2009; Kamanbedast and Mousavi 2017; Mirabi et al. 2021; Musavi-jahromi et al. 2016; Nohani 2014, 2015a; Nohani and Emamgheis 2015; Noruzi and Ahadiyan 2017; Rahimi and Razavi 2018; Sayadzadeh et al. 2020; Radmanesh et al. 2022).

Pyramidal, triangular, rectangular, and baleen bodies are distinct shapes of VB that have been installed on spillway crests to assess their impact on spillway performance. These various VB shapes have undergone evaluation to determine their effectiveness in mitigating the negative effects of vortex formation and improving overall spillway operation (Nohani and Emamgheis 2015; Sayadzadeh et al. 2020). Anti-vortex pier with different thicknesses is another VB form used to control vortex problems (Akbari et al. 2015; Christodoulou et al. 2010; Kamanbedast and Mousavi 2017; Mirabi et al. 2021; Nohani 2014, 2015a; Noruzi and Ahadiyan 2017; Rahimi and Razavi 2018). In order to determine the most effective number of VB for reducing vorticity, a range of numbers (i.e., 2, 3, 4, 5, 6, 8, and 12) were investigated by several researchers (Aghamajidi 2013; Aghamajidi et al. 2013; Christodoulou et al. 2010; Emami and Schleiss 2016; Musavi-jahromi et al. 2016; Nohani 2014; Nohani and Emamgheis 2015; Noruzi and Ahadiyan 2017; Sayadzadeh et al. 2020). The findings from these studies consistently indicated that the optimal number of anti-vortex devices is 6, as it provides the most effective reduction in vorticity.

Furthermore, researchers have examined the impact of altering the vertical bend configuration between the vertical shaft and the horizontal outlet tunnel in order to mitigate the risk of cavitation and enhance the hydraulic performance of spillways (Ehsani et al. 2019; Fais et al. 2015; Savic et al. 2014). The locations of the elbow's start and end points are particularly susceptible to cavitation due to geometric variations that cause a shift in the flow direction (Ehsani et al. 2019).

When the reservoir boundaries are located near the MGS crest, the occurrence of vortex flow can have a significant adverse impact on spillway capacity (Christodoulou et al. 2010). To address this issue, modifications have been made to the spillway's design in order to promote radial flow along the crest (Christodoulou et al. 2010; Emami and Schleiss 2016; Fattor and Bacchiega 2009). Fattor and Bacchiega (2009) enhanced the hydraulic characteristics of the spillway by lowering its location and excavating the area adjacent to the upstream face of the spillway. Also, Emami and Schleiss (2016) employed flow-directing piers on the spillway crest to eliminate flow disturbances caused by the proximity of reservoir abutments.

Cavitation is a potential issue that can occur in the MGS, particularly at the entrance of the spillway and during the transitions of the funnel inlet, shaft, and inside elbow, as highlighted by Ehsani et al. (2019). Some researchers studied the cavitation risk for various forms of MGS (Aghamajidi et al. 2013; Asadsangabi et al. 2014; Bordbar et al. 2010; Brakeni and Guryev 2020; Djillali et al. 2021; Ehsani et al. 2019; Aydin and Ulu 2023a; Salehi et al. 2023). To mitigate cavitation issues, modifications have been made to the traditional circular inlet of the spillway, transforming it into polygonal sections (Brakeni and Guryev 2020; Djillali et al. 2021). Different inlet profiles and elbow radii have been examined to control cavitation problems. It has been observed that, under free-flow conditions, increasing the elbow radius leads to a higher probability of cavitation occurrence, while under submerged flow conditions, enlarging the elbow radius reduces the likelihood of cavitation (Asadsangabi et al. 2014; Ehsani et al. 2019). Stepped MGS configurations have been tested and demonstrated to exhibit better resistance against cavitation hazards compared to classical smooth spillways (Aghamajidi et al. 2013; Bordbar et al. 2010).

In recent times, there has been a growing focus on employing a reliability-based design optimization approach for the safe and efficient design and operation of different types of spillways, including morning glory, labyrinth, stepped, and ogee structures (Ferdowsi et al. 2019; Mooselu et al. 2019; Haddad et al. 2010; Hosseini et al. 2016; Jafari et al. 2021a, 2021b; Jafari and Aghamajidi 2022; Kardan et al. 2017; Tabari and Hashempour 2019; Ohadi and Jafari 2021; Oukaili et al. 2021). The characteristics of the studies done in this field are listed in Table 1.

Moreover, several numerical models were developed to derive an equation to predict Cd (Aghamajidi 2013; Aghamajidi et al. 2013; Alfatlawi and Alshaikhli 2015; Camargo et al. 2006; Fais et al. 2015; Fais and Genovez 2009; Gouryev et al. 2020; Kamanbedast 2012; Kashkaki et al. 2018; Keihanpour and Kabiri-Samani 2021; Musavijahromi et al. 2016; Nohani 2015b; Sayadzadeh et al. 2020; Shemshi and Kabiri-Samani 2017). Some of them applied the ANN approach to estimate Cd (Alfatlawi and Alshaikhli 2015; Kamanbedast 2012; Kashkaki et al. 2018).

In the past two decades, extensive research has been conducted to enhance the hydraulic performance of the MGS using both numerical and physical models. Thus, the main aim of this review was to understand and identify the current trends that investigate the hydraulic properties of MGS, systematically review the most common and effective approaches, then find out the research gaps and provide recommendations for future trends. To the authors' knowledge, no review paper has been written in this field. So, a full review article is required to provide more details on the studies done in this field and compare their results and findings.

This research is divided into six sections and follows a specific structure. Section 2 introduces the research methodology. Section 3 provides an explanation of numerical and physical modeling in MGS, explores current literature trends, and presents the proposed ANN modeling approach for Cd prediction. Sections 4 and 5 focus on the results and discussions, respectively. Finally, Sect. 6 concludes the research with the findings, recommendations, and conclusions.

2 Methodology

A systematic review is performed to identify how scholars conducted studies to investigate MGS's hydraulic properties through developed numerical and physical models. This systematic review was conducted by following the procedures that were reported in the checklist of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al. 2009). For this purpose, an exhaustive literature search was undertaken to find the related studies published until the end of June 2023.

To systematically identify relevant literature for our survey, we employed Harzing's Publish or Perish (Version 8) software, which facilitated searches within the renowned academic databases of Google Scholar and Scopus. In certain cases, we extended our search efforts to include specific journals' websites, enabling us to locate targeted publications. Our search strategy encompassed the utilization of diverse combinations of terms in titles or keywords, intentionally disregarding constraints related to publication date or language, to ensure comprehensive coverage of the literature pertinent to our study. The specific keyword combinations employed were as follows: "morning glory spillway" OR "shaft spillway" OR "bell mouth spillway," "numerical model*" AND "morning glory spillway," "numerical model*" AND "shaft spillway," "numerical model*" AND "bell mouth spillway," "morning glory spillway" AND "physical model*" OR "experimental model*,""shaft spillway" AND "physical model*" OR "experimental model*," and "bell mouth spillway" AND "physical model*" OR "experimental model*".

Additionally, the title, abstract, authors' names, journals' names, publication year, and citations of the identified records were gathered into an MS Excel worksheet. The included articles were chosen based on this review paper's objectives to investigate the hydraulic properties of MGS using numerical and physical models. More specifically, unpublished papers, master and doctoral dissertations, editorial notes, textbooks, book chapters, and any articles that were not well organized or had vague ideas were excluded. Afterward, the reviewers performed an eligibility assessment by carefully screening the full texts of the remaining papers individually. At this time, disagreements between the reviewers were discussed and solved by consensus.

Searching for literature in the databases and search engines identified 338 records (Google Scholar (224),

Table 1 Review of prior literature on optimizing spillway dimensions

References	Approach	Type of spillway	Objective	Strengths	Weaknesses
Jafari and Aghamajidi (2022)	Genetic algorithm (GA)	Morning glory spillway (MGS)	Finding the optimum spillway's dimension and vortex breaker	It is a recent development aiming to enhance the design of both smooth and stepped MGS, resulting in a significant reduction of 39% in the amount of concrete employed	The literature review is not exhaustive, and it lacks comprehensive details regarding the decision variables and constraints. Also, consideration of parameter uncertainty and reliability index is absent in the analysis
Jafari et al. (2021a)	Monte Carlo simulation (MCS) with a hybrid ANN and Whale optimization algorithm (WOA)	Labyrinth spillway	Optimizing the total volume of the spillway while taking into account the desired safety levels	It provides an innovative framework and demonstrated its superiority in ensuring a secure design for labyrinth spillways. It introduces the notion of incorporating uncertainty into the design process within this particular domain	Some of the design variables in this study typically have a range of values whereas treated as constants. Furthermore, the optimization process aims to search for the optimal dimensions rather than providing an absolute optimal solution
Jafari et al. (2021b)	Hybrid gray wolf optimizer (GWO) and MCS	Ogee spillway	Optimizing the spillway dimensions by considering the surrounding uncertainties that contribute to spillway failure causes	The model's performance was assessed using various indices, and it also delivers a secure design with a minimal probability of failure	The objective function solely optimizes the length and height of the spillway as decision variables, overlooking other parameters that should be taken into consideration
Ohadi and Jafari (2021)	Non-dominated sorting genetic algorithm (NSGA) is integrated with MCS	Labyrinth spillway	Minimizing the volume of concrete consumption while maximizing both the discharge capacity and reliability index	An investigation was conducted to analyze the sensitivity of parameters that significantly impact the reliability index	The failure probability is highly responsive to variations in the upstream head and discharge coefficient, which leads to a decrease in the reliability index
Mooselu et al. (2019)	Fuzzy transformation method (FTM)	Stepped spillway	Maximizing both the energy dissipation and cavitation number, while simultaneously minimizing the volume of concrete used	Simultaneously optimized the hydraulic conditions and structural volume of the spillway	The uncertainty analysis focused solely on the flood flow rate, also the selection of optimization constraint boundaries remained unclear. Moreover, the investigation of the reliability index was not considered
Ferdowsi et al. (2019)	Hybrid evolutionary algorithm of the bat (BA) and particle swarm optimization (PSO)	Labyrinth spillway	Optimizing the spillway design with either a half-round or quarter-round crest shape	Through sensitivity analysis identified the best parameter values. Also, the HA algorithm demonstrated faster convergence compared to other algorithms	The probability of failure and reliability index were not taken into consideration

Table 1 (continued)

References	Approach	Type of spillway	Objective	Strengths	Weaknesses
Haddad et al. (2010)	Honey-bee mating optimization (HBMO) algorithm	Stepped spillway	Identifying the favorable combination of design variables in order to minimize the overall cost of both the spillway chute and stilling basin	A significant reduction of 33% was achieved in the total construction cost. Additionally, the algorithm quickly reaches a solution that is very close to the optimal outcome	The objective function only accounted for the excavation cost as the total cost. Factors such as the uncertainty of design parameters, probability of failure, and reliability index were not taken into consideration
Hosseini et al. (2016)	Differential evolution (DE) algorithm and GA	Labyrinth spillway	Optimizing the shape of the spillway by minimizing the construction cost	The efficacy of the proposed model was evaluated by employing various indices. Utilizing the GA and DE approaches resulted in a notable cost reduction of approximately 16.6 and 19.3%, respectively	Sensitivity analysis for the design parameters, probability of failure, and reliability index were not regarded
Kardan et al. (2017)	GA	Labyrinth spillway	Optimizing the shape of the trapezoidal labyrinth weir	The optimal concrete volume of the labyrinth weir reduced by 21% compared to its initial shape	The genetic algorithm exhibited a remarkably high sensitivity to both the population size and mutation operators, also no investigation was conducted regarding the reliability of parameter values
Tabari and Hashempour (2019)	A hybrid of PSO-GWO and direct search optimization (DSO)	Labyrinth spillway	Determining the optimum dimensions while minimizing the consumption of concrete volume	The spillway dimensions were optimized using both trapezoidal and triangular cross sections, resulting in a significant reduction in concrete usage and cost savings of 64% compared to the existing dam design	The sensitivity of the design parameters, failure probability, and reliability index was not considered in the study
Oukaili et al. (2021)	Computational fluid dynamics (CFD) software Code_Saturne	Ogee spillway	Numerical investigation of spillway design by employing a shape optimization process that relies on CFD software	In contrast to prior research, the optimization procedure in this study utilized the CFD software	The optimization process lacks specific constraint details that are unavailable. Additionally, there is a lack of investigation into the uncertainty of parameters and the reliability index

Scopus (106), and other sources (8)); 120 were removed due to duplicates, and 140 were eliminated in the initial screening of titles and abstracts, despite mentioning one or more of the selected keywords in their titles and/or keywords. Out of remained 78 papers, 70 full-text articles were carefully screened, while five articles were not accessible and three pieces were not found. At the end of the screened process, four full-text papers were excluded because they did not meet the eligibility criteria. Only Sixty-six full-text studies from 35 different Journals and 13 conference proceedings for systematic review were obtained. The adopted screening procedure is summarized and illustrated in Fig. 1.

Subsequently, the gathered information from the selected articles was meticulously summarized and reviewed to facilitate the conduction of this study. In addition, articles were reviewed and summarized according to various criteria such as journals or conferences names, the year of publication, the number of citations, the case study's location, applied method, research objectives, results, and findings. All the literature included in this study was classified into two main categories: numerical and physical approaches. Furthermore, these categories were further divided into more specific subcategories, as illustrated in Table 3.

Moreover, detailed figures and graphs were redrawn and discussed in detail using the previous data. We also developed an ANN model to predict the Cd based on the extracted data and relations from the literature. Figure 2 demonstrates a flowchart diagram that followed in this study.

3 Numerical and Physical Modeling of Flow in Morning Glory Spillways

Numerical and physical models are essential techniques for assessing the hydraulic performance of flow through spillways. From the reviewed papers, one can notice that most of the literature in which numerical models were developed, physical models were constructed, or experimental data was used to verify and validate the numerical results.

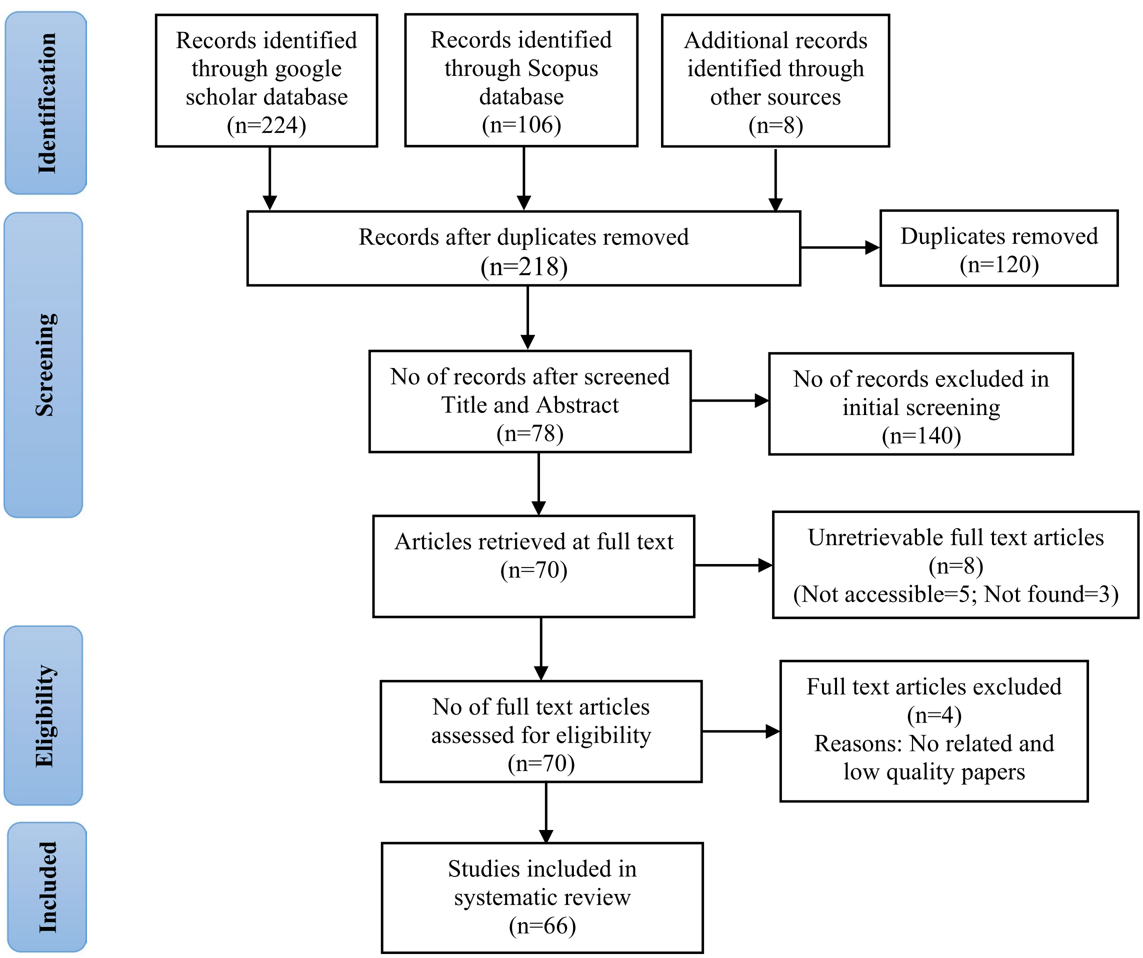

Fig. 1 Flowchart of literature selection based on the PRISMA method

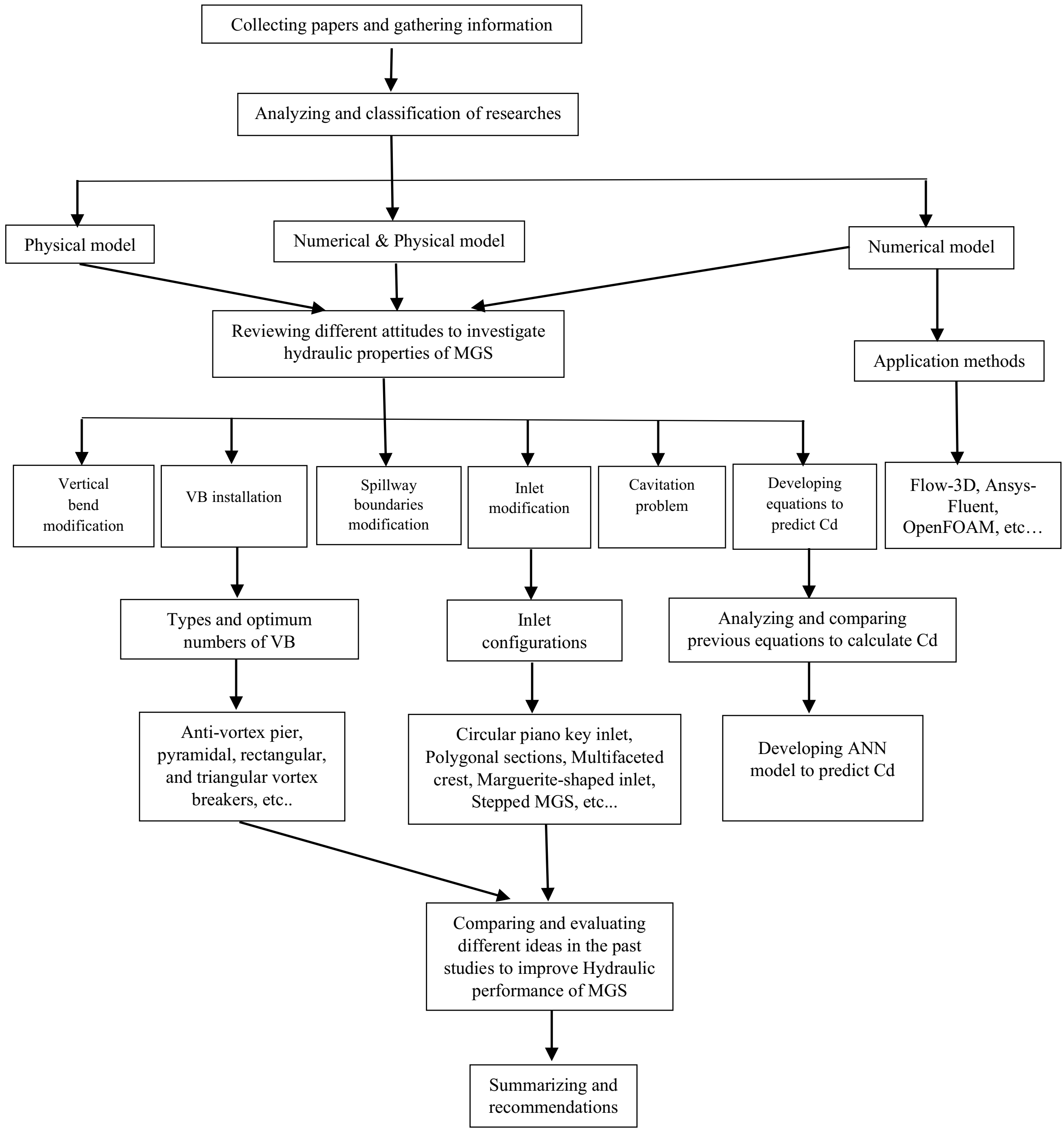

Fig. 2 Flowchart illustrating the methodology followed in this study

In the past, the assessment of hydraulic systems predominantly relied on physical models. However, with advancements in numerical methods, there is now a broader range of cost-effective options available that significantly reduce computational time while still providing accurate results (Nohani 2015c). Calibration of the numerical model is a crucial initial step to minimize the influence of external factors and align model behavior with prototype conditions. Therefore, it is imperative to calibrate and simulate the numerical model using appropriate boundary conditions to ensure its accuracy and reliability (Razavi and Ahmadi 2017a).

The introduction of computational fluid dynamics (CFD) models in hydraulic engineering has fundamentally transformed the conventional notion that physical models are the sole means for evaluating flow dynamics. Over the last few decades mesh-based CFD codes have dominated advanced studies and proven their accuracy in supporting decision-making processes (Moreira 2021).

However, the process of generating and refining meshes has been time-consuming and challenging. Moreover, mesh-based models face limitations when simulating specific problems like large free-surface deformations or complex geometries (Kevorkijan and Biluvs 2021). Handling free-surface computations in these models involves solving additional equations, often using the volume of fluid (VOF) method.

Furthermore, ensuring accurate specification of boundary conditions is essential for achieving realistic spillway modeling, must be accurately defined based on the design and operational conditions of the spillway. Also, calibration of numerical models using field or laboratory data is imperative to ensure precise predictions. Despite the significant achievements of traditional mesh-based numerical methods, these limitations hinder their computational efficiency and restrict their broader applications. Consequently, to mitigate these challenges researchers are continuously seeking improved numerical methods to overcome these challenges. In recent years, meshfree methods have emerged as a successful class of computational methods. These methods have made significant advancements in overcoming the initial limitations they faced during their early development (Moreira 2021). Meshfree methods are widely acknowledged for their advantages in simulating certain fluid problems. Most notably, they offer the freedom to simulate real-world scenarios with minimal to no simplifications, allowing for a more realistic representation of the system.

Physical models are constructed to properly simulate the prototype behavior and identify the most practical and reasonable solutions (Novak 1984). It should be built correctly to obtain reliable models (Yalin 1989). Some numerical ratios and scales should be considered. One of the most important things is the scale ratio between the physical model and the prototype. Decreasing the scale ratio will cause a scale effect because of changes in the coefficient related to the force ratio between the model and the prototype; thus, the amount of error will increase and causes more discrepancy between the model and the prototype results (Yildiz and Yarar 2018).

Spillway physical models are made according to Froude laws of similitude, and they are valid as the effect of surface tension and viscosity can be ignored (Fais and Genovez 2009). To control scale effects in physical models, the scientists recommend specific values of Reynold number (Re), Weber number (We), and minimum water depth over the spillway crest.

Usually, scale effects occur for low water depths above the spillway crest and small flow rates. Novák and Čabelka (1981) demonstrated that the minimum acceptable water depth is 30 mm, which means all measures above this value can be reliable. Also, Fais and Genovez (2009) reported that the water level above the spillway crest should be at least 12 mm. Fais et al. (2015) displayed that the lowest overflow depth is 40 mm to eliminate substantial scale effects.

The minimum values of Re and We to eliminate the effects of viscosity and surface tension according to different authors are demonstrated in Table 2.

Furthermore, Heller (2011) recommended that the scale of the spillway's physical model should be in the range of 1:50–1:100 to minimize scale effects.

3.1 Current Trends to Improve the Hydraulic Performance of MGS

Many techniques have been applied to increase the efficiency of MGS performance, such as crest geometry modification and VB installation. Figure 3 shows the percentage of each technique used in the literature. Table 3 presents the methods used to investigate the hydraulic properties of MGS.

The main reason for modifying the crest geometry and placing anti-vortex devices is to control vortex formation above MGS's crest and increase the discharge capacity. Also, the most common commercial code applied to develop numerical modeling was the Flow-3D program.

Furthermore, a detailed comparative analysis of the features regarding input parameters, performance metrics, and applicability of the previously discussed developed trends across a wide range of scenarios is presented in Table 4. The purpose of this specific comparison is to offer a comprehensive understanding and evaluation of how these trends measure up in different situations.

3.1.1 Inlet Modification

The modification of the traditional inlet shape of MGS is a commonly utilized approach in research studies, serving as a prominent method to enhance flow capacity and effectively tackle issues associated with vortex formation. Within the realm of crest modifications, various methods have been explored, such as incorporating steps or altering the shape to sectorial, polygonal, multifaceted, CPK inlet, and marguerite-shaped inlets. These techniques have been extensively

Table 2 Minimum recommended values of Re and We to avoid scale effects based on different research studies

References	Re	We
Anwar et al. (1978)	$\rho Q/(\mu S) > 20{,}000$	$\rho V^2 S/\sigma > 100$
Daggett and Keulegan (1974)	$\rho Q/(\mu D) > 30{,}000$	$\rho V^2 D/\sigma > 120$
Jain et al. (1978)	$\rho\ (gd^3)^{0.5}/\mu > 50{,}000$	$\rho V^2 D/\sigma > 120$
Odgaard (1986)	$\rho VD/\mu > 110{,}000$	$\rho V^2 D/\sigma > 720$
Padmanabhan and Hecker (1984)	$\rho VD/\mu > 77{,}000$	$\rho V^2 D/\sigma > 600$

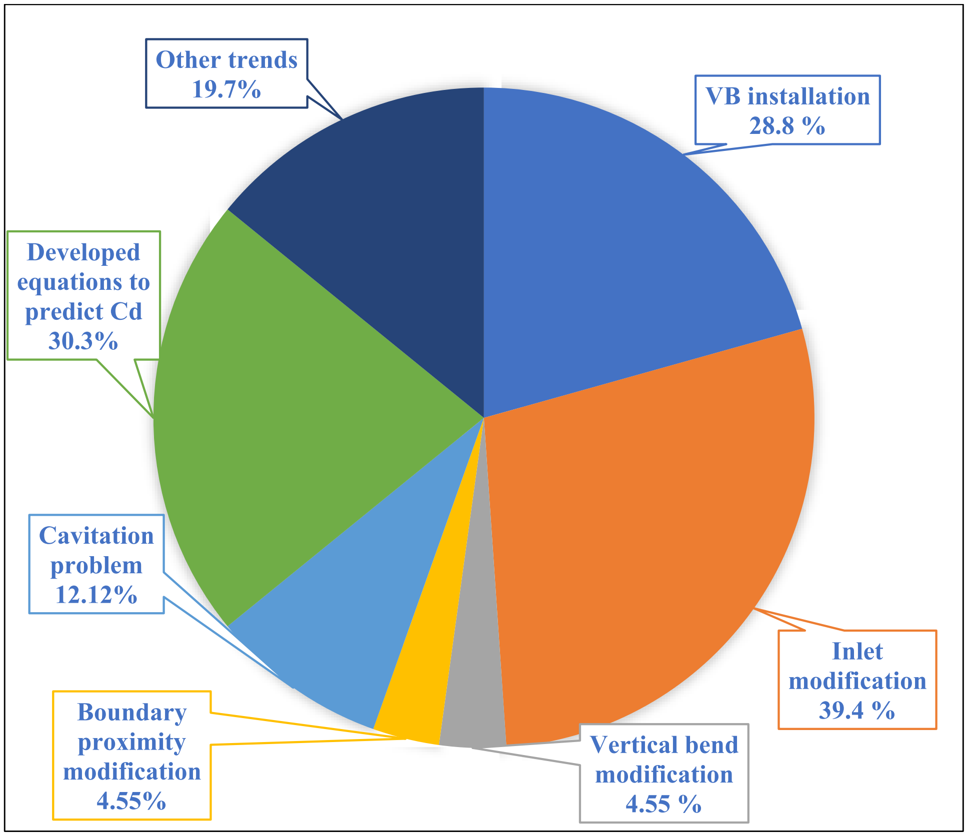

Fig. 3 The percentages of each technique implemented in the literature

discussed and examined in the relevant literature. Table 5 demonstrates the developed inlet shapes and their influences on improving spillway efficiency.

Based on Table 5, the CPK inlet, stepped MGS, and polygonal sections are the most popular types of crest modification. The hydraulic properties of the CPK inlet were investigated as a new entrance and compared with simple MGS (Kashkaki et al. 2019; Nasiri et al. 2021, 2022; Shemshi and Kabiri-Samani 2017). By investigating the hydraulic properties of the CPK inlet, engineers and researchers can assess the performance of this new entrance design in terms of flow rate, energy dissipation, and flow patterns. Understanding these hydraulic characteristics helps determine if the CPK inlet is capable of achieving the desired discharge capacity and hydraulic efficiency. Shemshi and Kabiri-Samani (2017) investigated swirling flow and spillway capacity at the CPK entry using an experimental model. The results showed that the whirling flow strength for flow through the CPK spillway is much less than for normal shaft spillways and improves release capacity by 6, 2, and 1.5 times larger than simple vertical shaft spillway, MGS, and PS, respectively.

Kashkaki et al. (2019) employed a physical model to study the CPK spillway and compared the hydraulic performance with the traditional shaft spillway without a reformed inlet. Experiments revealed that a CPK intake provided better hydraulic performance and improved the discharge capacity by 15.16%. Also, it can alleviate the cavitation risk at the vertical bend compared to the normal shaft spillway. Nasiri et al. (2021) tested the flow characteristics for various geometries of the CPK inlet spillways by applying numerical modeling. The outcomes showed that the CPK entrance substantially improves the discharge capacity by up to 40% compared to a standard vertical shaft and decreases the turbulent flow intensity.

The impacts of step configurations on the flow behavior and hydraulic parameters of a stepped MGS were examined via CFD simulation. Simulation consequences showed that the Cd rose, and the energy dissipation in the stepping MGS was significant for the measured discharge rates (Alkhamis 2021). Furthermore, the flow behavior of a smooth MGS was investigated and compared to a stepped spillway. The results indicated that a stepped spillway with six steps is the optimum number of steps in design and resistance to cavitation risk and concrete erosion (Aghamajidi et al. 2013). However, Bordbar et al. (2010) reported that eleven steps is the best number of steps to overcome cavitation risk. In addition, the performance of the spillway regarding energy dissipation was improved, when the step sizes increase for a specific value of chute's slope (Parsaie and Haghiabi 2019).

Different polygonal inlet sections were used as an alternative to the circular sections (Brakeni and Guryev 2020; Djillali et al. 2021; Gur'yev et al. 2021; Nan et al. 2017). It

Table 3 Classification of literature according to different attitudes to investigate the hydraulic properties of MGS

References	VB installation	Inlet modification	Vertical bend modification	Boundary proximity modification	Cavitation problem	Estimation of the value of Cd	Numerical model	Physical or experimental model	Computational method	Other trends
Aydin and Ulu (2023b)		√				√	√	√	Flow-3D	
Salehi et al. (2023)					√		√	√	Ansys-Fluent	
Aydin and Ulu (2023a)					√		√		Flow-3D	An innovative pressure-controlled siphon-shaft profile was developed
Aghamajidi (2022)	√					√		√		
Nasiri et al. (2022)		√					√		Ansys-Fluent	
Jafari and Aghamajidi (2022)								√		Utilized genetic algorithm to optimize the geometric dimensions and vortex breaker
Talebi et al. (2022)		√				√		√		
Radmanesh et al. (2022)	√					√		√		
Sukerta et al. (2022)										Involved a comparison of the design and operational effectiveness between MGS and lateral spillway
Haghbin et al. (2022)	√					√	√	√	SVR-IWO	
Alkhamis (2021)		√					√	√	Flow-3D	
Gur'yev et al. (2021)		√								
Keihanpour and Kabiri-Samani (2021)		√				√		√		
Nasiri et al. (2021)		√					√		Ansys-Fluent	
Kabiri-Samani and Keihanpour (2021)		√						√		
Mirabi et al. (2021)	√						√		Ansys	Evaluated the effects of unbalanced construction in the spillway crest on the hydraulic behavior of the spillway
Djillali et al. (2021)		√			√			√		
Broucek et al. (2021)	√						√	√	Ansys-CDF	
Brakeni and Guryev (2020)		√			√			√		
Sayadzadeh et al. (2020)	√					√		√		
Aghebatie and Hosseini (2020)							√		OpenFOAM	Investigated the slug flow phenomenon in MGS to prevent the destructive effects

Table 3 (continued)

References	VB installation	Inlet modification	Vertical bend modification	Boundary proximity modification	Cavitation problem	Estimation of the value of Cd	Numerical model	Physical or experimental model	Computational method	Other trends
Jalil et al. (2020)							√	√	Ansys-CFX	Experimentally examined the shaft spillway to analyze and visualize the flow performance for this structure
Gouryev et al. (2020)						√				
Parsaie and Haghiabi (2019)						√		√		
Kashkaki et al. (2019)		√						√		
Sabeti et al. (2019)		√					√		Flow-3D	
Rouzegar et al. (2019)		√						√		
Ehsani et al. (2019)			√		√		√	√	Flow-3D	
Kashkaki et al. (2018)						√	√	√	ANN	
Rahimi and Razavi (2018)	√						√	√	Flow-3D	
(Liu et al. 2018)		√					√	√	Ansys-Fluent	
Razavi and Ahmadi (2017b)							√	√	Flow-3D	Estimated the flow parameters like flow rates, flow depth, velocity, and pressure at different spillway sections
Gomez et al. (2017)							√		Flow-3D	Effects of tailwater on the spillway discharge capacity
Kamanbedast and Mousavi (2017)	√	√						√		
Shemshi and Kabiri-Samani (2017)		√				√		√		
Nan et al. (2017)		√						√		
Razavi and Ahmadi (2017a)							√		Flow-3D	Studied the influences of adding suspended load to inflow discharge on discharge spillway capacity
Noruzi and Ahadiyan (2017)	√						√	√	Flow—3D	
Emami and Schleiss (2016)	√			√				√		
Banejad et al. (2016)		√						√		
Enjilzadeh and Nohani (2016)							√	√	Flow-3D	Investigated the flow behavior and control conditions of MGS

Table 3 (continued)

References	VB installation	Inlet modification	Vertical bend modification	Boundary proximity modification	Cavitation problem	Estimation of the value of Cd	Numerical model	Physical or experimental model	Computational method	Other trends
Musavi-jahromi et al. (2016)	√					√		√		
Nohani (2015c)							√		Flow-3D	The hydraulic parameters like the coefficient of discharge, water level profile, and pressure distribution were estimated and compared with the data obtained from USACE and USBR models
Nohani (2015a)	√							√		
(Akbari et al. (2015)	√						√	√	Flow-3D	
Nohani and Emamgheis (2015)	√							√		
Fais et al. (2015)			√			√		√		
Nohani (2015b)						√		√		Examined the downstream submergence on discharge capacity
Alfatlawi and Alshaikhli (2015)						√	√	√	ANN and MNLR	
Savic et al. (2014)			√					√		
Bagheri and Nohani (2014)		√						√		
Asadsangabi et al. (2014)		√			√		√	√	Ansys-Fluent	
Nohani (2014)	√							√		
Aghamajidi et al. (2013)	√	√			√	√		√		
Naderi et al. (2013)		√						√		
Aghamajidi (2013)	√	√				√		√		
Kamanbedast (2012)						√	√	√	Qnet2000	
Cicero et al. (2011)		√						√		
Bagheri et al. (2010)		√						√		
Bordbar et al. (2010)		√			√			√		
Christodoulou et al. (2010)	√			√				√		
Fattor and Bacchiega (2009)	√			√				√		

Table 3 (continued)

References	VB installation	Inlet modification	Vertical bend modification	Boundary proximity modification	Cavitation problem	Estimation of the value of Cd	Numerical model	Physical or experimental model	Computational method	Other trends
Fais and Genovez (2009)						√		√		Analyzed the discharge flow rating curve and proposed equations to minimize scale effects for low water heads
Chen et al. (2009)								√		Measuring velocity and wall pressure of shaft spillway through whirling current in a model experiment
Camargo et al. (2006)						√	√	√	ANN	
Braz (2000)										Investigated the instability of an embankment earth-fill dam caused by the malfunction of the spillway

has been reported that a polygonal cross section is simpler to construct and reduces construction and technical costs. Brakeni and Guryev (2020) showed that a 12-side polygonal configuration (see Fig. 4) allows the water jet to enter without separation in the elbows and maintain a direct connection to the wall. The maximum water level (MWL) was reduced by 0.68 m, and the Cd was improved up to 12%, allowing for greater dependability and reducing the risk of cavitation.

Djillali et al. (2021) reported that a polygonal shape of 12 sides for a free entrance funnel could boost the Cd by 20% without increasing the water head over the spillway crest to risk cavitation. The polygonal funnel prevented the rotational flow, which aids in increasing the spillway's discharge capacity and efficiency rate and decreases the erosion of the downstream river channel (Nan et al. 2017).

Another modern entrance shape called the marguerite-shaped inlet has been the subject of examination in recent studies (Kabiri-Samani and Keihanpour 2021; Keihanpour and Kabiri-Samani 2021). Samani and Keihanpour (2021) studied the vertical shaft spillways with a different number of lobed marguerite-shaped inlets experimentally, as shown in Fig. 5. The findings of the study revealed that the implementation of three-lobed inlets yielded the highest efficiency. These inlets demonstrated the capability to increase the discharge release up to four times more than a conventional MGS without submergence, while simultaneously reducing the likelihood of vortex formation and air entrainment.

The hydraulic characteristics of flow at marguerite-shaped inlets with holes at the bottom of their lobes were also explored with minor variations (Keihanpour and Kabiri-Samani 2021). It raised the discharge capacity by approximately 6, 3, and 2 times compared to a simple shaft spillway, a CPK inlet, and a standard marguerite-shaped inlet, respectively. Additionally, this improvement resulted in reduced vortex flow intensity and enhanced hydraulic performance for simple shaft spillways.

Based on the combination of a regular MGS with a piano key weir, a new type known as PS was established (Banejad et al. 2016; Cicero et al. 2011). Three various angles of PSs (45, 60, and 90 degrees), as displayed in Fig. 6, were investigated (Banejad et al. 2016). The papaya model with a 90-degree angle had lower circulation effects than the other models. So, it can release more discharge through the shaft.

Cicero et al. (2011) emphasized the possibility of using PS and showed that this technique improves the crest length by 85% without varying the spillway's standard sizes. Also, the discharge was 70% greater for the same water level than the traditional MGS.

The hydraulic characteristics of circular and square labyrinth inlets were examined, revealing that the square inlet outperforms the circular inlet in terms of circulation control

Table 4 Comparison of key features among developed current trends

Trends	Related parameters	Investigation method	Performance measurement	Application in different scenarios
Inlet modification	Water head, crest radius, effective crest length, sectorial crest angle, threshold submergence, critical submergence, spillway height, no. of polyhedral faces, marguerite-lobed height-to-shaft diameter ratio, marguerite-lobed length-to-shaft diameter ratio	Numerical, experimental	Cd, RSS, R^2, MAE, RAE, RMSE, RSE, SE, NRMSE, MAPE, EF, RMSPE, WQD, and CSS	1. Testing different sector angles of spillway crest to determine their impact on the discharge capacity 2. Investigation of various designs for multifaceted spillway crests and marguerite-shaped inlets with different numbers of lobes 3. Technically adjusting the funnel intake, giving it a polygonal cross section 4. Examination of how polyhedral spillway crests affected the intensity of water discharge 5. Introduction of spiral spillways that featured daisy, piano key, and zigzag inlets
VB installation	Water head, crest radius, VB height, VB width, VB length, VB thickness, number of VB, flow velocity, tangential velocity, circulation number, circulation strength, air index, relative discharge	Experimental, numerical	Cd, R^2, MAE, RMSE, NRMSE, RSS, RAE, SER, SE	1. Analyzing the effects of using different numbers of VB with varying dimensions 2. Installing pyramidal VBs with both square and triangular bases
Vertical bend modification	Water head, spillway height, crest radius, bend radius, tunnel diameter, bend radius-to-tunnel diameter ratio	Experimental, numerical	Cd, cavitation index, critical index	1. Examining different diameters for the bend section and elbow radius 2. Studying the effect of placing a deflector at the start of the vertical bend 3. Hydraulically evaluating a novel parabolic bend design, comparing it with a 90º circular bend and a polycentric bend with a variable radius
Spillway boundaries modification	Spillway height, relative discharge, clear distance-to-shaft diameter ratio, experimental-to-theoretical head ratio, relative submergence	Experimental, numerical	Cd, efficiency, circulation strength	1. Investigation of the effects of removing the adjacent wall surrounding the spillway entrance as a means to eliminate vortex formation and improve the spillway's capacity 2. Examining the strategic positioning of piers at specific locations along the ogee crest to minimize flow disturbances 3. Implementing semi-MGS as an alternative approach to minimize the requirement for extensive excavation

Table 4 (continued)

Trends	Related parameters	Investigation method	Performance measurement	Application in different scenarios
Cavitation problem	Pressure, vapor pressure, Froude number, flow velocity, energy, fluid density, gravitational acceleration, dynamic viscosity	Experimental, numerical	Cd, cavitation index, critical index, energy dissipation, MAER	1. Modifying the conventional entrance profile to variable step sizes spillway to introduce air into the flows of the spillway to mitigate the risk of cavitation damage 2. Evaluation of a new technique to address the cavitation issue by enlarging the cross section of the shaft in an upward direction
Cd investigation	Discharge release, water head, crest length, crest radius, spillway height, Froude number, submergence ratio, spillway height-to-radius ratio	Experimental, numerical, ANN-Qnet2000, and ANN-MNLR,	R^2, RMSE, MSE, NMSE, standard deviation	1. Examining of vertical intake, to explore various mouth shapes with different curvature radii 2. Testing different configurations of VBs in terms of their numbers and shapes, to enhance the Cd 3. Applying experiments to study different spillway shapes, specifically circular and quadrate designs 4. Assessing the performance of Wagner, Creager, and circular profiles for inlet shapes

and enhancing discharge release (Kamanbedast and Mousavi 2017; Rouzegar et al. 2019; Aydin and Ulu 2023b).

Some researchers conducted an empirical investigation to assess the suitability of polyhedral shapes, namely the trihedral, pentahedral, and heptahedral configurations, as alternatives for a spillway crest shape depicted in Fig. 7 (Bagheri et al. 2010; Bagheri and Nohani 2014). The results showed that the trihedral form is more efficient than other forms.

In addition, sectorial MGS, displayed in Fig. 8, was examined using different angles, demonstrating the influences of these changes on the flow characteristics for different water elevations in the reservoir (Sabeti et al. 2019).

3.1.2 Installing Vortex Breaker (VB) over the Spillway Crest

Generally, MGS operates as a free mode with radial and axial velocity; therefore, the overflow discharge directly enters the spillway, while during the occurrence of the vortex phenomenon, the tangential velocity increases due to changes in the flow path of the direct mode, then the flow energy is dissipated, and it lowers the discharge capacity of the spillway (Rahimi and Razavi 2018). Therefore, this section is dedicated to investigating various methodologies aimed at mitigating this phenomenon. Among the proposed solutions, the installation of anti-vortex devices on the spillway crest emerges as an effective strategy to alleviate the occurrence of vortices. By preventing the formation of vortices, a more consistent and controlled flow pattern can be maintained. This, in turn, promotes stability, reduces flow disturbances, and ensures the reliable conveyance of water downstream, eliminating the potential for hydraulic instabilities. Table 6 demonstrates different types and numbers of VBs installed at spillway's crests. Figures 9 and 10 show the frequency of the number and optimum number of VBs used in the literature.

From Fig. 9, the most common numbers of VBs installed in the past studies are 3, 4, and 6 VBs with different forms. Also, Fig. 10 demonstrates that the most efficient number of VB applications in the past is six VBs (Aghamajidi 2013; Aghamajidi et al. 2013; Christodoulou et al. 2010; Emami and Schleiss 2016; Musavi-jahromi et al. 2016; Nohani 2014, 2015a; Nohani and Emamgheis 2015; Noruzi and Ahadiyan 2017; Sayadzadeh et al. 2020; Aghamajidi 2022; Radmanesh et al. 2022). It is worth noting that installing more than six VBs blades on spillway crests does not appear to be beneficial (Musavi-jahromi et al. 2016). Also, increasing the thickness of VB blades causes a reduction in the spillway discharge capacity because it decreases the effective length of the shaft spillway, which decreases the outflow from the spillway (Nohani 2015a).

The effect of different VB (pyramidal, square, and triangular bases) was investigated through a physical model (Sayadzadeh et al. 2020). The findings demonstrated that

Table 5 Developed inlet shapes and their effects on the efficiency of spillway operation

References	Types of new inlet shapes	Effects on efficiency of spillway operation
Aydin and Ulu (2023b)	Labyrinth-shaft spillway	The ability to release water was superior in comparison to traditional shaft spillways having identical weir heads
Nasiri et al. (2022)	CPK inlet	Significantly contributed to a notable increase in the rate of flow discharge while concurrently reducing the intensity of turbulent flow
Talebi et al. (2022)	Bow-tied shape inlet	This inlet offered a superior economic benefit (31% improvement) compared to the MGS
Sabeti et al. (2019)	Sectorial MGS ($\theta = 62°$, $\theta = 99°$, $\theta = 127°$and $\theta = 152°$)	Sectoral spillway ($\theta = 152°$) for higher water levels resulted in a 160% increase in the discharge rate
Alkhamis (2021)	Stepped MGS	Increased Cd and energy dissipation up to 45.8 and 12%, respectively, compared to normal MGS
Kamanbedast and Mousavi (2017)	Square and circular inlets	Circular inlet shape has better performance
Shemshi and Kabiri-Samani (2017)	CPK inlet	Increased the flow discharge up to 2 times compared with a normal MGS
Aghamajidi et al. (2013)	Stepped morning spillway with 6 steps	Improved the spillway resistance against cavitation risk and concrete erosion
Banejad et al. (2016)	Papaya spillway (PS)	It offered minor circulation strength and passing a higher amount of discharge through the shaft
Kashkaki et al. (2019)	CPK inlet with an angle of 90, 60, and 45 degrees	CPK spillway (with an angle of 90 degrees) increased overflow discharge capacity by about 15.16% compared with shaft spillway
Gur'yev et al. (2021)	Polygonal cross section (4, 8, and 12 sides)	Shaft spillways with a polygonal cross section simplify construction technology and building the structure with design parameters
Bagheri et al. (2010)	polyhedral spillway crest (trihedral, pentahedral, and heptahedral)	The trihedral spillway crest increased Cd up to 64.8%
Liu et al. (2018)	Inlet swirling-flow-generating piers	During flood conditions, the vertical shaft can maintain a suitable flow state without the problem of inhaling water
Nan et al. (2017)	Polygonal shaft spillway (12 sections)	Enhanced the discharge capacity of the spillway, while also offering advantages in terms of easy construction, low engineering costs, and high durability
Bagheri and Nohani (2014)	Multifaceted crest (basis, trihedral, pentahedral, and heptahedral)	The trihedral shape increased the Cd for crest and orifice controls by 49 and 31.61%, respectively, compared to the base case
Cicero et al. (2011)	PS	Increased the release capacity of the spillway by four times higher than a traditional MGS
Bordbar et al. (2010)	Stepped MGS (3, 4, 6, and 11 steps)	In terms of design and resistance against cavitation risk and concrete erosion, stepped spillways with 11 steps have been identified as the most optimal type
Keihanpour and Kabiri-Samani (2021)	Marguerite-shaped inlets with holes at the bottom	Improved the flow rates by approximately six, three, and two times greater than flow discharges through a simple shaft spillway, a CPK inlet, and a simple marguerite-shaped inlet, respectively
Nasiri et al. (2021)	CPK inlet	It significantly increased the flow discharge and reduce the turbulent flow intensity compared with a simple shaft or even MGS
Kabiri-Samani and Keihanpour (2021)	Marguerite-shaped inlet	Increased flow discharge up to four times greater than classical MGS and the strength of swirling flow is significantly decreased also
Brakeni and Guryev (2020)	12-section polygonal configuration	Increased Cd up to 0.52 and decreased reservoir water level by 0.68 m during maximum flood discharge

Table 5 (continued)

References	Types of new inlet shapes	Effects on efficiency of spillway operation
Djillali et al. (2021)	12-section polygonal configuration	Improved the Cd by 20%, without exposing the head of the weir to the risk of cavitation
Aghamajidi (2013)	Stepped and smooth MGS	Smooth spillways with ogee shapes provide better Cd
Asadsangabi et al. (2014)	Wagner, Creager, and circular inlet profile shapes	Wagner and Creager models are more economical than circular models due to construction costs. Comparing the cavitation index, Creager model performed better than Wagner model
Rouzegar et al. (2019)	Square and circular inlets of Labyrinth MGS	A circular inlet has more discharge capacity than a square inlet

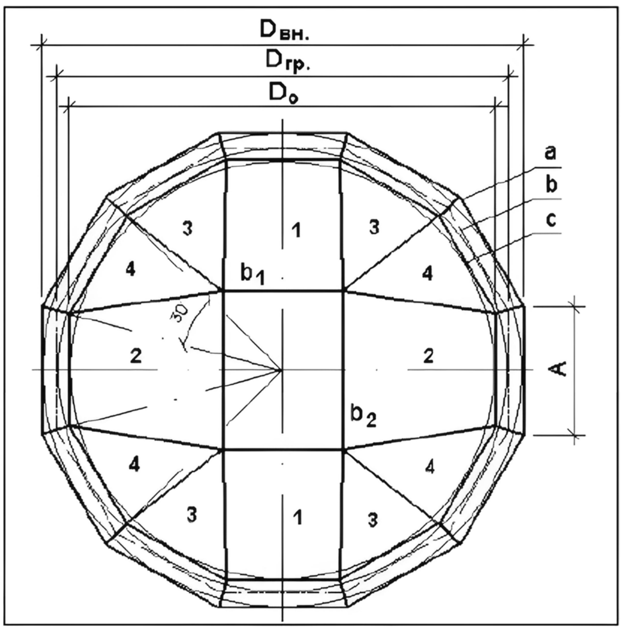

Fig. 4 Plan of the shaft of the polygonal cross section (Brakeni and Guryev 2020)

when a group of six VBs was employed, it resulted in a significant increase in the Cd by up to 50.97% for crest control. Furthermore, in the case of orifice control, the utilization of six VBs led to an improvement of up to 16.13% in the coefficient of discharge.

The study conducted by Christodoulou et al. (2010) comprehensively investigated the effects of the number and configuration of anti-vortex piers. Notably, their findings revealed that the inclusion of 5–6 piers resulted in a substantial reduction of approximately 50% in the water level for discharges exceeding the design value. However, it is important to consider that the piers exhibited only a minor adverse effect for cases with small H values ($H/R < 0.2$). Also, it has been reported that increasing the spillway shaft height above the reservoir bed and placing piers on the spillway leads to a reduction in flow asymmetry.

The influence of different forms of anti-vortex blades, including rectangular, triangular, and baleen bodies (as shown in Fig. 11) on the Cd of the MGS was investigated (Nohani and Emamgheis 2015). The findings demonstrated that among the different blade forms investigated, the baleen types exhibited a more notable influence in enhancing the efficiency of the spillway's Cd.

Noruzi and Ahadiyan (2017) established a Flow-3D numerical model to assess the effects of putting different numbers of VB blades on the MGS crest. The outcomes were compared to experimental results, and the findings revealed that inserting blades raises the Cd by 42% and drops the reservoir water level by 25%.

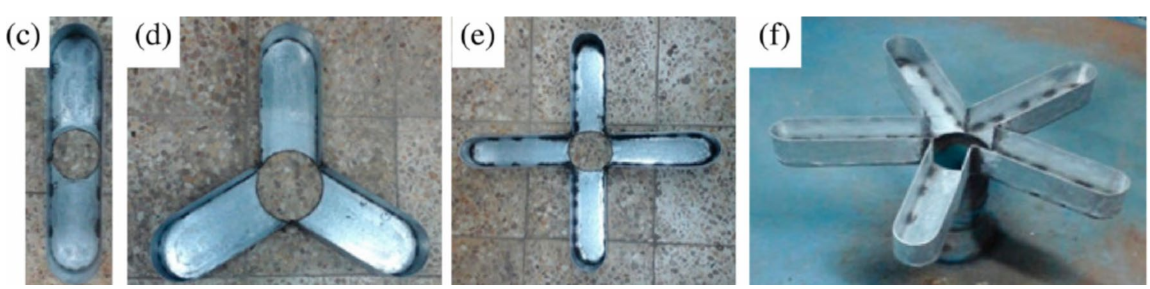

Fig. 5 (**c**–**f**) Images of two- to five-lobed marguerite-shaped inlet (Kabiri-Samani and Keihanpour 2021)

Utilizing a blade-VB leads to improved Cd, which is greater in a sharp edge than a wide-edge. The blade VB shifts the flow lines into the shaft spillway from a spiral to a straight path due to the compressed flow lines; as a result, it offered a greater Cd (Nohani 2014).

In contrast to the aforementioned papers, four anti-vortex devices were identified as optimum numbers to improve hydraulic performance and eliminate vortex flow problems (Kamanbedast and Mousavi 2017; Mirabi et al. 2021; Rahimi and Razavi 2018). Anti-vortex piers increase the submergence threshold, cope circulation, and vortexes and then allow the spillway to release more discharge without being submerged.

Furthermore, various numbers of VBs (as displayed in Fig. 12) were tested to discover the optimal number for increasing the flow rate. The outcomes showed that using 12 VBs of dimensions of $5\times8\times10$ cm significantly boosted the flow rate compared to the normal spillway without VB (Akbari et al. 2015).

3.1.3 Cavitation Problem and Modifications in the Vertical Bend

Generally, cavitation is one of the problems facing designers due to the existence of high flow velocity in spillways. Usually, it occurs when the flow pressure falls below the fluid vapor pressure and should be avoided as much as possible (Aghamajidi et al. 2013). Cavitation can be estimated using the cavitation index according to the following equation (Asadsangabi et al. 2014):

$$\sigma = \frac{P - P_v}{\frac{\rho V^2}{2}} \quad (1)$$

where (P) is the absolute pressure, (P_v) vapor pressure, (V) flow velocity, and (ρ) fluid density.

Cavitation occurrence is expected at the spillway's entrance, the funnel's entrance junction, the vertical shaft, and within the elbow (Ehsani et al. 2019). Many research studies have been devoted to determining the most probable locations of this problem and providing possible solutions to control it (Aghamajidi et al. 2013; Asadsangabi et al. 2014; Bordbar et al. 2010; Brakeni and Guryev 2020; Djillali et al. 2021; Ehsani et al. 2019; Aydin and Ulu 2023a; Salehi et al. 2023).

Replacing the standard circular inlet of the spillway with a polygonal section allows the water jet to enter without separation in the connecting elbow and maintain a direct connection to the wall. It allows for more dependability and reduces cavitation risk (Brakeni and Guryev 2020; Djillali et al. 2021).

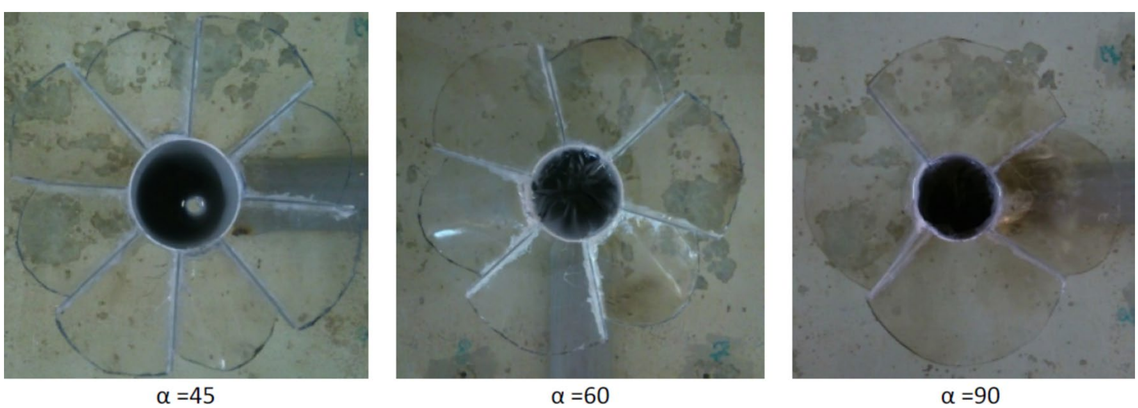

Fig. 6 Physical models of PS with various angles (Banejad et al. 2016)

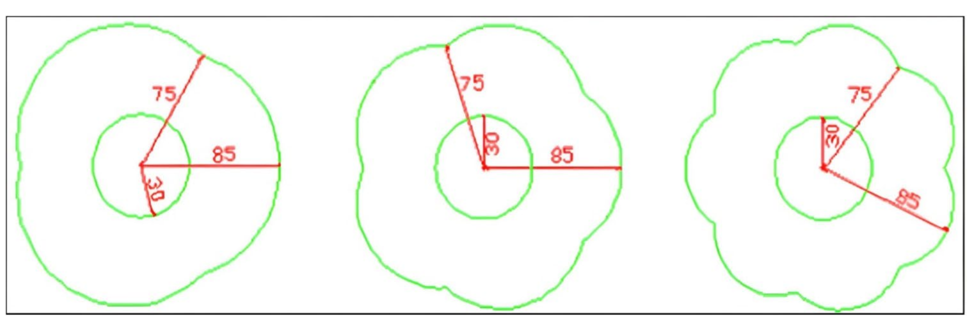

Fig. 7 Trihedral, pentahedral, and heptahedral MGS with a crest diameter of 17 cm (Bagheri et al. 2010)

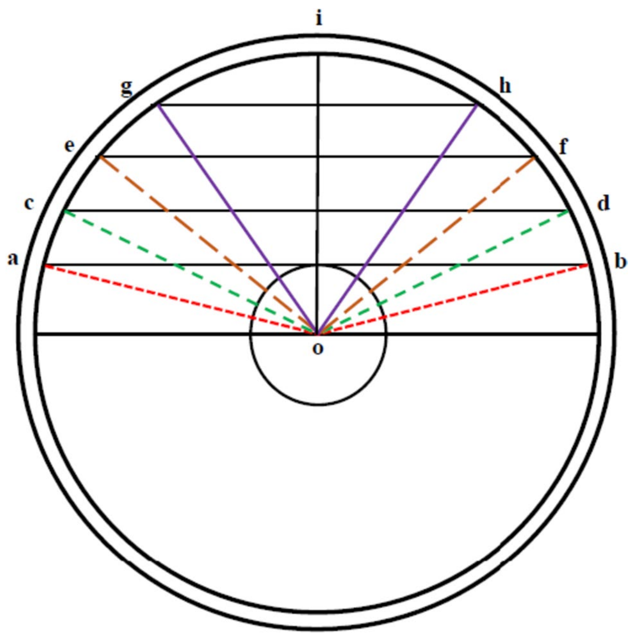

Fig. 8 Crest plan of MGS with different angles to create the crest sectors (Sabeti et al. 2019)

Ehsani et al. (2019) developed a numerical model utilizing the Flow-3D program to investigate flow velocity and pressure close to the elbow wall, and the findings were compared with experimental results. The results showed that the highest-pressure heads were found in the bottom of the elbow for different discharges and various elbow radii, which is demonstrated in Fig. 13. So, the start and end points of the elbow are the most likely places for cavitation due to geometric changes that cause variation in the flow course.

Asadsangabi et al. (2014) investigated three different types of MGS inlet shapes (Wagner, Creager, and circular forms). The primary focus of their study was to assess the minimum probability of cavitation by evaluating the cavitation index. Cavitation indexes for various inlet configurations were calculated and compared with each other. The results showed that the Creager model performed better than the Wagner and the circular model, as shown in Fig. 14.

Furthermore, it was observed that the stepped MGS design demonstrated enhanced efficiency in terms of design and resistance to the risks of cavitation and concrete erosion when compared to a smooth spillway (Aghamajidi et al. 2013; Bordbar et al. 2010).

Additionally, new geometry for the vertical bend between the shaft and the tunnel was examined (Fais et al. 2015; Salehi et al. 2023). Fais et al. (2015) compared the performance of a new parabolic shape with a 90o circular bend and a polycentric bend with a variable radius. The study was conducted in a spillway model of the Paraitinga hydropower plant in Brazil. Figure 15 presents a schematic representation of three bend configurations. The findings of the study revealed that the proposed novel bend exhibited an enhanced discharge rating curve compared to the existing configurations. These results underscore the importance of considering the new bend configuration when designing MGS.

3.1.4 Modification in Physical Boundaries of MGS

Usually, this type of spillway is located close to hills or dam abutments; therefore, local boundary circumstances could significantly affect the flow behavior. To ensure radial flow and eliminate vortex flow over the crest, a MGS should be constructed as far away from reservoir rims as possible (Christodoulou et al. 2010).

Fattor and Bacchiega (2009) conducted an investigation focused on enhancing flow behaviors in spillway boundaries. They explored several modifications including lowering the spillway position, adjusting the physical boundaries to improve approximation, modifying the placement and number of anti-vortex piers, and excavating the ground to deeper levels near the upstream face of the spillway. These modifications resulted in increased discharge capacity, reduced circulation currents directly upstream of the inlet section, and enabled larger discharges without submergence or drowning.

Emami and Schleiss (2016) applied an experimental study to examine the impact of the proximity of the spillway to dam abutments. The researchers observed disruptions in the flow lines of the approaching flow near the abutments, which had a negative influence on the efficiency and performance of the spillway. It was determined that the placement of piers at specific locations along the crest of the spillway was the most effective solution for mitigating flow disturbances.

3.1.5 Proposed Empirical Equations to Calculate the Discharge Coefficient (Cd)

Musavi-jahromi et al. (2016) and Sayadzadeh et al. (2020) used the SPSS software to obtain numerical equations to calculate the Cd of MGS with different kinds of VB. The following two equations were derived for the crest and orifice control, respectively (Sayadzadeh et al. 2020):

$$\begin{aligned} \mathrm{Cd} = {} & 1309.6 * \left(\exp\left(\frac{H}{D}\right)\right)^{-0.01} + 131.3\frac{b}{D} - 156.9\frac{h}{D} \\ & + 0.241(n)^{0.757} + 477.5(\mathrm{Fr})^{0.001} \\ & + 0.6 * (\exp(a))^{-0.476} - 1784.8 \end{aligned} \tag{2}$$

Table 6 Different types and numbers of VBs were installed at the crest of the spillway in the previous studies

References	Type of VB	No. of VB	Best no. VB	Effects on the efficiency of spillway operation
Aghamajidi (2022)	VB (variable dimensions)	3, 4, and 6	6	The flow rate improved by 23%. Also, increasing the vortex breaker's thickness by over 7% of the spillway radius has no considerable effect
Radmanesh et al. (2022)	VB (variable dimensions)	3 and 6	6	Utilizing six vortex breakers with a stepped MGS exhibited significantly superior performance than non-stepped configurations
Kamanbedast and Mousavi (2017)	Anti-vortex pier	4, 8, and 12	4	Maximum Cd was observed when four VBs were installed at an angle of 90 degrees
Aghamajidi et al. (2013)	Anti-vortex piers	4, 3 and 6	6	Increased water flow discharge by more than 12%
Aghamajidi (2013)	Three types of VB	3, 4, and 6	6	The flow rate was increased by more than 15% on average
Rahimi and Razavi (2018)	Anti-vortex plate	4	4	
Christodoulou et al. (2010)	Anti-vortex pier	2, 4, 5, and 6	5 and 6	For the discharges greater than the design value, the presence of 5–6 piers over the crest reduced the reservoir water level by 50%
Mirabi et al. (2021)	Anti-vortex pier	4	4	Anti-vortex structures absorbed most of the unbalanced forces and fewer stresses will be generated in the spillway structure
Musavi-jahromi et al. (2016)	VB with longitudinal angles of 0°, 15°, 30°, and 45°	3, 4, 5, and 6	6	Six VBs of 45° is the best situation to improve the Cd value
Nohani and Emamgheis (2015)	Triangular, rectangular and baleen body VBs	6	6	Baleen body, rectangular, and triangular shapes increased the Cd by 52, 39, and 32%, respectively
Noruzi and Ahadiyan (2017)	Anti-vortex blade at 45 degree	3, 4, and 6	6	The Cd has been increased by 40–57 percent approximately
Emami and Schleiss (2016)	Flow directing piers	2, 3, 4, and 6	6	Inserted six directing piers on the crest the flow disturbances could be eliminated
Nohani (2014)	Blade VB	3 and 6	6	Increased the spillway Cd up to 20%
Nohani (2015a)	Anti-vortex blade	6 (thickness 3 mm) 6 (thickness 5 mm)	6 (thickness 3 mm)	Using a smaller blade thickness improves discharge capacity more than a larger thickness
Akbari et al. (2015)	Anti-vortex plate	3, 6, and 12	12	Increased discharge rate by 36%
Sayadzadeh et al. (2020)	Pyramidal VB	3, 4, and 6	6	Increased Cd up to 50.97 and 16.13% in the crest and orifice control conditions, respectively

$$\mathrm{Cd} = 0.662 * \left(\exp\left(\frac{H}{D}\right)\right)^{-2.725} + 49.223\frac{b}{D} - 60.289\frac{h}{D} + 1.442(n)^{0.014} + 1.239(\mathrm{Fr})^{-0.866} - 1.103(a)^{0.062} - 0.34 \quad (3)$$

Additionally, Musavi-jahromi et al. (2016) proposed Eq. (4) to estimate Cd:

$$\mathrm{Cd} = 2.63 * \left(\exp\left(\frac{H}{D}\right)\right)^{-2.93} - 1.21 * (n * \theta)^{-0.02} \quad (4)$$

where H is the water level above the spillway crest, D is the crest diameter, h, and b are the height and width of VB, n is the number of VB, α is the inclination angle of pyramidal VB with vertical axis, and θ is the angle of VB that makes with the horizontal in radian.

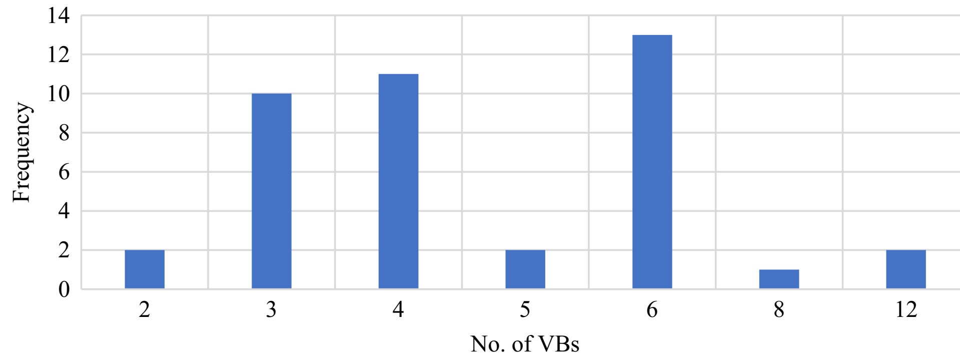

Fig. 9 Frequencies of various numbers of VBs used in the literature

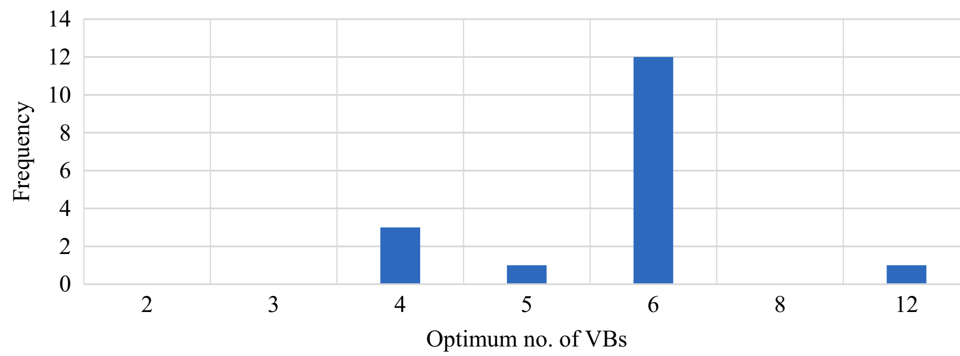

Fig. 10 Frequencies of optimum number VB

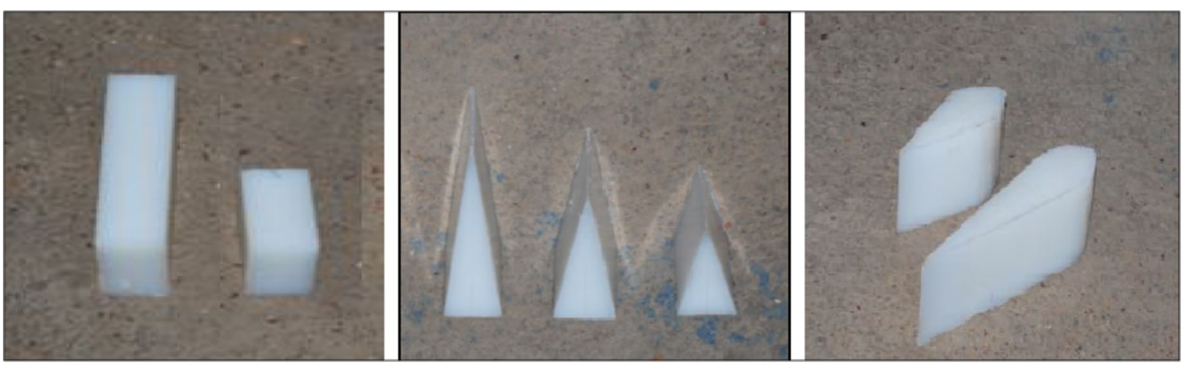

Fig. 11 Different sizes of rectangular, triangular, and baleen body anti-vortex blades (Nohani and Emamgheis 2015)

Fig. 12 A view of the shaft spillway's physical model with different VB numbers in the laboratory (Akbari et al. 2015)

Haghbin et al. (2022) investigated the ability of some computational methods to estimate Cd, based on obtained results they reported that the Support Vector Regression-Invasive Weed Optimization (SVR-IWO) is more efficient than other models to evaluate the Cd value. Several authors have also used ANN as a powerful tool to investigate the Cd of MGS (Alfatlawi and Alshaikhli 2015; Camargo et al. 2006; Kamanbedast 2012; Kashkaki et al. 2018). Kamanbedast (2012) evaluated Cd values for different vortex numbers, with the results demonstrating that 55.93% of the estimated outputs closely matched the actual values, indicating the accuracy of the model's evaluation. Also, Camargo et al. (2006) utilized ANN to interpolate and extrapolate nonlinear relation curves. The outcomes highlighted the importance of ANN as a valuable support tool in the design and analysis of MGS, particularly in predicting Cd and flow rating curves, as depicted in Fig. 16.

Furthermore, for comparison purposes, ANN and multiple nonlinear regression (MNLR) methods were applied to predict the Cd of circular and quadrate-stepped MGS (Alfatlawi and Alshaikhli 2015). The outcomes indicated that the highest recorded RMSE for the ANN approach prediction is 1.4%, while the maximum RMSE for MNLR formulae is 1.74% for four-stepped circular MGS. Both the ANN and MNLR approaches accurately anticipate the coefficient of discharge of the analyzed spillway. Also, from the MNLR results, two equations were extracted to predict the

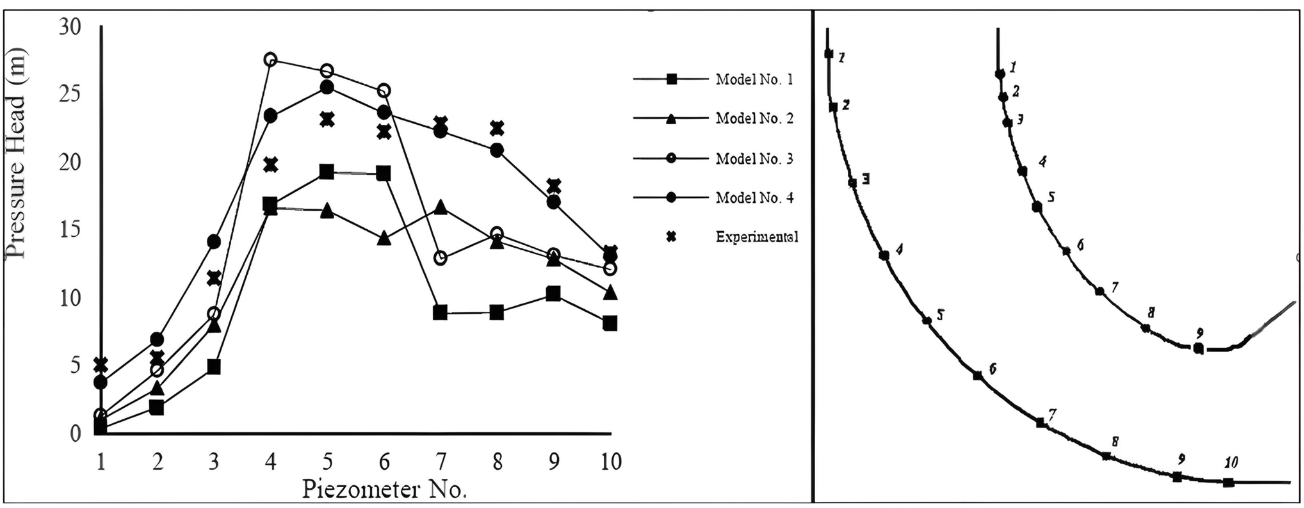

Fig. 13 Left side: pressures for different points in the elbow for different cell sizes. Right side: location of the piezometers on the bottom and roof of the elbow (Ehsani et al. 2019)

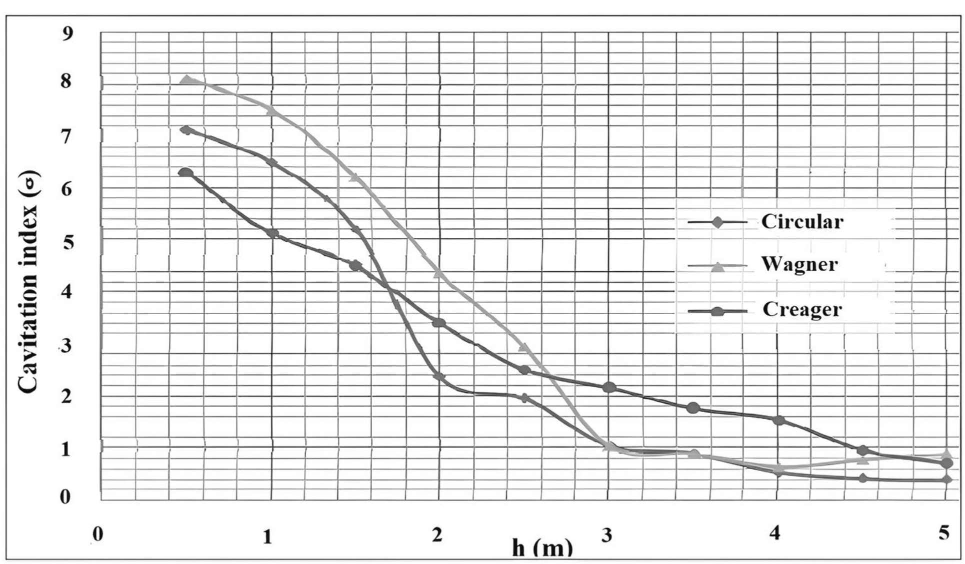

Fig. 14 Cavitation index versus relative head for the three models (Asadsangabi et al. 2014)

Cd for circular and quadrate shapes as written in Eq. (5) ($R^2 = 0.955$) and Eq. (6) ($R^2 = 0.952$) , respectively:

$$\mathrm{Cd} = 0.784 * N^{0.132} * \left(\frac{H}{R}\right)^{0.118} * \mathrm{Fr}^{1.068} \quad (5)$$

$$\mathrm{Cd} = 0.846 * N^{0.101} * \left(\frac{H}{l}\right)^{0.102} * \mathrm{Fr}^{1.068} \quad (6)$$

where H is the head above the spillway crest, R is the MGS crest radius, N is the number of steps, and l is the length of the quadrate side.

Kashkaki et al. (2018) predicted the Cd of a CPK spillway using an ANN model. The ANN models were trained and tested using the results obtained from an experimental study. The coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE), and mean absolute percentage error (MAPE) were used to assess the ANN performance. The authors reported that the ANN model estimated the values of the Cd of the CPK spillway with higher accuracy.

However, Fais and Genovez (2009) investigated the discharge flow rating curve in a vertical shaft with a morning glory entrance to eliminate scale effects for low water heads. For this purpose, they conducted an experimental study on the Paraitinga dam spillway model on a scale of 1:51.02. As a result, equations for correcting the Cd for low water heads were developed as follows:

$$C = 0.17 + 0.242\sqrt{33 - \left[5.5 - \frac{H}{R}\right]^2 + \left[1 + 1.2\frac{H}{R}\right]^{-4/9}} \quad (7)$$

$$C = 2.967\left(\frac{H}{R}\right)^{0.178} \quad (8)$$

where H is the water head above the spillway crest and R is the crest radius. The corrected discharge rating curves were compared with the ones obtained by Genovez (1997) for the same spillway in model scales of 1:63.17 and 1:83.29 as shown in Fig. 17.

The lack of agreement between the discharge rating curves of the models and prototype is evident for discharges smaller than 0.002 m^3/s (at a scale of 1:83.29), 0.004 m^3/s (at a scale of 1:63.17), and 0.007 m^3/s (at a scale of 1:51.02), as shown in Fig. 17a. While, the proposed equations showed a good agreement between the model and the prototype results, with a maximum divergence of 2.5%. On the other hand, Gouryev

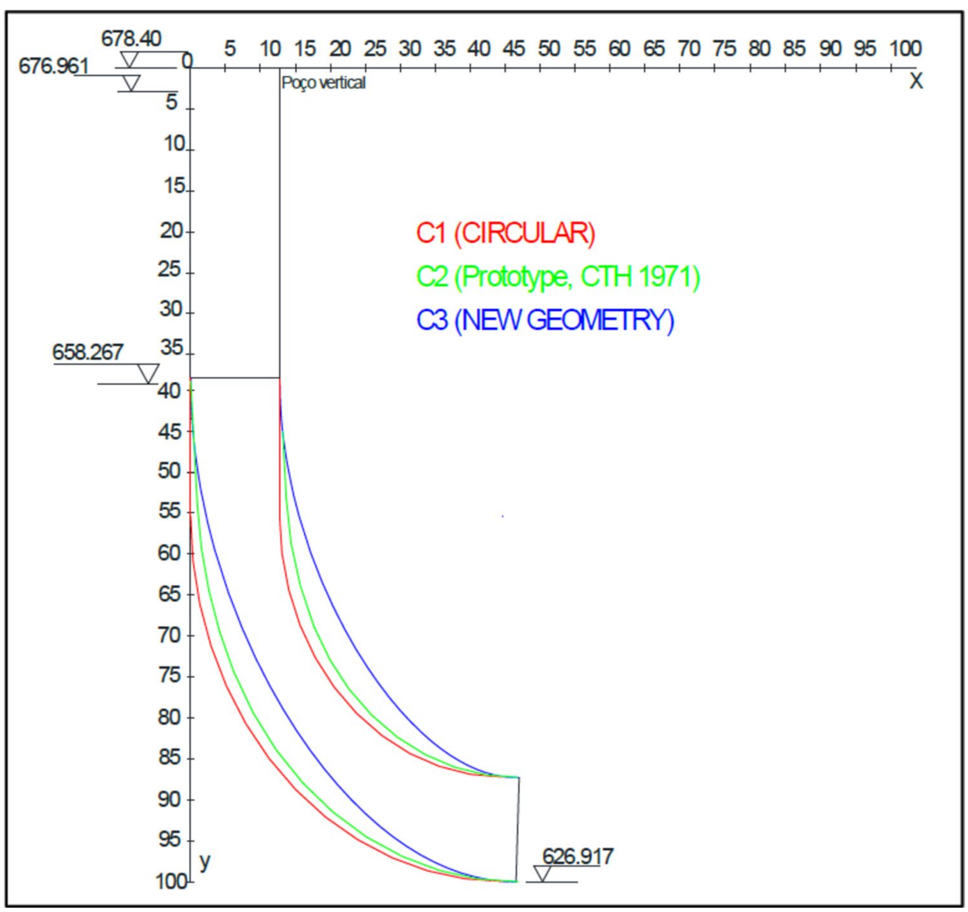

Fig. 15 Schematic of the three tested bends (Fais et al. 2015)

et al. (2020) mentioned that the value of the Cd of a shaft spillway working under a tiny head varies from 0.270 to 0.272.

Nohani (2015b) derived a relation between *H/D* and Cd using regression analysis. The *H/D* at shaft spillways is conversely related to the Cd values of the spillway.

Aghamajidi et al. (2013) developed two empirical equations to calculate the Cd value for smooth and stepped MGS as follows:

For a smooth spillway:

$$\mathrm{Cd} = 1.725 * \left(\frac{H}{R}\right)^{-0.133} * 0.147(\mathrm{Fr})^{-1.38} \tag{9}$$

For stepped spillway:

$$\mathrm{Cd} = 0.016 * \left(\frac{H}{R}\right)^{-1.629} * 1.949(\mathrm{Fr})^{0.364} \tag{10}$$

Additionally, Aydin and Ulu (2023b) derived a new formula through regression analysis to estimate the discharge coefficients of the labyrinth-shaft spillway specifically for *H/P* ratios greater than 0.2.

$$\mathrm{Cd} = 0.91 * \left(\frac{L}{L_S}\right)^{-4.06\frac{H}{P}} + 0.59 * \exp\left(-0.62\frac{H}{P}\right) \tag{11}$$

where L is the length of the labyrinth weir crest and L_S is the crest length of the bell mouth shape.

Figure 18 provides a summary of various relationships found in the literature, which depict the discharge coefficient as a function of relative submergence (*H*/*D*) for MGS

Figure 18 indicates that the coefficient of discharge (Cd) values exhibit a proportional decrease as the *H/D* ratio increases for MGS. It is worth noting that most of the available equations for estimating Cd are predominantly applicable to lower values of *H/D*, specifically in the crest control condition. This preference is attributed to the high variability observed in Cd values under this flow condition.

3.1.6 Further Studies on Flow Properties in MGS

Some researchers studied further problems that may happen during the spillway operation and might cause efficiency reduction. Razavi and Ahmadi (2017a) through a numerical model investigated the effect of adding suspended load to flow on discharge rate. For different water levels over the spillway crest, suspended loads of 3000, 6000, 9000, and 12,000 ppm were added to the flowing water. The findings revealed that as the amount of suspended loads in the flowing water increased, there was a corresponding reduction in the discharge rate passing through the spillway, as shown in Fig. 19.

The hydraulic parameters such as pressure, velocity, flow depth over the crest, and discharge rate were studied through employed numerical models to investigate the hydraulic performance of the MGS (Enjilzadeh and Nohani 2016; Nohani 2015c; Razavi and Ahmadi 2017b). Jalil et al. (2020) studied the effect of air entrainment and free-flow condition on flow properties through standard pipe elbow as shaft spillway by establishing a CFD numerical model. The visual results show that the switching flow condition's speed depends on the radius of air entrainment, and it is dropped by 2.1 times when the water depth at the crest increases 3.3 times and disappears when the ratio of water depth to the length of the shaft reaches 40%. The amount of air entrainment and vortex formation directly leads to changing flow phenomenon.

Furthermore, the instability of an embankment was investigated due to the insufficient operation of MGS (Braz 2000). After several inspections inside and outside of the spillway tunnel, it is observed that air explosions in the downstream end of the dissipation basin during flood season caused some problems inside the spillway, such as developing a piping process and separating joints of the spillway tunnel. Also,

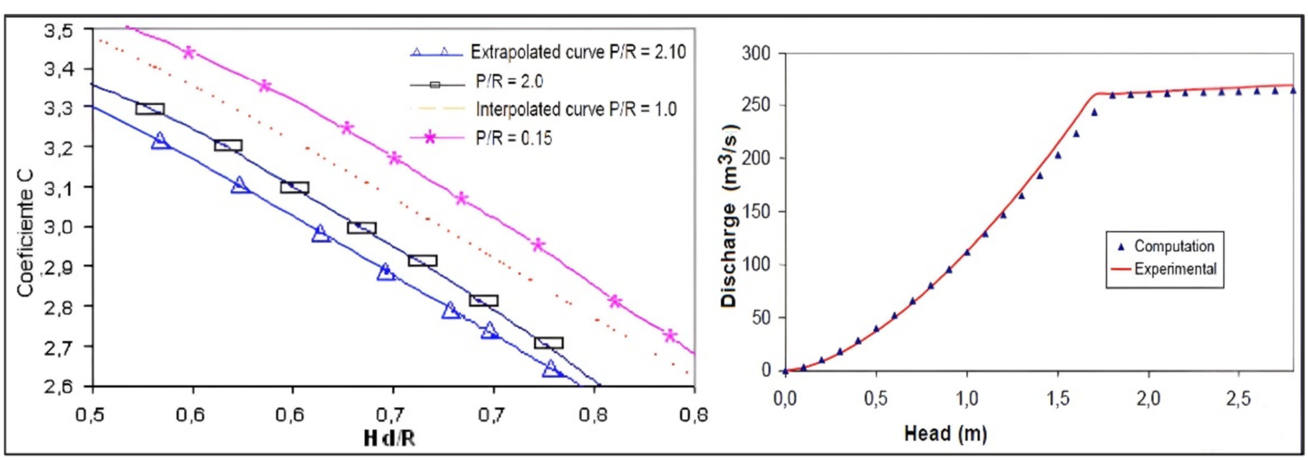

Fig. 16 ANN's capabilities to interpolate and extrapolate C_d and predict discharge rating curve (Camargo et al. 2006)

when the outlet tunnel is submerged, air enters and subsequent release by floodwaters generated vibrations in the concrete tunnel and adjacent embankment.

Aghebatie and Hosseini (2020) examined the occurrence of slug flow and implemented various techniques for decreasing its negative consequences, such as modifications in tunnel slope, diameter, and radius of curvature. The results showed that the values of $D/H > 1$ employed in the spillway are more operative for decreasing the creation of strong slugs, with the maximum pressure decreased by 25% and the minimum pressure raised by 33% compared to the same situation for $D/H \leq 1$.

3.2 Proposed ANN Modeling to Predict Cd

This section focuses on the development of a data-driven model to calculate the Cd of MGS. The MATLAB software (version 9.8) was utilized, employing the Levenberg–Marquardt algorithm for training the ANN tool. This algorithm was chosen due to its superior speed compared to other back-propagation algorithms available (Kashkaki et al. 2018). The network consisted of one input layer and one output layer. The model's input was H/D, and the output was Cd. Several experimental studies in the past confirmed that the most important dimensionless parameter to control Cd values of MGS is *H/D* ratio (Aghamajidi et al. 2013; Bagheri et al. 2010; Bagheri and Nohani 2014; Christodoulou et al. 2010; Kamanbedast and Mousavi 2017; Nohani 2014, 2015b; Nohani and Emamgheis 2015; Noruzi and Ahadiyan 2017; Rouzegar et al. 2019; Sayadzadeh et al. 2020).

A trial-and-error process was applied to choose the suitable number of hidden layers and their neurons. Fifty experimental datasets from the literature were acquired and divided into three groups at random: 70% for training and 15% for each of the model's testing and validation. Assessment criteria for evaluating the performance of the model, including R^2, RMSE, MAE, and MAPE, were utilized to analyze and evaluate the effectiveness of the proposed model, and they can be calculated using the following formulas:

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(\mathrm{Cd_m} - \overline{\mathrm{Cd_m}}\right)\left(\mathrm{Cd_p} - \overline{\mathrm{Cd_p}}\right)}{\sqrt{\left[\sum_{i=1}^{n} \left(\mathrm{Cd_m} - \overline{\mathrm{Cd_m}}\right)^2\right]\left[\sum_{i=1}^{n} \left(\mathrm{Cd_p} - \overline{\mathrm{Cd_p}}\right)^2\right]}} \right)^2 \tag{12}$$

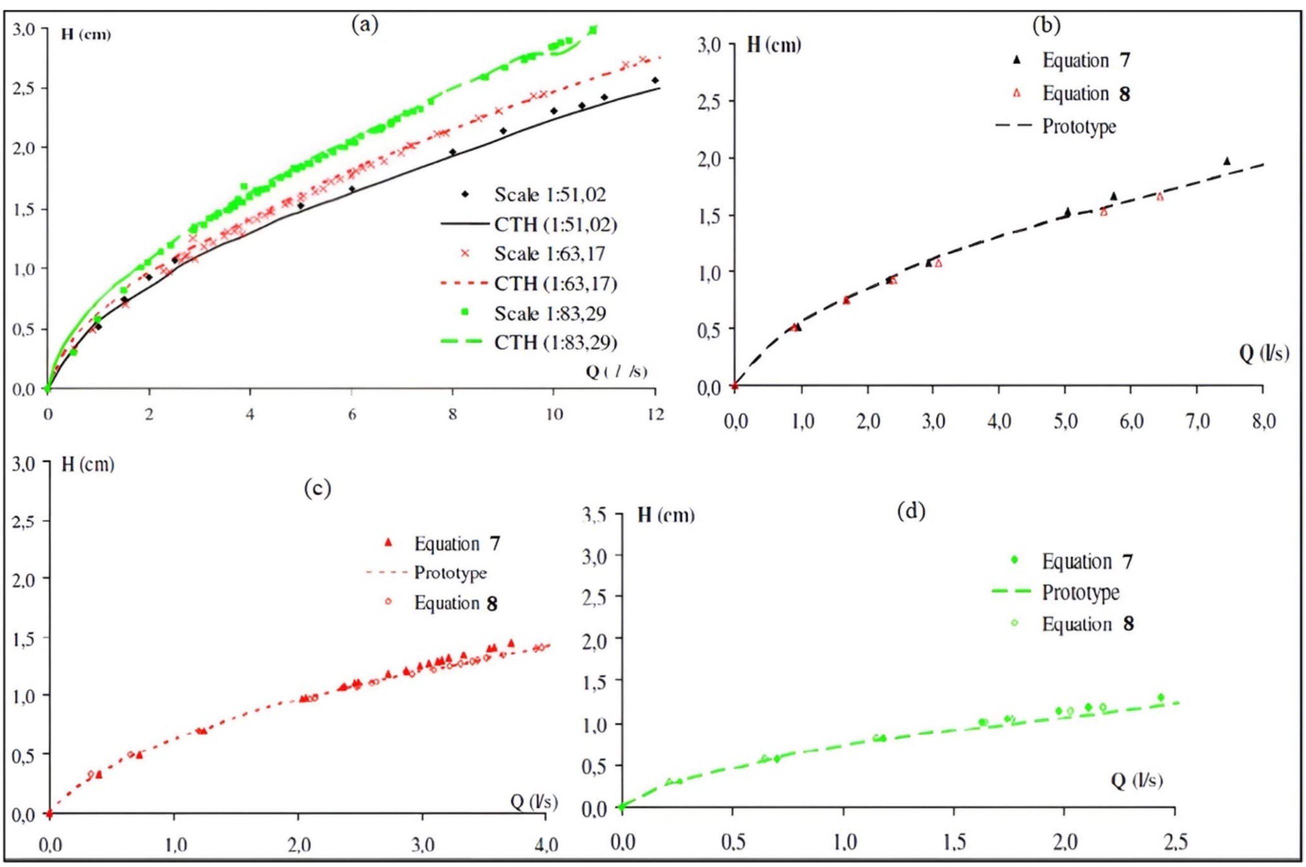

Fig. 17 **a** Model discharge rating curves in scales 1:51.02, 1:63.17, and 1:83.29; **b**, **c**, and **d** are corrected discharge rating curves based on model scales 1:51.02, 1:63.17 and 1:83.29, respectively (Fais and Genovez 2009)

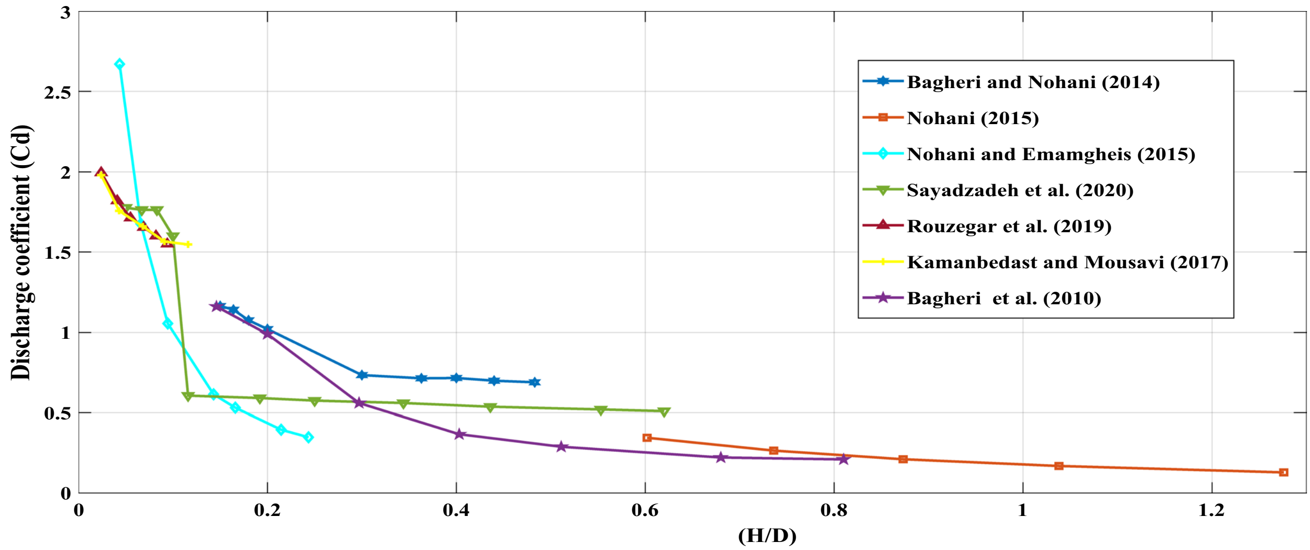

Fig. 18 Different relationships of Cd versus H/D of MGS

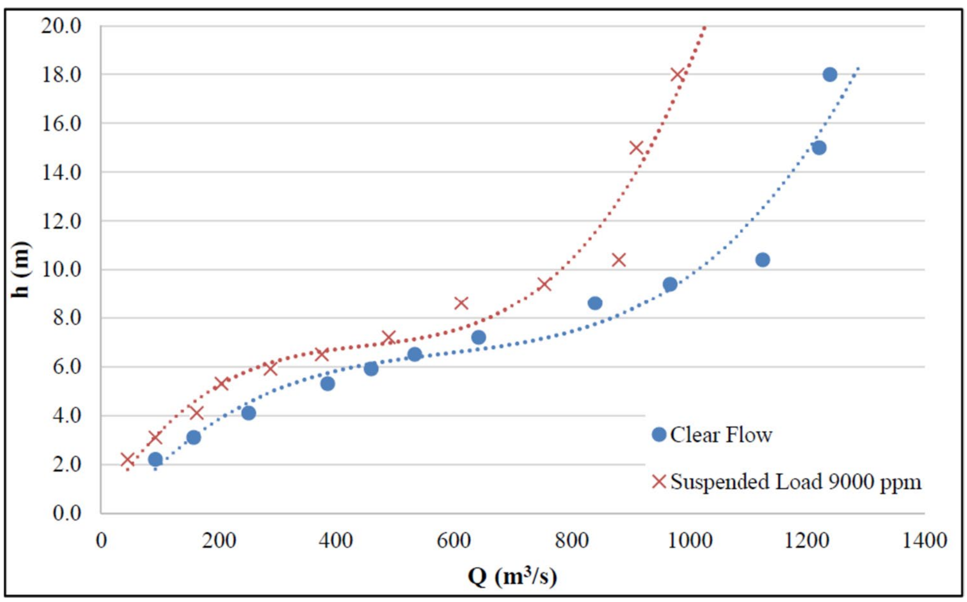

Fig. 19 Rating curve for net flow and flow with a suspended load of 9000 ppm (Razavi and Ahmadi 2017a)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(\text{Cd}_\text{m} - \text{Cd}_\text{p}\right)^2}{n}} \tag{13}$$

$$\text{MAE} = \frac{\sum_{i=1}^{n} \left|\left(\text{Cd}_\text{m} - \text{Cd}_\text{p}\right)\right|}{n} \tag{14}$$

$$\text{MAPE} = \frac{\sum_{i=1}^{n} \left|\frac{(\text{Cd}_\text{m} - \text{Cd}_\text{p})}{\text{Cd}_\text{m}}\right|}{n} \tag{15}$$

where n, Cd_m, Cd_p, $\overline{\text{Cd}_\text{m}}$, $\overline{\text{Cd}_\text{p}}$ are the number of data, measured Cd, predicted Cd, the average value of measured Cd, and the average value of the predicted Cd, respectively.

The best value for all the assessment factors mentioned before is zero, except for R^2 where the optimum value is one.

Figure 20 represents the relation between target (actual) and output (predicted) Cd for training, validation, testing, and all datasets. Figure 21 illustrates the actual and predicted Cd versus *H/D* (input) with residual error for all dataset groups. The model's R^2, RMSE, MAE, and MAPE are 0.87, 0.224, 0.166, and 0.245, respectively. According to this model, the Cd values decrease with increasing the *H/D* ratio.

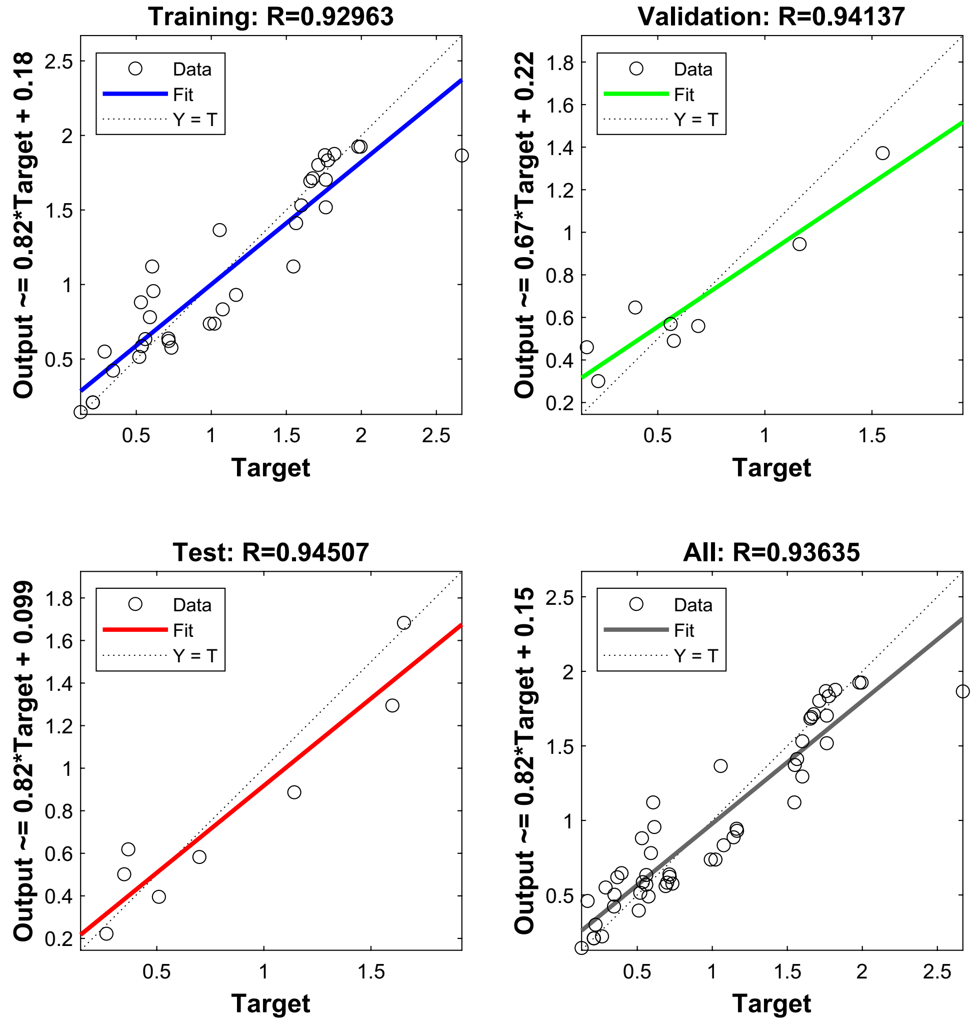

Fig. 20 Regression plots for training, testing, and validation of ANN model in MATLAB

4 Results

A comprehensive search across multiple databases and search engines resulted in the identification of 338 records. After a careful screening and evaluation process, 66 complete research studies were selected from a diverse range of 35 different Journals and 13 conference proceedings. These chosen studies have been utilized to conduct a systematic review. Most of the included articles (about 85%) appear to have been published in the last decade, between 2013 and 2023, with the highest numbers of published papers (7, 7, 8, and 7, respectively) in the years 2015, 2017, 2021, and 2022. However, only 15% of the papers were published between 2000 and 2012. Figure 22 displays the number of published papers each year.

The geographical distribution of the studies is depicted in Fig. 23. The majority of the studies (7) were conducted in Iran, followed by Brazil (3), Algeria (3), Argentina (2), and the USA (2).

Table 7 displays the names of the journals and conferences along with the corresponding number of included articles. The results indicated that 74% of the reviewed articles were published in journals, and 26% were published in conference proceedings. The top three journals based on the number of articles published are Flow Measurement and Instrumentation (four papers), Civil Engineering Journal (three papers), and World Applied Sciences Journal (three papers) as well as both the Advances in Water Resources and Hydraulic Engineering and the Institution of Civil Engineers-Water Management, stand out as prominent conference proceedings, each publishing of three research papers.

Table 8 lists the most cited papers with the author names, article titles, journal or conference names, and the number of citations. The article citations were determined using the Google Scholar web portal as the primary source.

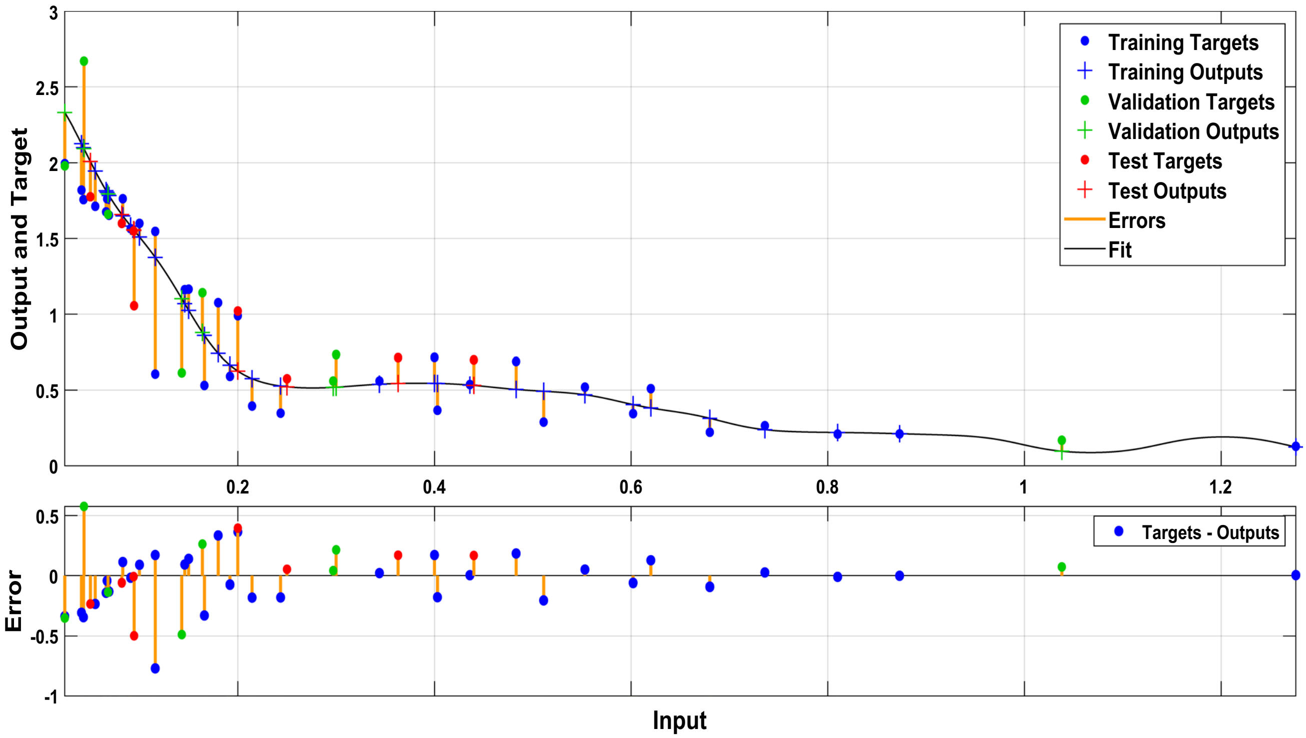

Fig. 21 Function fit and residual error for output element (training, testing, and validation) obtained with ANN model

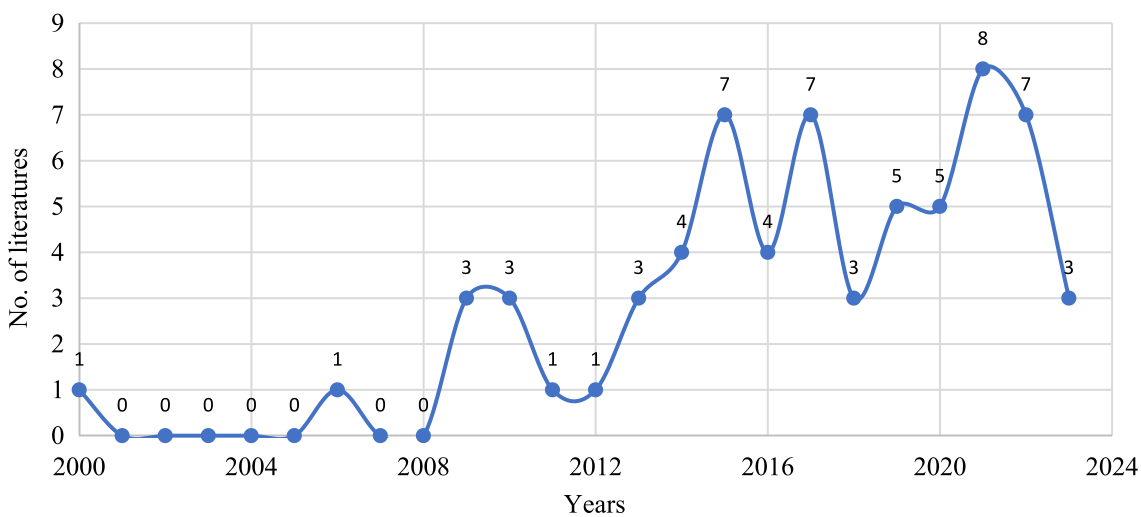

Fig. 22 Number of selected literature per year

5 Discussion

A comprehensive review, analysis, and evaluation of many research studies related to the MGS topic is provided. The following paragraph wraps up and summarizes some of the major points.

- Research interests in flow characteristics through MGS increased substantially in the last decade (2013–2023), with almost 85% of studies surveyed published in this period. However, only 15% of the research studies were conducted between 2000 and 2012.
- The diversity of the journals and conference proceedings that published the articles is also observed. Based

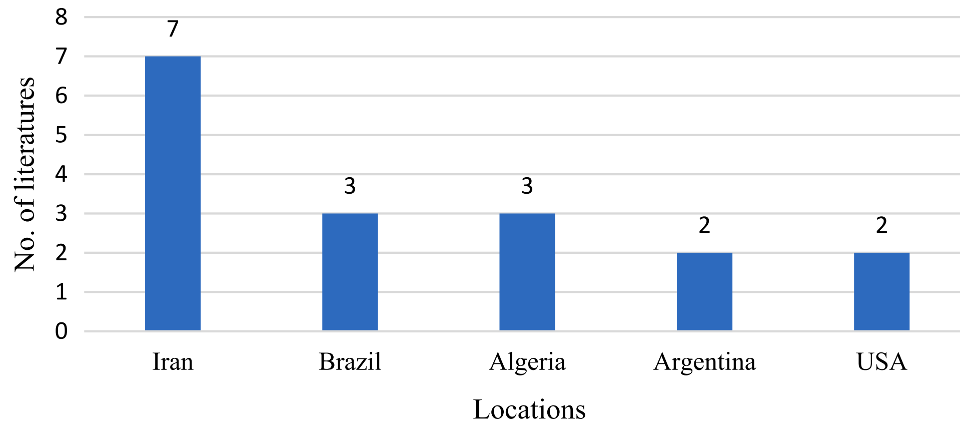

Fig. 23 Research studies locations

on our survey statistics, the top three journals are Flow Measurement and Instrumentation, Civil Engineering Journal, and World Applied Sciences Journal. The most popular location for case study research is Iran, with seven studies, followed by Brazil and Algeria, with three articles for each.

- Several researchers tried to improve the spillway hydraulic performance by applying different techniques to avoid abnormal flow conditions and increase the discharge capacity.
- The MGS spillways have three flow conditions: crest control for low water heads over the crest, orifice control, and pipe control for high water levels. MGSs are typically designed to operate as crest control conditions due to reduced discharge efficiency in the orifice and pipe controls.
- Investigation of the MGS spillways was focused on modifying the crest geometry, installing VB at the spillway crest, vertical bend modification, excavation of the physical boundaries of the spillway, dealing with the cavitation problem, and deriving equations to predict the Cd value.
- The surveyed studies make it abundantly evident that numerical and physical models are required to assess the hydraulic performance of flow conditions through the spillways.
- Typically, physical models of spillways were built using Froude laws of similitude and certain restrictions on the values of head over the crest, Re, and We are advised to reduce the scale effects.
- Vortex formation above the spillway crest is the most frequent issue that is likely to happen with this type of spillway. It causes a reduction in the discharge capacity and has negative consequences on spillway operation.
- Placing VB over the crest is an effective method to overcome flow vorticity and improve spillway capacity, especially for high water levels. The most practical and efficient number of VBs is 6.
- New forms of spillway inlet (CPK inlet, Marguerite-shaped inlets, polygonal sections, etc.) were developed to promote the capacity and eliminate malfunction of the spillway.
- The elbow section connecting the vertical shaft and horizontal tunnel of the spillway exhibits the highest susceptibility to cavitation. This vulnerability is primarily attributed to flow direction changes and the presence of high velocities within this region.
- Slug flow is an additional flow regime that can arise in the outlet tunnel of MGS, characterized by the presence of air–water flow where large air bubbles form within the tunnel. This flow pattern disrupts the smooth flow and induces pressure fluctuations that adversely impact the structural integrity and performance of the spillway.
- The Cd of MGS varies according to the spillway's nearby topography, physical boundaries, and inlet shape. Therefore, many pieces of research were carried out to derive a suitable equation to calculate the Cd value.
- This study used the ANN approach to establish a new model to estimate Cd based on the gathered dataset from the literature.

6 Conclusions and Recommendations

Following the PRISMA reporting guidelines, a systematic review of 66 peer-reviewed articles was conducted to investigate and enhance the flow behavior of MGS. Based on the findings, the following conclusions can be drawn:

1. Currently, the most prevalent approach for studying the hydraulic properties of spillways is the development of numerical models using commercial software. This method is favored due to its cost-effectiveness and the relatively shorter computational time required to obtain results compared to physical modeling techniques.

Table 7 Academic journals and conferences in which articles relating to MGS were published

No.	Journal title	No. of related papers	% Total publication
1	Flow Measurement and Instrumentation	4	6.1%
2	Civil Engineering Journal	3	4.5%
3	World Applied Sciences Journal	3	4.5%
4	Journal of Hydraulic Research	2	3%
5	Ain Shams Engineering Journal	2	3%
6	Science International	2	3%
7	Indian Journal of Fundamental and Applied Life Sciences	2	3%
8	Journal of Civil Engineering and Urbanism	2	3%
9	Journal of Water and Soil Science	2	3%
10	Civil and Project Journal	2	3%
11	Iranian Journal of Science and Technology. Transactions of Civil Engineering	1	1.5%
12	Instrumentation Mesure Metrologie	1	1.5%
13	International Journal of Hydraulic Engineering	1	1.5%
14	Journal of Hydraulic Engineering	1	1.5%
15	International Journal of Life Sciences	1	1.5%
16	UPB Scientific Bulletin, Series D: Mechanical Engineering	1	1.5%
17	Modares Civil Engineering Journal	1	1.5%
18	SN Applied Sciences	1	1.5%
19	Water Supply	1	1.5%
20	International Journal of Farming and Allied Sciences	1	1.5%
21	International Journal of Modern Physics	1	1.5%
22	International Journal of Civil and Environmental Engineering	1	1.5%
23	Water Science and Engineering	1	1.5%
24	LARHYSS Journal	1	1.5%
25	Bulletin of Environment, Pharmacology and Life Sciences	1	1.5%
26	Iranian Journal of Irrigation and Drainage	1	1.5%
27	Irrigation Sciences and Engineering	1	1.5%
28	Journal of Engineering Research	1	1.5%
29	International Journal of Agriculture and Crop Sciences	1	1.5%
30	Journal of Rehabilitation in Civil Engineering	1	1.5%
31	Journal of Soft Computing in Civil Engineering	1	1.5%
32	Applied Water Science	1	1.5%
33	International Journal of Health Sciences	1	1.5%
34	Journal of Water and Land Development	1	1.5%
35	Irrigation and Drainage Structures Engineering Research	1	1.5%
No.	**Conference title**	**No. of related papers**	**% Total publication**
1	Advances in Water Resources and Hydraulic Engineering	3	4.5%
2	Proceedings of the Institution of Civil Engineers-Water Management	3	4.5%
3	2017 ASDSO-Dam Safety, Conference Proceedings	1	1.5%
4	Joint Conference on Water Resource Engineering and Water Resources Planning and Management July 30–August 2, 2000, Minneapolis, Minnesota, United States	1	1.5%
5	International Symposium on Hydraulic Structures Ciudad Guayana, Venezuela, october 2006	1	1.5%
6	1st IAHR European Congress, Edinburgh, Scotland—2010	1	1.5%
7	International Symposium on "Appropriate technology to Ensure Proper Development, Operation and Maintenance of Dams in Developing Countries", Johannesburg, South Africa, 2016	1	1.5%
8	15th Iranian Hydraulic Conference 2016	1	1.5%

Table 7 (continued)

No.	Conference title	No. of related papers	% Total publication
9	E3S Web of Conferences 2021	1	1.5%
10	International Conference on Energy, Power and Environmental Engineering (ICEPEE 2017)	1	1.5%
11	Proceedings of the International Conference on Labyrinth and Piano Key Weirs (PKW 2011), Liège, Belgium, 2011	1	1.5%
12	E-Proceedings of the 36th IAHR World Congress, 2015, The Hague, The Netherlands	1	1.5%
13	IOP Conference Series: Materials Science and Engineering 2021	1	1.5%

Table 8 Top ten most cited articles

No.	References	Article titles	Journal or Conference	No. of citations
1	Liu et al. (2018)	Experimental and Numerical Investigation of Flow in a Newly Developed Vortex Drop Shaft Spillway	Journal of Hydraulic Engineering	47
2	Shemshi and Kabiri-Samani (2017)	Swirling flow at vertical shaft spillways with circular piano key inlets	Journal of Hydraulic Research	39
3	Parsaie and Haghiabi (2019)	The hydraulic investigation of circular crested stepped spillway	Journal of Flow Measurement and Instrumentation	37
4	Cicero et al. (2011)	Study of a piano key morning glory to increase the spillway capacity of the Bage dam	Proceedings of the International Conference on Labyrinth and Piano Key Weirs (PKW 2011)	14
5	Christodoulou et al. (2010)	Experimental study on the effect of piers and boundary proximity On the discharge capacity of a morning glory spillway	1st IAHR European Congress, Edinburgh, Scotland—2010	14
6	Kamanbedast (2012)	The Investigation of Discharge Coefficient for the Morning Glory Spillway Using Artificial Neural Network	World Applied Sciences Journal	13
7	Savic et al. (2014)	Shaft spillway with deflector downstream of vertical bend	Proceedings of the Institution of Civil Engineers Water Management 2014	13
8	Asadsangabi et al. (2014)	Two phase flow modeling in shaft spillways using Volume of fluid (VOF) method	Iranian Journal of Science and Technology. Transactions of Civil Engineering	12
9	Enjilzadeh and Nohani (2016)	Numerical Modeling of Flow Field in Morning Glory Spillways and Determining Rating Curve at Different Flow Rates	Civil Engineering Journal	11
10	Bagheri et al. (2010)	Hydraulic evaluation of the flow over polyhedral morning glory spillways	World Applied Sciences Journal	11

2. Based on the classification of the included studies, it was determined that the articles were published across 35 journals and 13 conference proceedings.
3. Several mechanisms were practiced to promote the hydraulic performance and investigate flow properties, like reformed inlet and vertical bend, testing various numbers and shapes of VBs, modifying the spillway boundaries, dealing with cavitation problems, and providing equations to predict Cd. Almost 39.4%, 30.3%, and 28.8% of the studies tried to improve spillway capacity by modifying the entrance shapes, deriving equations to estimate Cd, and applying VB, respectively.
4. Regarding crest control, the performance of the MGS spillway is commendable. However, as the H/D ratio increases and the flow condition transitions to pipe control, there is a significant decline in the Cd value, which exhibits a converse relationship with the (H/D) value.
5. The use of VB on the spillway crest has shown effective results in reducing vortex flow. Out of the available choices, utilizing six VB devices has been identified as the optimal solution, delivering superior performance and functionality.

6. The proximity of the spillway inlet to the reservoir boundaries is one of the reasons for producing asymmetric flow above the crest.
7. Using the ANN approach, we created a new correlation between *H/D* and Cd, achieving assessment parameters of 0.87 for R^2, 0.224 for RMSE, 0.166 for MAE, and 0.245 for MAPE.
8. In recent times, there has been extensive consideration given to the utilization of reliability-based design optimization approaches for achieving both safe and optimal design and operation of spillways.

Herein lie several research areas that necessitate further exploration, accompanied by recommendations for potential future studies:

1. Limited attention has been given in the existing literature to studying air entrainment in the MGS. Consequently, conducting additional research in this area would significantly contribute to our comprehension of the aeration mechanism involved in MGS structures.
2. Slug flow is an unfavorable occurrence that can occur within spillways, particularly in pressurized spillway tunnels where the flow does not emerge continuously. Instead, it discharges intermittently in a pulsating manner, leading to structural vibrations and instability. Consequently, it is strongly advised to conduct comprehensive studies on the phenomenon of slug flow and develop effective strategies for mitigating its destructive effects.
3. In recent literature, optimization approaches have been utilized to address the safe and optimal design and operation of various spillway types such as labyrinth, Ogee, and stepped spillways. However, there is a limited amount of research focusing on the application of optimization methods to MGS and other types of flow control structures.
4. Investigate and develop advanced two-phase flow models to accurately capture the complex interactions between air and water in MGS. Consider the effects of aeration, air–water interface dynamics, and the impact of entrained air on flow characteristics.

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Declarations

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