



Hydrodynamic behavior and cavitation-prone regions in spillways under varying discharge conditions

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Abstract

In the present study, the hydraulic characteristics of flow such as velocity, pressure, and cavitation index were investigated along the floor and sidewalls of the Nazlou dam spillway for discharges of 300 (minimum design discharge), 400, 600, 830 (10,000-year flood), 1000, 1200, 1400, 1600, 1800, 2000, and 2270 (Probable Maximum Flood) m³/s using FLOW-3D. The flow velocity significantly increases when passing over the crest spillway, and this increase continues gradually along the chute section of the spillway. Due to the steep slope of the chute section, the maximum flow velocity occurs in this region. Ultimately, upon entering the stilling basin, the dynamic energy of the flow is dissipated. Longitudinal pressure measurements along the spillway indicated a decrease in pressure from upstream to downstream, with the greatest pressure drop occurring at the end of the chute section. The maximum flow velocities corresponding to discharges of 300, 830, and 2270 m³/s were 34.25, 41.80, and 44.90 m/s, respectively each occurring at the downstream end of the chute. Similarly, the minimum flow pressures for the aforementioned discharges were recorded as 1.23, 1.52, and -5.9 kPa, respectively. An analysis of the cavitation index along the spillway floor revealed that for all inflow discharges, the chute section is susceptible to cavitation. However, the examination of the cavitation index along the sidewalls indicated that the sidewalls of the crest, chute, and the initial portions of the chute are safe from cavitation. In contrast, the cavitation index in the downstream end of the chute section falls below the critical threshold.

Keywords Spillway hydraulics · Cavitation assessment · Flow characteristics · Numerical simulation

Introduction

One of the most critical hydraulic issues threatening spillways is the phenomenon of cavitation, which occurs as a result of increased flow velocity and a corresponding decrease in pressure to levels below atmospheric pressure [24]. In high dam spillways, the increased flow velocity makes the system particularly susceptible to cavitation.

Any alteration in the channel geometry, surface roughness, curvature in the flow path, or the presence of construction joints along the spillway walls can lead to flow separation and localized pressure drops below the vapor pressure of water [8, 17]. Under such conditions, cavitation occurs as water transforms from liquid to vapor at ambient temperature, leading to the formation of vapor bubbles known as cavitation bubbles [7]. Cavitation results in surface erosion and degradation of the concrete, and if sustained, can cause severe structural damage. Notable examples of cavitation-induced damage include the severe deterioration of the Karun 1 Dam spillway in Iran in 1977, the Glen Canyon Dam spillway in the United States in 1983, the Hoover Dam spillway in 1941, and the sidewalls of the tunnel spillway of Zipingpu Dam in China. To evaluate the potential for cavitation, the dimensionless Cavitation Index, introduced by Falvey [12], is commonly used. According to this criterion, a cavitation index less than or equal to 0.2 indicates a high likelihood of cavitation, while values greater than

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0.2 suggest that the flow is unlikely to experience cavitation within the channel.

Chanson [3] investigated high-velocity supercritical flows in open channels. Using new experimental data collected from a 25 m long flume with a 4-degree slope, he studied the characteristics of air–water flows and the distribution of the air–water interfacial area. The results showed that even with a small amount of entrained air, the interfacial area between air and water could be significantly large. These findings emphasize the importance of air bubble entrainment in gas transfer processes between air and water in supercritical flows. Dargahi [9] conducted a three-dimensional simulation of flow over a crest spillway using Fluent software. He investigated the free surface profile and velocity distributions by applying various turbulence models and wall functions. His results demonstrated good agreement between key flow parameters and experimental data, however, this agreement was highly dependent on the mesh size, turbulence model, wall function, and Reynolds number. The study confirmed the importance of using finer meshes near the walls in spillway simulations. The RNG- $k-\epsilon$ turbulence model provided more accurate predictions of velocity fields near the walls compared to other models. Nonetheless, the appropriate selection of wall functions for solid boundaries was found to be even more critical than the choice of turbulence model. Overall, free surface elevations were predicted with an error margin between 1.5% and 2.9% relative to experimental measurements across various spillway heads. Dong et al. [10] investigated the effects of air entrainment on flow conditions and cavitation damage mitigation. Their experiments were conducted in a water tunnel consisting of four consecutive sections: the aeration section, contraction section, observation section, and diffusion section. The introduction of air into the flow increased pressure in the cavitation zone (observation section). Results indicated that aeration led to a significant increase in pressure within the cavitation region. Furthermore, comparisons of pressure waveforms generated by collapsing cavitation bubbles under both aerated and non-aerated conditions showed that air entrainment significantly reduced the intensity of pressure waves. Ruan et al. [23] examined the effects of air entrainment in the tunnel spillway of the Goupitan Project based on gravitational similarity criteria and flow velocity conditions exceeding 6 m/s. Their findings showed that aerators producing higher air concentrations downstream could effectively protect the tunnel spillway from cavitation damage. Pfister and Hager [21] conducted laboratory experiments to investigate the characteristics of aerated flows, including air concentration profiles. The downstream flow conditions following aeration were categorized into three regions: the jet region, the impact point, and the downstream region beyond the impact. They reported air concentration

values at the flow surface, average air concentration, and bottom air concentration for each of the three regions. Results showed that air concentration on the spillway bottom reached its maximum near the jet region and persisted until the point of impact, beyond which it began to decline. A strong aeration gradient was also observed at the jet impact location on the spillway bottom. Pfister et al. [22], using a hydraulic model, studied the effects of air concentration introduced by an aeration ramp on various flow parameters. The average inflow air concentration ranged from 0.04 to 0.25, while average air concentration for uniform flow was between 0.18 and 0.23. Results showed that an increase in the average inflow concentration caused a slight reduction in the aeration coefficient, although the overall impact was minimal. At the beginning of the aeration region (end of the ramp), the mean concentration exceeded the initial inflow concentration. Furthermore, as the inflow air concentration increased, the overall average air concentration increased accordingly. Conversely, the bottom air concentration of the flow decreased with increasing inflow air concentration. Pfister [20] investigated variations in the hydraulic characteristics of two-phase flows, focusing on parameters such as aeration coefficient, jet length, and the distribution of air concentration under the influence of two key factors: the deflector angle and sub-pressure inside the cavity. The results indicated that deflectors with steeper slopes performed more effectively in entraining air into the flow, as higher slopes led to increased air intake. However, their effect on air concentration was relatively minor. Furthermore, increasing the sub-pressure inside the cavity resulted in reductions in both jet length and the aeration coefficient. It also caused a decrease in the bottom air concentration on the spillway. Zhenwei et al. [25] conducted a simulation of flow over a spillway under flood level conditions using Fluent software to evaluate the designed flood level. The numerical results for flow depth, pressure, and velocity along the spillway showed good agreement with experimental data, with a discrepancy of less than 6% in average velocity between numerical and experimental values. Eghbalzadeh and Javan [11] performed a numerical comparison between the VOF and Mixture models for simulating two-phase flows. The study, conducted in Fluent, simulated flow over a stepped spillway, focusing on the water surface profile and air entrainment into the flow. The results were compared with experimental data from Chen et al. [4]. It was found that the Mixture model provided more accurate predictions of the water surface and entrained air volume compared to the VOF model. Kermani et al. [18] examined potential cavitation-prone regions on the spillway of Karun 1 Dam using a hydraulic model. Two parameters flow velocity and cavitation index were used to identify five critical zones susceptible to cavitation damage. Their

Fig. 1 Aerial image of Nazlou reservoir dam lake



Table 1 Characteristics of the Nazlou reservoir dam

Type of dam	Soil with a clay core
Dam threshold level	1502 m above sea level
River bed level	1400 m above sea level
Height of the dam from the riverbed	100 m
Dam threshold length	430 m
Dam threshold width	12 m
Width of the base of the largest dam section	460 m

findings showed that as flow velocity increases along the spillway, the likelihood of damage rises in sections closer to the downstream end. Chakib [2] numerically investigated the initiation point of natural air entrainment from the water surface over a stepped spillway. Several candidate locations for the onset of natural aeration were assessed and compared with experimental results and theoretical models. The study also analyzed surface air entrainment points under varying discharge conditions. The results indicated that with increasing discharge, the initiation point of surface aeration shifted further downstream. For a discharge of $0.82 \text{ m}^3/\text{s}$, no aeration occurred on the spillway steps, and air entrainment was only observed in the stilling basin. Furthermore, air entrainment into the flow reduced wall friction and increased flow velocity. Chinnarasri et al. [5] investigated the hydraulic and turbulence characteristics of flow over both smooth and stepped spillways. The VOF method was used for capturing the free surface, and the RNG turbulence model was employed for simulating turbulent flow. The results demonstrated that velocity profiles in both types of spillways were in good agreement with experimental data. The highest deviation in velocity distribution occurred in the chute spillway, with a maximum error of 17%. The turbulence

intensity analysis indicated that the highest turbulence levels occurred near the spillway bottom in the chute configuration. Luna-Bahena et al. [19] conducted laboratory experiments to measure air entrainment into the flow in two configurations of bottom-aerated spillways: one with a base structure and one without. Their findings showed that the spillway model with a base entrained more air than the model without one. This increase was attributed to wave formation downstream of the base, which facilitated air entry into the flow and helped reduce cavitation. In the base-structured spillway, air concentration was found to be non-uniform across the flow section, with higher concentrations near the sidewalls compared to the spillway center. Jamali and Manafpour (2019) investigated the occurrence of cavitation in the bottom outlet of the Simereh Dam using FLOW-3D software. Their results indicated that the cavitation index values along the channel bed from section X=41 m to the end of the channel were below the critical value of 0.2 for gate openings of 10%, 20%, 30%, 40%, and 80%. Additionally, the channel walls at section X=41 m experienced cavitation for all openings except the 100% case, and at section X=42 m, cavitation occurred for all gate openings. Ghazi et al. [15] conducted a three-dimensional numerical simulation of the Shahid Madani Dam spillway using FLOW-3D to investigate the potential occurrence of cavitation. The study indicated that the cavitation number remained above the critical threshold under all investigated discharge conditions, suggesting that cavitation is unlikely to occur in the spillway. Jamali et al. [16] conducted a numerical study on the effect of the sidewall divergence angle on the cavitation index in supercritical flows. Their findings showed that cavitation did not occur for divergence angles between 0° and 10° at Froude numbers less than

Table 2 Characteristics of the dam spillway

Type of spillway	Free ogee spillway
Spillway equation	$Y=0.1015X^{1.536}$
Spillway threshold level	1492 m above sea level
The level of the channel bed overlooking the spillway	1486 m above sea level
Height behind the spillway	6 m
Gross length of threshold	42 m
Net length of the threshold	40 m
Horizontal length of the spillway from the back to the beginning of the arch	9.51 m
The level of the beginning of the arch	1489.27 m above sea level
Radius and angle of the arch	24.30 m and 35.81 degrees
Arch end alignment	1483.70 m above sea level
Horizontal length of the arch	13.86 m

Table 3 Characteristics of dam chute

First alignment	1483.70 m above sea level
Width of the first alignment	42 m
End width	30 m
Longitudinal slope	4 and 32 degree
Horizontal length of the first inclined surface	129.87 m
Arch radius and angle	100 m and 28 degrees
Horizontal length of the arch	46.02 m
Arch edge alignment	1461.06 m above sea level
Horizontal length of the slope	104.11 m

Table 4 Characteristics of dam stilling basin

Bed level	1396 m above sea level
Length	43 m
Width	30 m
The slope at the end of the stilling basin	1–3 horizontal height

4.49. However, for divergence angles greater than 6° and Froude numbers exceeding 14, the cavitation index dropped below the critical value of 0.2. Furthermore, the results suggested that no wall divergence should be applied for Froude numbers greater than 17.5.

Due to the growing need for surface water storage for various purposes, the construction of high dams has significantly increased. Spillways, as key hydraulic structures associated with dams, are responsible for safely conveying water from the upstream to the downstream. A review of the literature indicates that cavitation is one of the most critical challenges facing spillways and has caused substantial damage to dam infrastructure. Therefore, to mitigate this phenomenon and achieve efficient designs for future spillways, a comprehensive understanding of flow patterns particularly flow velocity and pressure fields is essential to

prevent cavitation and propose effective solutions when it does occur. The main contribution of this study lies in the comprehensive numerical investigation of cavitation-prone regions along both the spillway floor and sidewalls of the Nazlou Dam spillway under a wide range of inflow discharges, ranging from the minimum design discharge to the Probable Maximum Flood (PMF) condition. Unlike previous studies that have primarily focused on flow characteristics or cavitation assessment limited to the spillway floor, the present work simultaneously evaluates the flow velocity, pressure distribution, and cavitation index along both the floor and sidewalls of the spillway. Another important contribution of this research is the identification of the precise locations and longitudinal extents of cavitation-prone zones under different discharge conditions using FLOW-3D numerical simulations. Furthermore, the study provides practical recommendations for cavitation mitigation through the implementation of aeration systems in critical regions of the spillway.

Materials and methods

Nazlou dam

The Nazlou reservoir dam is located in the northwest of Urmia city, within West Azerbaijan Province in Iran, and has been constructed on the Nazlouchay River. The river is formed from three main tributaries: The Bardok, Sarow, and Marmisho Rivers. Among these, the Bardok River (a tributary of the Gonbad River) receives almost all of its flow from within Iranian territory. In contrast, a significant portion of the Sarow River originates from its headwaters located in Turkey. The objective of the project is the optimal utilization of water and land resources in the region through the regulation and control of the Nazlouchay river's flow. The regulated water is intended to be used for irrigating approximately 43,100 hectares of farmland in the plains of Nazlou, Rowzeh, Kahriz, and Northern Anzal. Additionally, it aims to partially supply industrial water demands of the industrial zones in the Urmia plain, provide part of the domestic water needs of nearby cities, prevent flood damages, and meet environmental water requirements. The qualitative objective of the project is to improve the economic and social conditions in the northern part of the Urmia plain. Figure 1 illustrates the reservoir area of the Nazlouchay dam, and Table 1 presents the technical specifications of the dam.

Nazlou dam spillway

The flood discharge system of the dam comprises an approach channel, an ogee spillway, a converging chute,

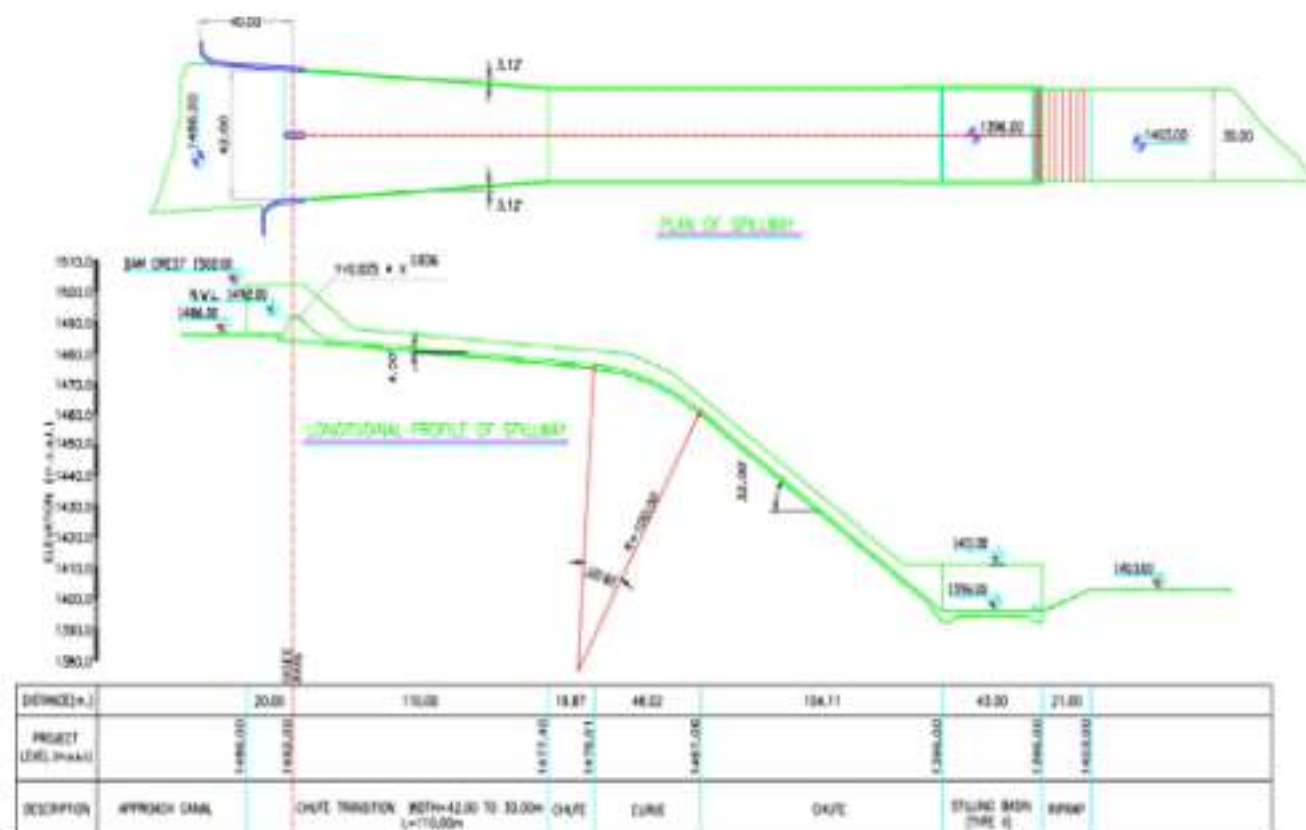


Fig. 2 Plan and profile of the Nazlou dam

and an energy dissipation basin, all located on the right abutment of the dam body. The spillway control section is an ogee-shaped structure with a crest elevation of 1492 m above sea level. The effective length of the spillway is 40 m. The upstream face of the ogee is designed using circular arcs with radii of 4.75 and 1.5 m, while the downstream face follows a parabolic profile defined by the equation $Y=0.1015X^{1.076}$, in accordance with internationally recommended standards. A slope of 3 vertical to 1 horizontal connects the upstream ellipse of the ogee to the approach channel. At a distance of 6 m downstream from the parabolic profile, a circular arc with a radius of 24.3 m and a central angle of 35.81 degrees links the ogee crest to the chute channel. This arc begins at an elevation of 1498.27 m above sea level. To accommodate a bridge over the spillway, a 2 m wide central pier has been designed along the longitudinal axis of the spillway. Consequently, the gross length of the spillway is 42 m. Full technical details of the spillway, along with its plan and profile, are provided in Tables 2, 3, 4 and Fig. 2, respectively.

Physical model components

A 1:40 scale physical model of the Nazlou dam reservoir spillway system was constructed at the Water Research

Institute of the Iranian Ministry of Energy for the purpose of evaluating the structure's performance (Fig. 3) [1]. The main objective of developing this hydraulic model was to optimize and enhance the flood discharge system's performance. Mathematical analyses combined with existing experience are not always sufficient to provide complete and reliable information to ensure the correct operation of an expensive hydraulic structure. Therefore, hydraulic modeling studies can be useful for gaining further insight into the real-world behavior of the structure. Under suitable conditions, results obtained from a scaled hydraulic model can be generalized to the prototype. The use of physical models is highly effective due to their ability to simulate the three-dimensional geometry of the studied environment, enabling direct observation and measurement of flow parameters such as depth, velocity, and pressure. This allows for efficient and timely optimization and improvement of the proposed design. The dimensions of the upstream reservoir in the model are 7.50 m in width, 7.60 m in length, and 3.50 m in height. The topography, inlet channel, guide walls on both sides of the inlet, and a longitudinal section of the dam body on the left side of the spillway were constructed using building materials. The extent of the constructed model is shown in Fig. 3b. The inlet channel was made from building materials with a smooth cement coating, the guide walls were



Fig. 3 Hydraulic model of the Nazlou dam



Fig. 3 (continued)

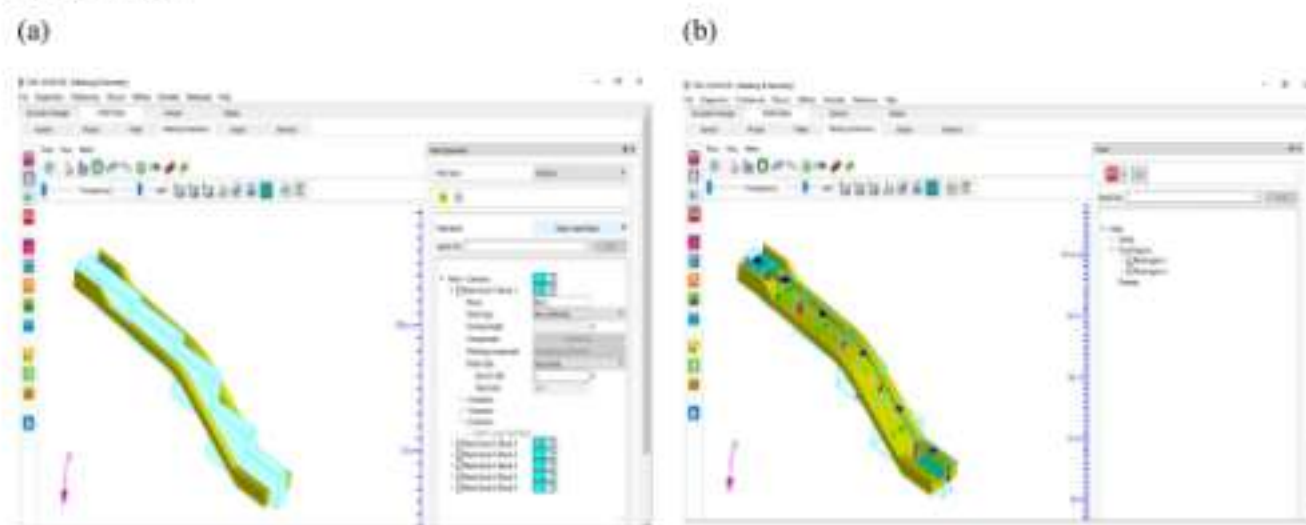


Fig. 4 a Meshing the model. b Defining boundary and initial conditions for the model

constructed from wood and painted with oil-based paint, and the reservoir topography and dam slope were modeled using rough cement. An overview of the inlet channel in the model is depicted in Fig. 3c, while a general view of the spillway is shown in Fig. 3d. The chute and its sidewalls were constructed from transparent Plexiglas, as illustrated in Fig. 3e. The stilling basin was also built using transparent Plexiglas, while the energy dissipating blocks were made from wood coated with oil-based paint. Images of the stilling basin are shown in Fig. 3f, and an overall view of the reservoir is presented in Fig. 3g.

Governing equations

One of the powerful software tools in the field of fluid mechanics based on the finite volume method is FLOW-3D. This software discretizes the continuity and Navier–Stokes equations to perform three-dimensional simulations of fluid

motion. The continuity equation, or mass conservation equation, for a fluid flow is expressed as follows (Flow Science Inc., 2016):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

In this equation, u_i is the component of the velocity vector in the i direction. The software solves the Navier–Stokes equations for three-dimensional flow analysis using the finite volume method on a discretized grid. The equations are derived in Cartesian coordinates as follows [13, 14]:

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u A_x) + \frac{\partial}{\partial y} (\rho v A_y) + \frac{\partial}{\partial z} (\rho w A_z) = R_{SDR} + R_{DRF} \quad (2)$$

$$\frac{\partial u}{\partial t} + \frac{1}{V_F} \left(u A_x \frac{\partial u}{\partial x} + v A_y \frac{\partial u}{\partial y} + w A_z \frac{\partial u}{\partial z} \right) = -\frac{1}{\rho} \frac{\partial P}{\partial x} + G_x + f_x \quad (3)$$

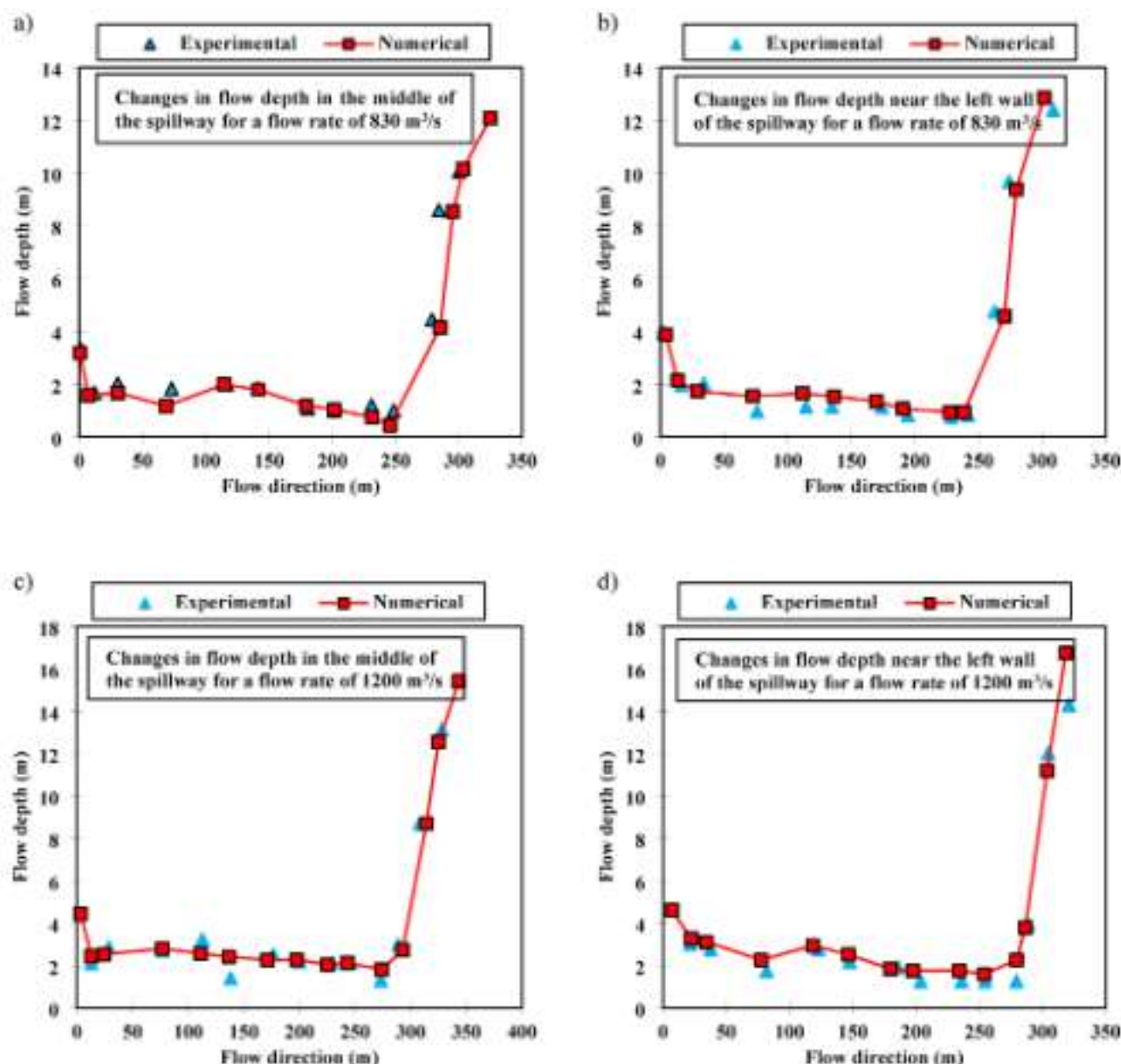


Fig. 5 Verification of flow depth changes in the middle and near the left wall of the spillway at different discharges

$$\frac{\partial v}{\partial t} + \frac{1}{V_F} \left(u A_x \frac{\partial v}{\partial x} + v A_y \frac{\partial v}{\partial y} + w A_z \frac{\partial v}{\partial z} \right) = -\frac{1}{\rho} \frac{\partial P}{\partial y} + G_y + f_y \quad (4)$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F} \left(u A_x \frac{\partial w}{\partial x} + v A_y \frac{\partial w}{\partial y} + w A_z \frac{\partial w}{\partial z} \right) = -\frac{1}{\rho} \frac{\partial P}{\partial z} + G_z + f_z \quad (5)$$

In the above equations, u , v and w are the velocity components, A_x , A_y and A_z are the area fractions associated with the flow, G_x , G_y and G_z are the body accelerations, f_x , f_y and f_z are the viscous forces in the x , y and z directions, respectively. R_{SOR} is the source term of mass, R_{DIF} is the turbulent diffusion term, V_F is the volume fraction of the fluid,

and P represents the pressure. This equation, in general, is expressed as Eq. (6).

$$\rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_i} + B_i + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] \quad (6)$$

In the above equations, B_i represents the body force in the i direction, μ is the fluid's dynamic viscosity, and ρ is the density of water. x_i , x_j and x_k represent the flow's spatial coordinates in the i , j , and k directions, respectively. Additionally, δ_{ij} is the Kronecker delta, which equals 1 when

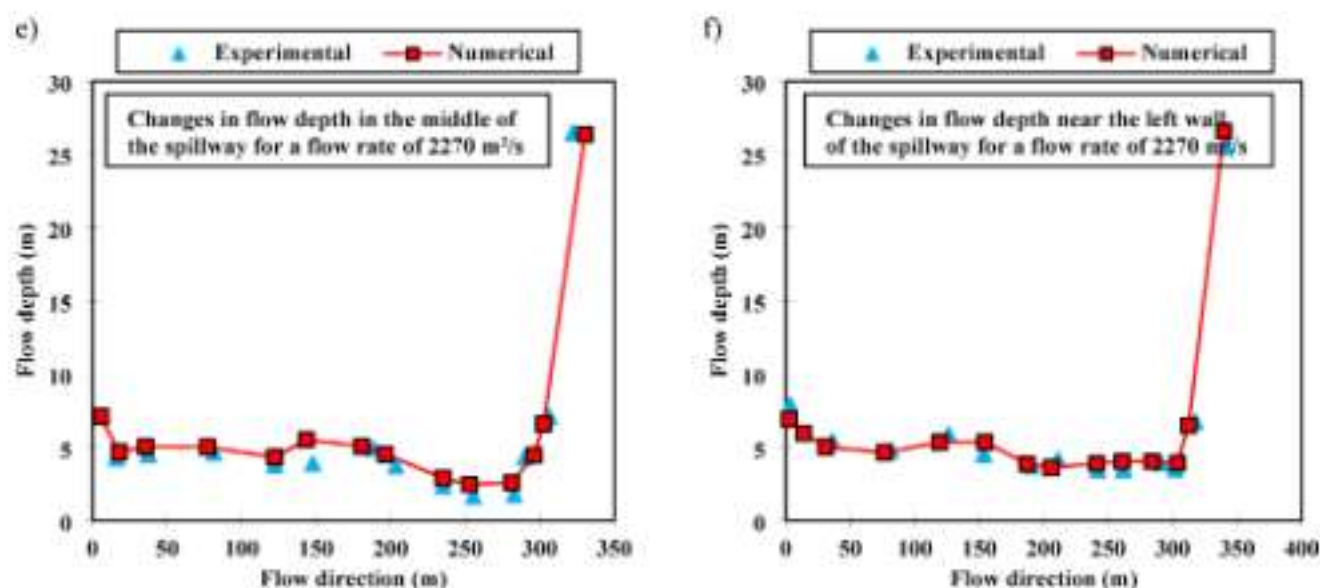


Fig. 5 (continued)

$i=j$ and equals 0 otherwise [6]. The fluid is assumed to be incompressible, meaning that its density remains constant throughout the flow field and does not vary with pressure or temperature changes within the scope of the present analysis.

Model geometry, mesh generation, and boundary conditions

In the present study, based on the dimensions of the spillway, four different mesh sizes were chosen, and through mesh sensitivity analysis, the optimal mesh was selected. The method of applying the computational grid in each direction and other mesh generation details are shown in Fig. 4a. In this research, due to the creation of several Mesh Blocks, the common face between two mesh blocks is defined as Symmetry. For the inlet flow, the boundary condition of volume flow rate was applied, and to examine the hydraulic parameters of the flow in each simulation, the inlet flow rate was introduced to the software. For the outlet section of the channel, the Outflow boundary condition was applied. For the walls and floor of the mesh, which represent the walls and floor of the channel, the Wall boundary condition was used. For the Z max boundary, the Symmetry boundary condition was applied Fig. 4b. In this study, the RNG turbulence model was selected for simulating the models investigated in this research. The reasons for choosing this model include its reliability in responding to various issues, its accuracy in solving the equations, its high precision in depicting flow details, and its alignment with previous studies.

Results and discussions

Model validation

The first step in a numerical model for extracting results is model calibration. This means minimizing the effects of external factors and ensuring that the numerical model conditions are as close as possible to the laboratory or real-world conditions. In order to ensure the validity of the numerical model's calculations, the results obtained from the numerical model should be compared with the laboratory results. If the error is within an acceptable range, the numerical model results can be considered reliable. After accounting for various conditions, the results from the numerical model were compared with the available laboratory model results. If a reasonable discrepancy is found, the model is considered calibrated, and its results can be utilized. In the present study, to validate the numerical model, the depth and velocity of the flow at the center and near the left wall of the spillway at flow rates of 830, 1200, and 2270 m³/s extracted from the hydraulic model tests of the Nazlou dam spillway were used. Figure 5 shows the trend of flow depth changes at the center and near the left wall of the spillway, and Fig. 6 shows the trend of flow velocity changes at the center and near the left wall of the spillway for the mentioned flow rates.

After validating the results of the numerical model, the study proceeds to investigate the hydraulic characteristics of the flow, including velocity profiles, pressure, and cavitation index on the floor (at the center of the channel along the longitudinal direction) and on the spillway walls at different cross-sections for the input flow rates of 300 (the

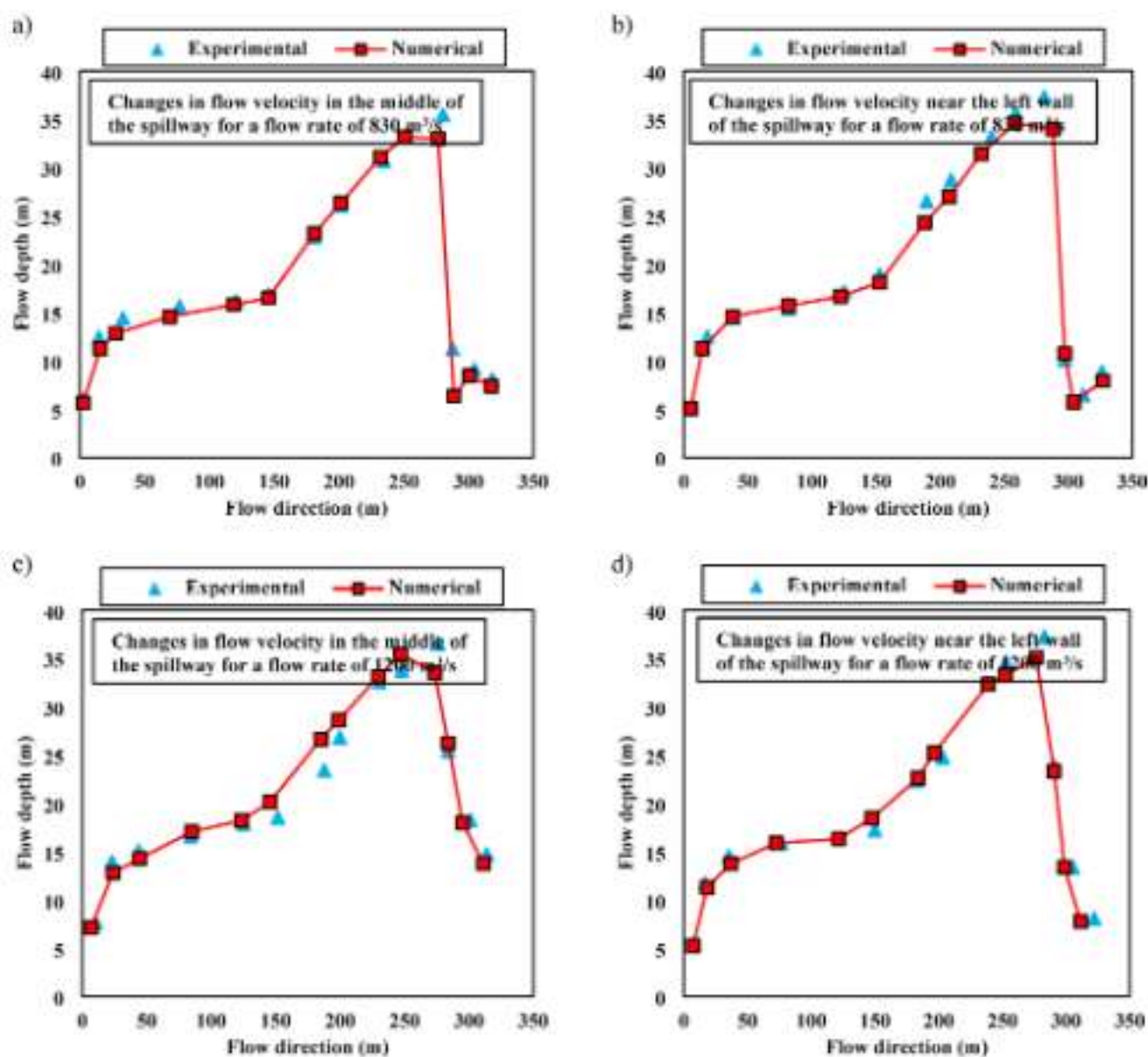


Fig. 6 Verification of flow velocity changes in the middle and near the left wall of the spillway at different discharges

lowest design flow rate), 400, 600, 830 (flood discharge of 10,000 years), 1000, 1200, 1400, 1600, 1800, 2000, and 2270 (maximum probable flood discharge, P.M.F) m³/s. Finally, for the conditions likely to cause cavitation, appropriate prevention measures are proposed.

Investigation of flow velocity variations along the longitudinal direction of the spillway for different input flow rates

Figure 7 shows the flow velocity profiles for input flow rates of 300, 400, 600, and 830 m³/s at the center of the spillway along the longitudinal direction of the flow. The results indicate that as the flow moves from upstream to downstream

of the spillway, the static energy of the flow is converted into dynamic energy, and the flow velocity increases. Specifically, the flow velocity in the channel inlet Sect. (0–40 m from the spillway crest) is uniform due to the constant slope, then as it passes over the ogee spillway (40–65 m from the spillway crest), the velocity increases sharply due to the increasing slope of the spillway floor. As the flow enters the chute Sect. (60–200 m from the spillway inlet), the flow velocity increases gradually with a mild slope. Upon entering the steep water Sect. (200–320 m from the spillway inlet), the velocity increases sharply due to the steep slope of the chute. Finally, as the flow enters the stilling basin (320–380 m from the spillway inlet), the dynamic energy of the flow is dissipated, and the flow velocity decreases.

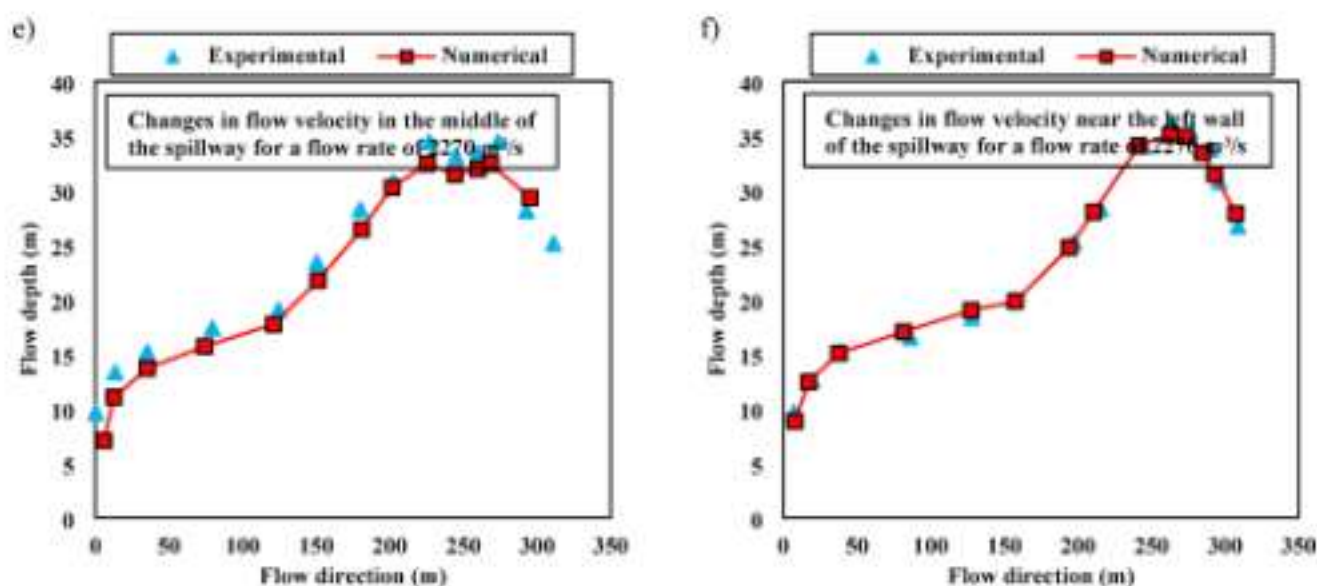
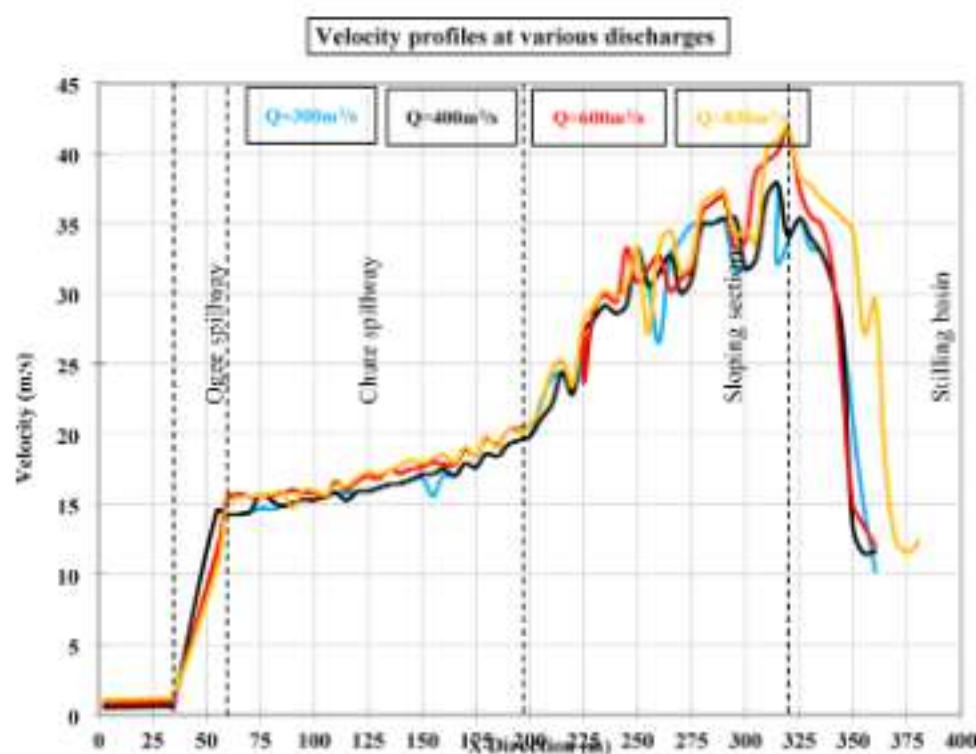


Fig. 6 (continued)

Fig. 7 Flow velocity profiles along the spillway for different discharges



By comparing the values of flow velocity for different input flow rates, it was observed that for a flow rate of $300 \text{ m}^3/\text{s}$, the flow velocity at the channel inlet is 0.52 m/s . This value increased to 0.58 m/s , 0.85 m/s , and 1.07 m/s for flow rates of 400 , 600 , and $830 \text{ m}^3/\text{s}$, respectively. As the flow passes over the ogee spillway, the velocity increases to 14.49 m/s , 14.73 m/s , 15.38 m/s , and 15.52 m/s , respectively. In the chute section, the flow velocity continues to rise, reaching 19.81 m/s , 19.92 m/s , 20.32 m/s , and 20.58 m/s . The steep

water section, which has the highest channel slope, shows the maximum flow velocities. For the mentioned flow rates, the flow velocities are 34.25 m/s , 35.2 m/s , 38.42 m/s , and 41.80 m/s , respectively. Finally, in the stilling basin, the dynamic energy of the flow is dissipated, and the flow velocity decreases to values ranging between 10.22 m/s and 11.58 m/s .

In Fig. 8, by examining the flow velocity values for input flow rates of 1000 , 1200 , 1400 , and $1600 \text{ m}^3/\text{s}$ along the

Fig. 8 Flow velocity profiles along the spillway for different discharges

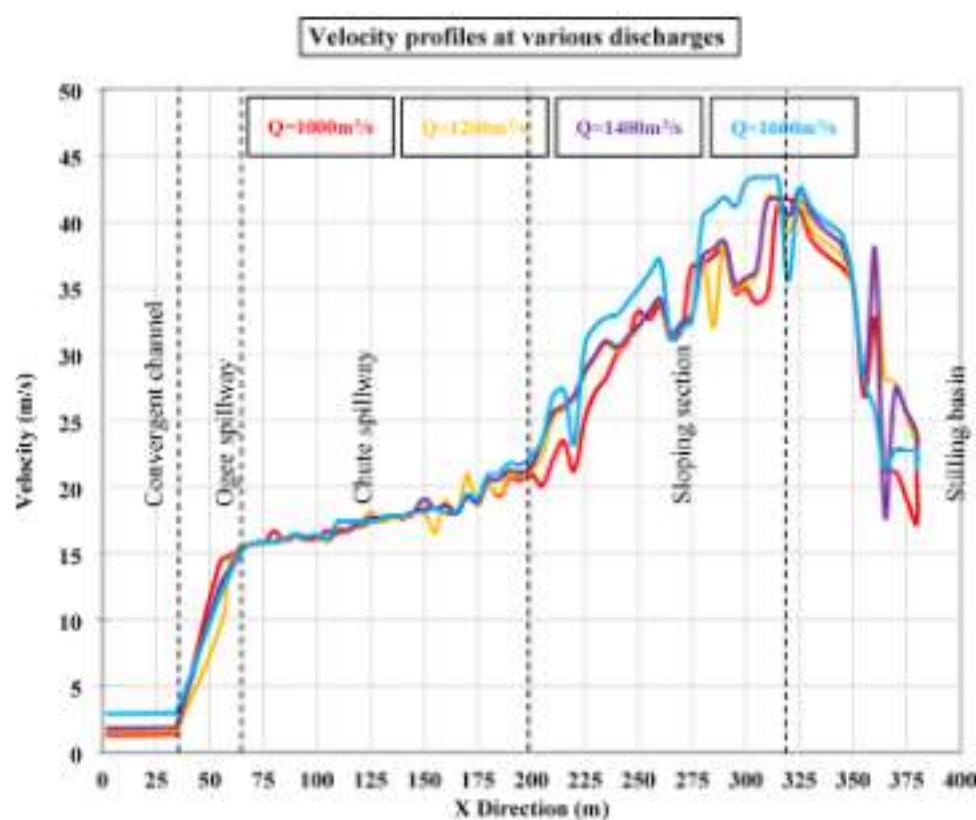
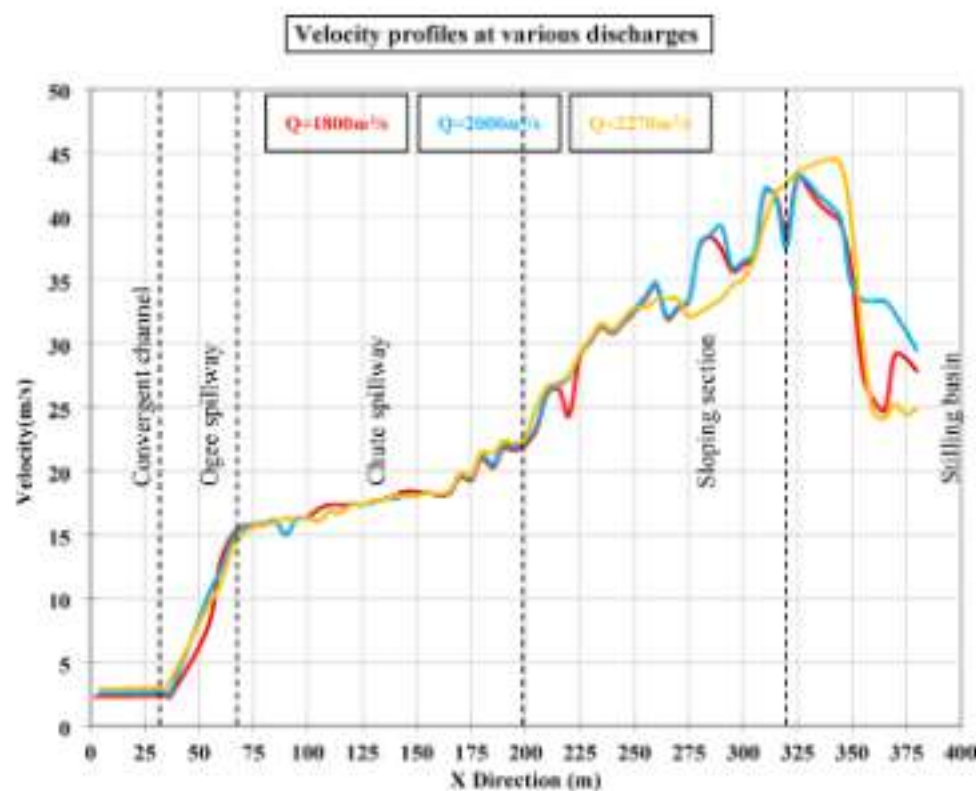


Fig. 9 Flow velocity profiles along the spillway for different discharges



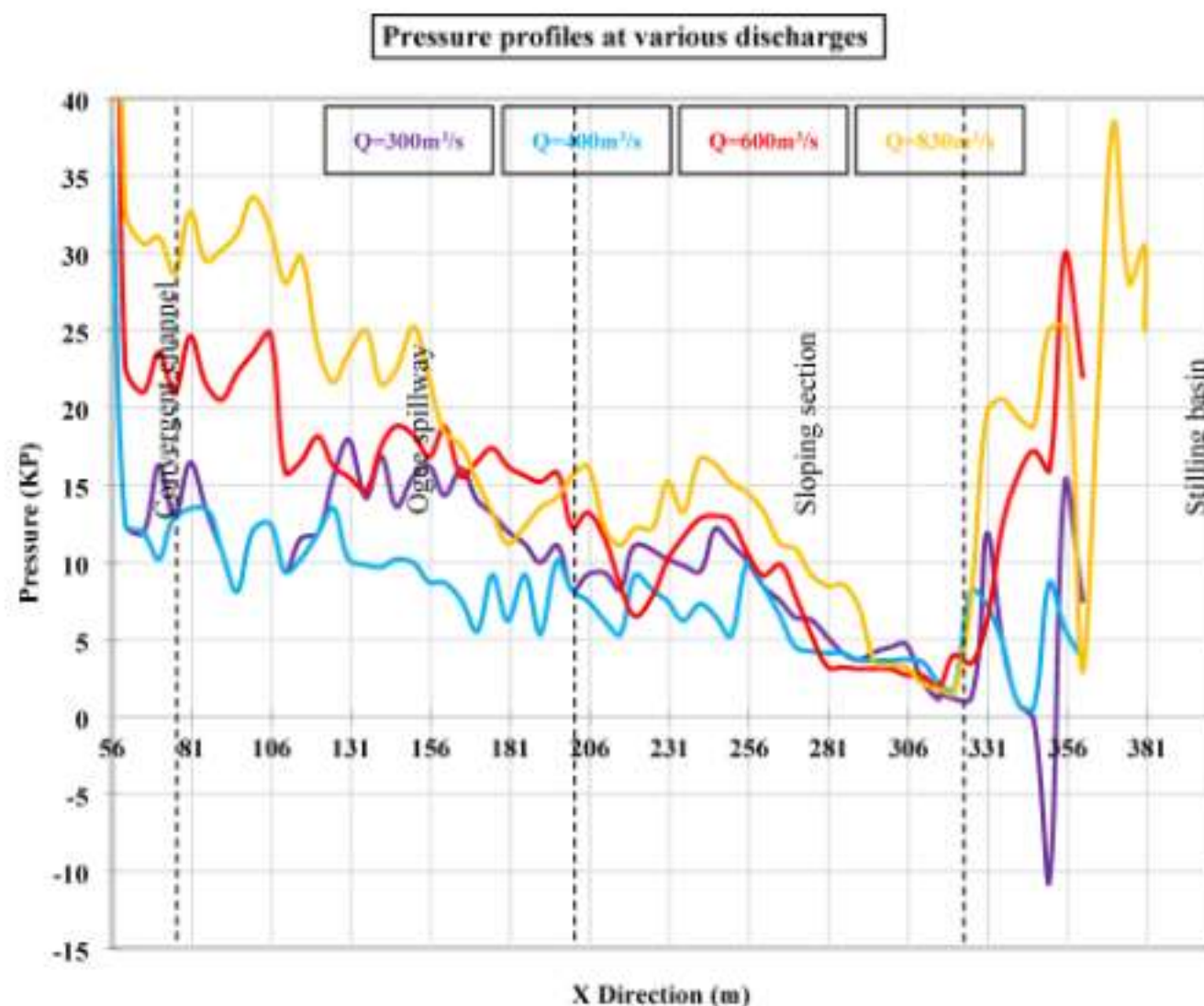


Fig. 10 Flow pressure profiles along the spillway for different discharges

longitudinal direction of the spillway, it was observed that the velocity in the converging channel section ranged from 1.29 to 2.93 m/s. As the flow rate increased, the flow velocity also increased. In the ogee spillway section, the flow velocity values for the mentioned flow rates were 15.65 m/s, 15.80 m/s, 15.91 m/s, and 16.10 m/s, respectively. Furthermore, in the chute spillway section, the flow velocity continued to increase, reaching values of 20.99 m/s, 21.26 m/s, 21.64 m/s, and 22.39 m/s. In the steep water section, where the maximum flow velocity occurs, the flow velocity values reached 41.69 m/s, 41.90 m/s, 42.49 m/s, and 43.35 m/s, respectively. Finally, in the stilling basin section, the flow velocity decreased and ranged between 17.21 m/s and 21.4 m/s.

The analysis of flow velocity results in Fig. 9 for input flow rates of 1800, 2000, and 2270 m³/s along the longitudinal direction of the spillway showed that the maximum

value of this parameter occurred at a flow rate of 2270 m³/s in the steep water section. According to the results obtained, the flow velocity in the converging channel section for the mentioned flow rates ranged between 2.35 m/s and 3.01 m/s. Then, as the flow entered the ogee section, the velocity increased, reaching values of 16.12 m/s, 16.16 m/s, and 16.28 m/s, respectively. In the chute spillway section, the flow velocity continued to increase at a gentler slope compared to the steep water and ogee sections, reaching values of 22.12 m/s, 23.48 m/s, and 24.97 m/s. The steep water section, which has a steeper bed slope compared to other areas and is longer, exhibited the maximum flow velocity, with flow velocity values of 43.22 m/s, 44.16 m/s, and 44.90 m/s at the end of the steep water section. Finally, as the water entered the stilling basin, the flow velocity decreased, reaching values of 20.20 m/s, 23.10 m/s, and 24.89 m/s, respectively.

Fig. 11 Flow pressure profiles along the spillway for different discharges

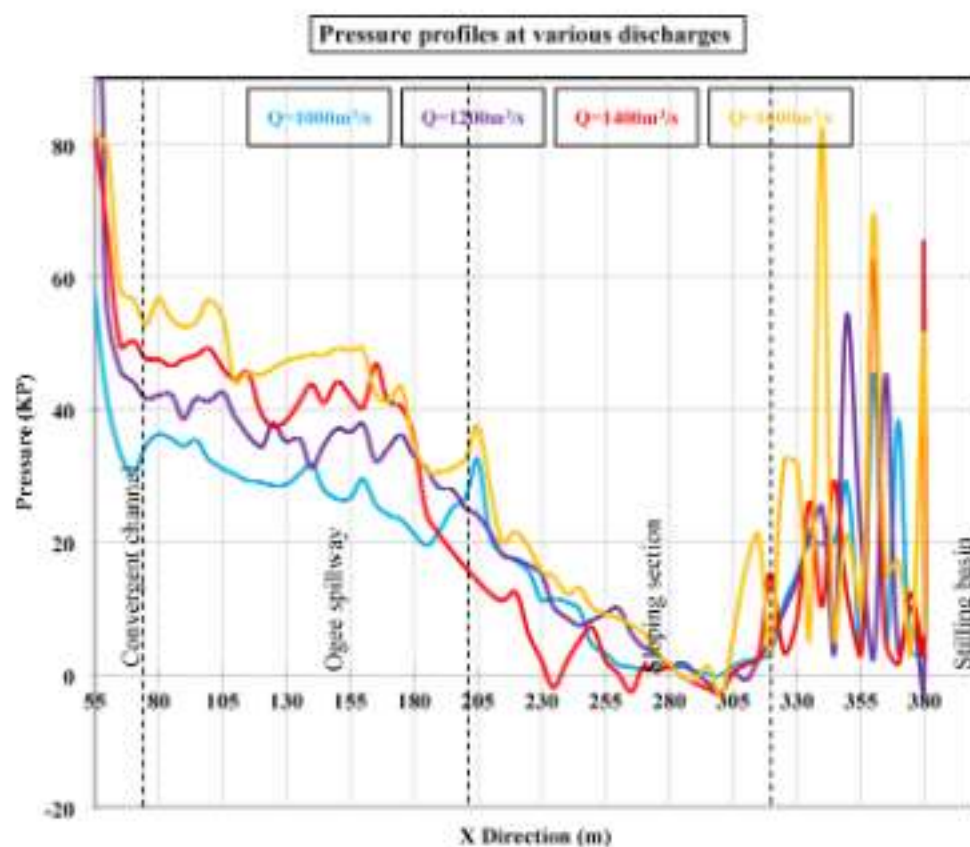
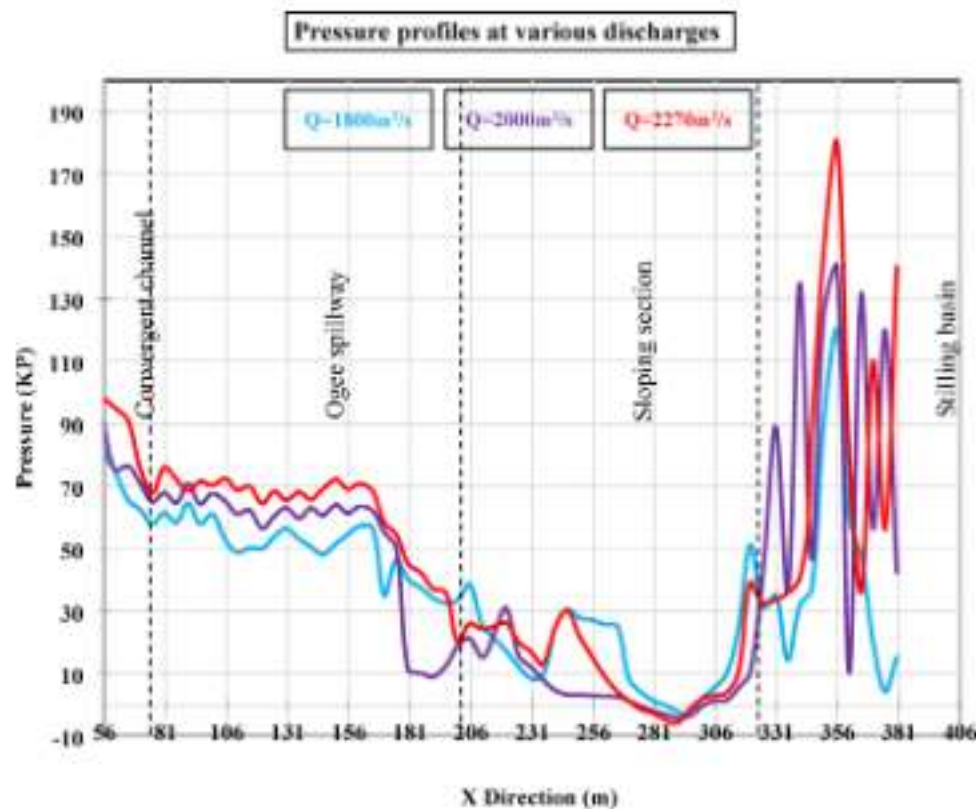


Fig. 12 Flow pressure profiles along the spillway for different discharges



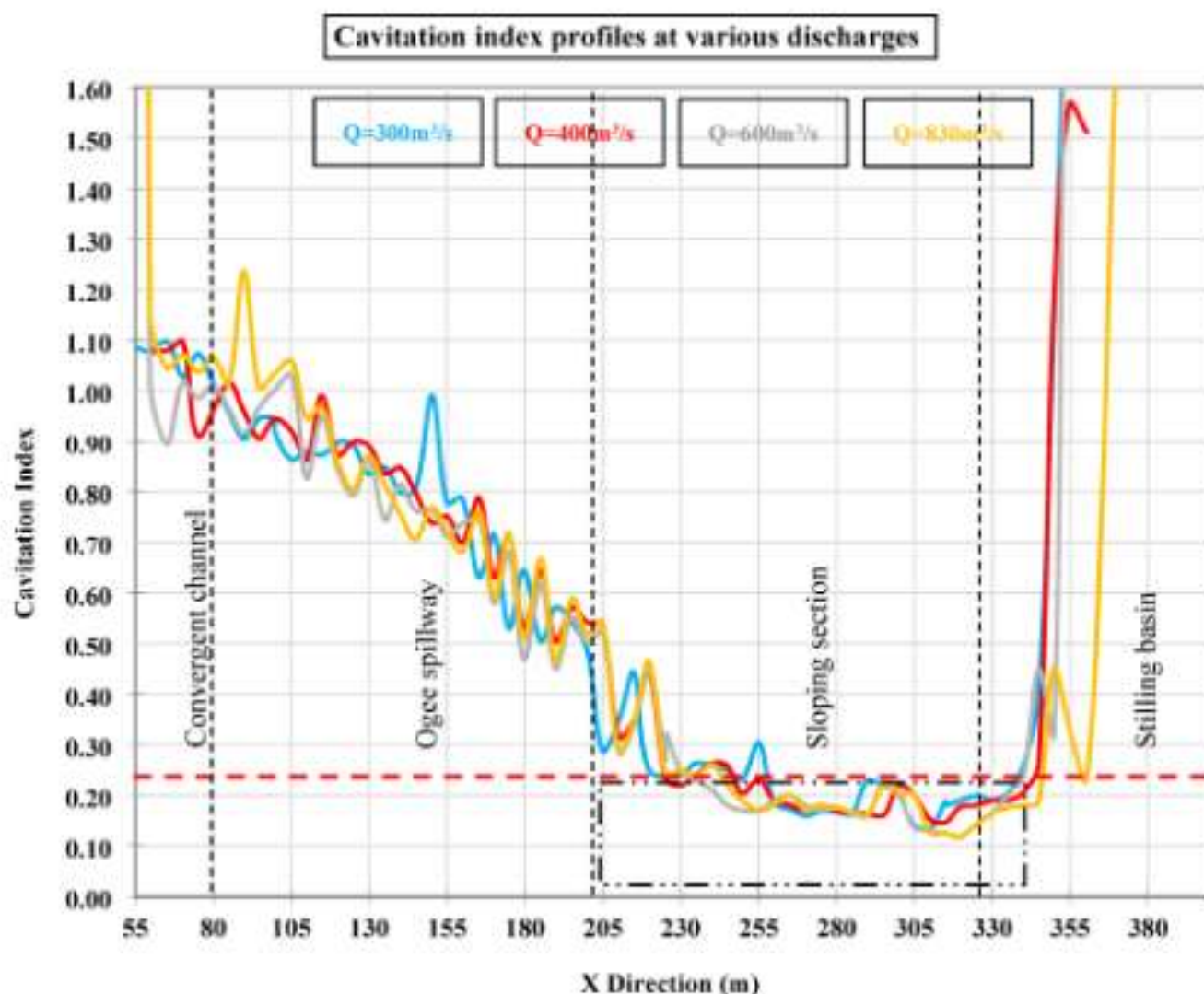


Fig. 13 Cavitation index profiles along the spillway longitudinal direction for different discharges

Since the obtained flow velocity values in the steep water section exceed 30 m/s, the occurrence of cavitation in this section is likely. Therefore, it is essential to examine the pressure values of the flow along the channel to predict the occurrence of cavitation.

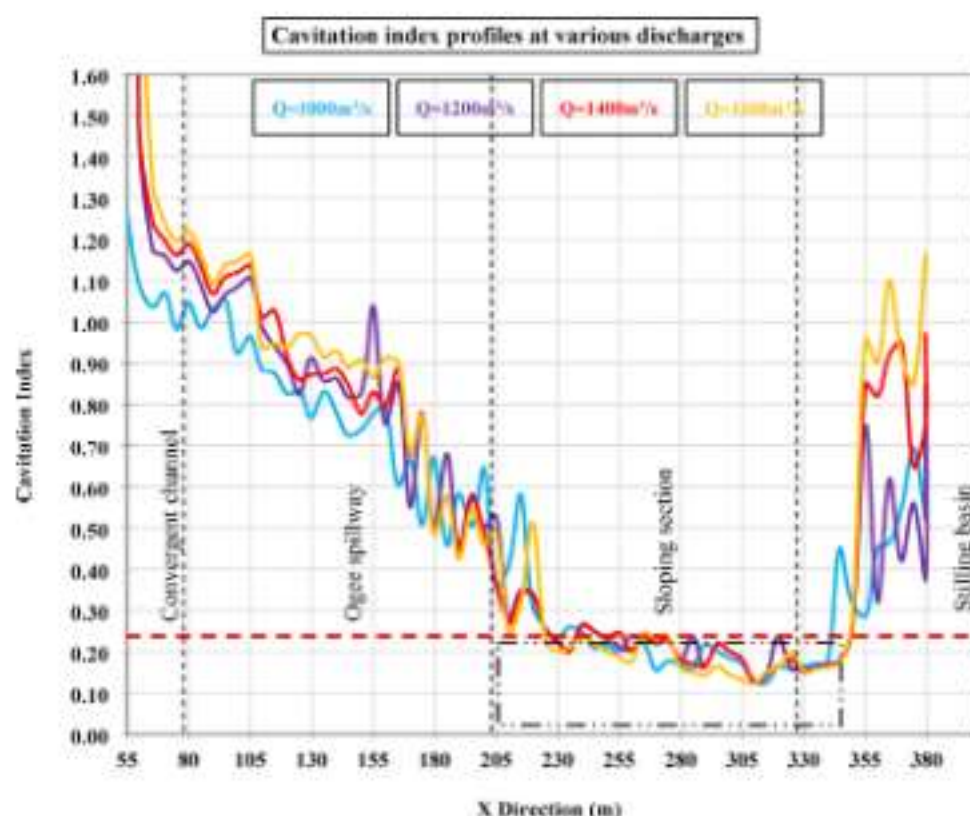
Examination of pressure variation along the spillway for different inflow discharges

The results obtained for the pressure values on the spillway floor along the longitudinal direction showed that, in general, as the flow moves downstream from the spillway, the pressure decreases. Additionally, as the flow enters the stilling basin, due to the high turbulence of the flow, the pressure experiences more fluctuations. As shown in Fig. 10, as the flow moves from the ogee spillway towards the end of the stilling basin, the pressure values for inflows of 300, 400, 600, and 830 m³/s decrease from 38.5 to 1.23, 38.20 to 1.72,

63.80 to 1.89, and 77.25 to 1.52 kPa, respectively. Furthermore, inside the stilling basin, the minimum and maximum pressure values were obtained as −10.63 kPa for a discharge of 300 m³/s and 38.50 kPa for a discharge of 830 m³/s.

The results obtained for flow pressure for inflows of 1000, 1200, 1400, and 1600 m³/s, shown in Fig. 11, indicated that in areas where flow velocity and consequently flow turbulence are lower, the flow pressure is predominantly hydrostatic. As the discharge increases, the flow depth also increases, and consequently, the flow pressure increases, which can be observed in the ogee spillway and chute spillway sections. However, with the increase in flow velocity and turbulence, particularly in the stilling basin and the chute section, the pressure fluctuations become more pronounced, and a parameter called dynamic pressure becomes involved in determining the trend of this parameter. The results showed that the maximum and minimum values of this parameter from the ogee spillway to the end

Fig. 14 Cavitation index profiles along the spillway longitudinal direction for different discharges



of the chute spillway for the aforementioned inflow rates are 132.54 and -0.1 , 143.15 and -2.7 , 153.08 and -2.9 , and 162.27 and -3.2 , respectively, indicating a general decrease from upstream to downstream. In the stilling basin, the pressure fluctuations are more pronounced due to high turbulence, varying between 1.2 and -82.5 .

The results obtained for flow pressure corresponding to inflow discharges of 1800, 2000, and 2270 m^3/s , as shown in Fig. 12, indicate that the flow pressure for the aforementioned discharges decreases by 84.5, 95.2, and 105.75 kPa from the ogee spillway to the end of the chute, respectively. Specifically, the highest pressure values at the beginning of the ogee spillway were 81.5, 91.2, and 99.33 kPa, while the lowest pressure values at the end of the chute were recorded as -3.5 , -4.5 , and -5.9 kPa, respectively. Moreover, with increasing discharge, the pressure fluctuations in the stilling basin also intensified. These variations in the stilling basin ranged between 2.4 and 180.22 kPa.

Investigation of cavitation index variations along the longitudinal axis of the spillway floor for different inflow discharges

According to Bernoulli's equation, as the flow velocity increases, the pressure exerted on a surface decreases. Conversely, as the pressure drops below the vapor pressure, the likelihood of cavitation increases. In dam spillways, as

the flow moves from the upstream to the downstream section, its velocity increases and, consequently, the pressure decreases. Therefore, pressure evaluation is crucial to prevent the destructive phenomenon of cavitation. In the following, the cavitation index along the floor and sidewalls of the spillway is examined for various inflow discharges. Figure 13 illustrates the cavitation index values along the longitudinal axis of the spillway floor from the beginning of the ogee crest to the end of the stilling basin for inflow discharges of 300, 400, 600, and 830 m^3/s . The results indicate that, for all the mentioned discharges even for the minimum design discharge the spillway channel experiences cavitation at the end of the chute and the beginning of the stilling basin. Specifically, for discharges of 300 and 400 m^3/s , the cavitation index falls below the critical value of 0.2 from the 260 m to the 335 m section downstream from the spillway inlet. Additionally, for discharges of 600 and 830 m^3/s , the spillway floor from the 240-m to the 340 m section is exposed to cavitation. The minimum recorded cavitation index was 0.13, which occurred at the 320 m section from the spillway entrance, located at the end of the chute, for a discharge of 830 m^3/s . It is noteworthy that the converging channel section was excluded from this analysis due to its low flow velocity and correspondingly higher pressure and cavitation index.

The results presented in Fig. 14 for the cavitation index values corresponding to inflow discharges of 1000, 1200,

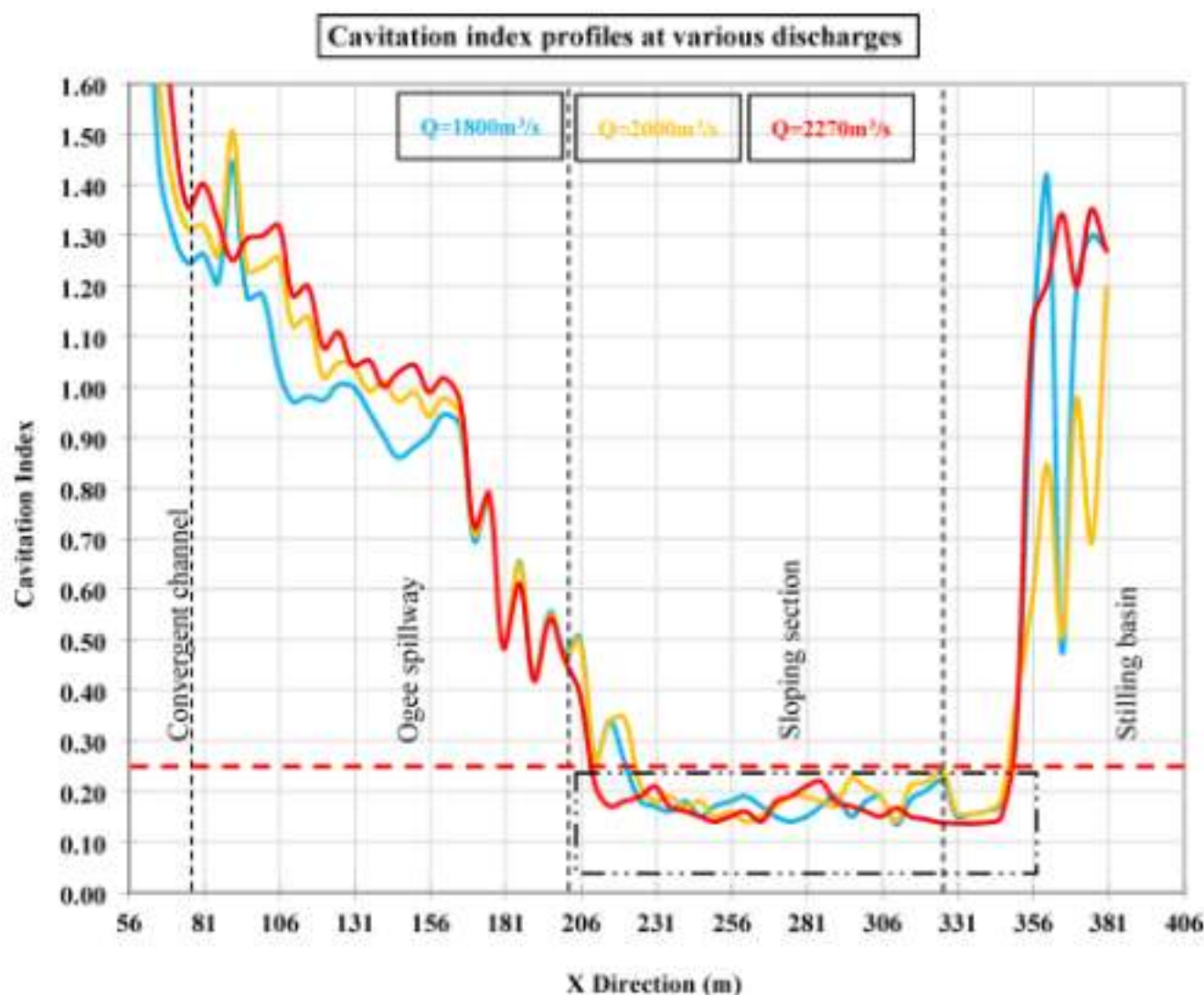


Fig. 15 Cavitation index profiles along the spillway longitudinal direction for different discharges

1400, and 1600 m^3/s along the longitudinal axis of the channel floor indicate that, with increasing discharge, a larger portion of the chute is exposed to the occurrence of cavitation. Specifically, the cavitation index drops below the critical value of 0.2 from the 225 m to the 345 m section for the 1000 m^3/s discharge, and from the 225 m to the 350 m section from the spillway inlet for the other discharge values. Moreover, the minimum cavitation index recorded in the chute section was 0.12, and in the stilling basin section, it was 0.17, both corresponding to a discharge of 1600 m^3/s . As the flow progresses toward the end of the stilling basin, energy dissipation leads to a reduction in flow velocity and a subsequent increase in the cavitation index.

With increasing flow rates to 1800, 2000, and the maximum probable flood (P.M.F) discharge of 2270 m^3/s , the results obtained for the cavitation index, as shown in Fig. 15, along the longitudinal axis of the spillway floor from the

beginning of the ogee crest to the end of the stilling basin indicate that for discharges of 1800 and 2000 m^3/s , the cavitation index drops below the critical value of 0.2 between the 225 m and 345 m sections from the spillway inlet. In contrast, for the discharge of 2270 m^3/s , this threshold is reached starting from the 210 m section. According to the results, the minimum cavitation index value of 0.15 occurs at the end of the chute and the beginning of the stilling basin for the 2270 m^3/s discharge.

Investigation of cavitation index variations along the sidewalls of the spillway for different inflow discharges

The cavitation index values along the sidewalls of the spillway were evaluated at various cross-sections located at distances of 55.5 m (ogee crest), 70, 110, 150, and 190 m

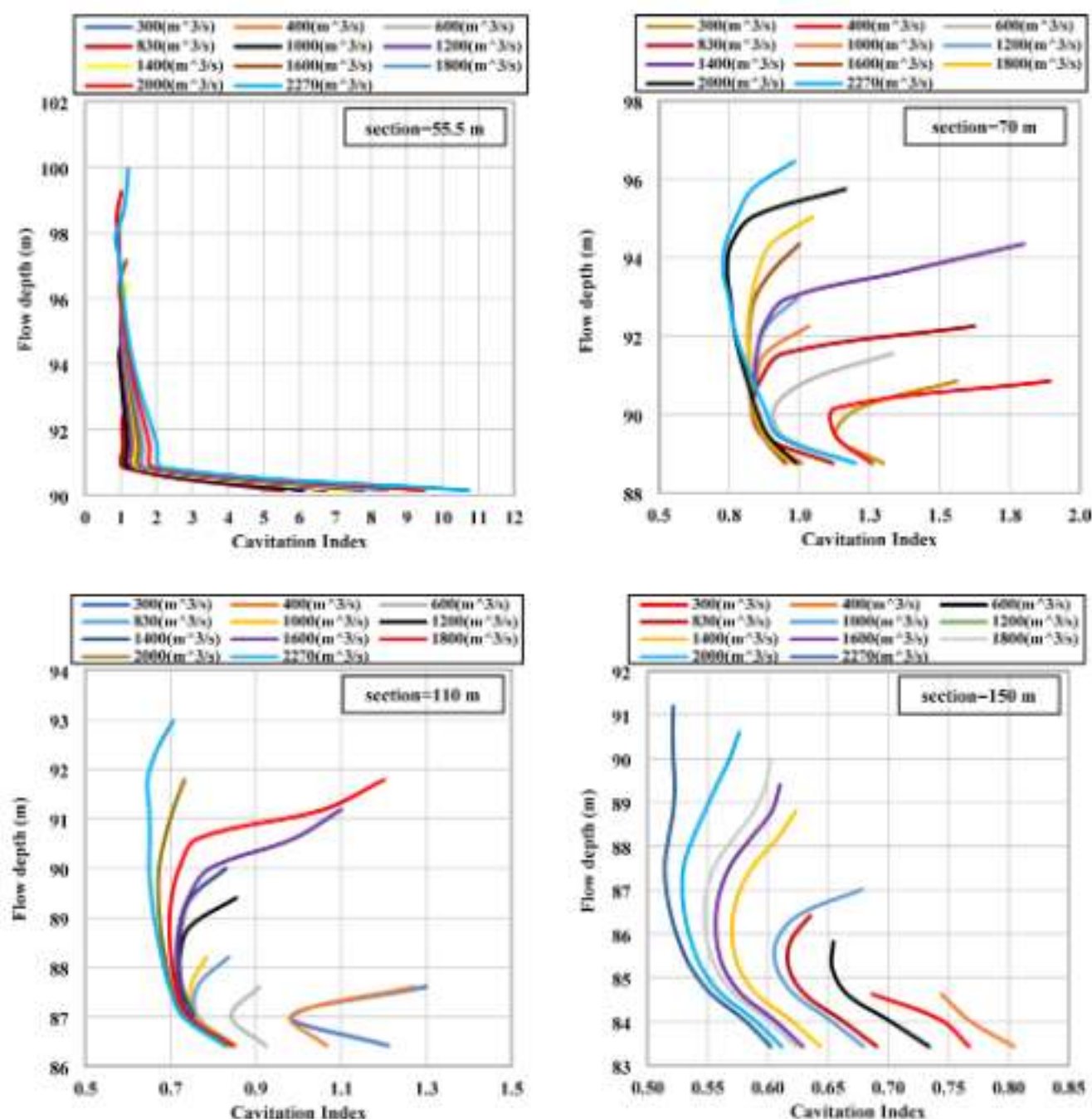


Fig. 16 Cavitation index profiles in the vertical direction of flow on the side wall at different sections of the spillway inlet for different flow rates

(chute spillway), 230 and 270 m (chute), and finally 310 and 350 m (stilling basin) from the spillway inlet, for different inflow discharges. The results indicated that the cavitation index decreases with increasing discharge. Additionally, the index values are generally higher near the bottom, due to surface roughness, and near the water surface due to air entrainment. Figure 16 presents the cavitation index values at the aforementioned sections for various discharges. The minimum cavitation index values at these sections were found to be 0.85, 0.73, 0.65, 0.51, 0.38, 0.26, 0.11, 0.15,

and 0.14, respectively. Based on these values, it can be concluded that the sidewalls in the ogee crest Sect. (55.5 m), chute spillway Sect. (70, 110, 150, and 190 m), and the upstream part of the chute (230 m) are safe from cavitation. However, the sidewalls in the downstream chute and stilling basin Sects. (270, 310, and 350 m) are susceptible to cavitation. A detailed examination of the cavitation index values at the 270 m and 310 m sections showed that the sidewalls at these locations experience cavitation for all inflow discharges. Specifically, the minimum cavitation index values

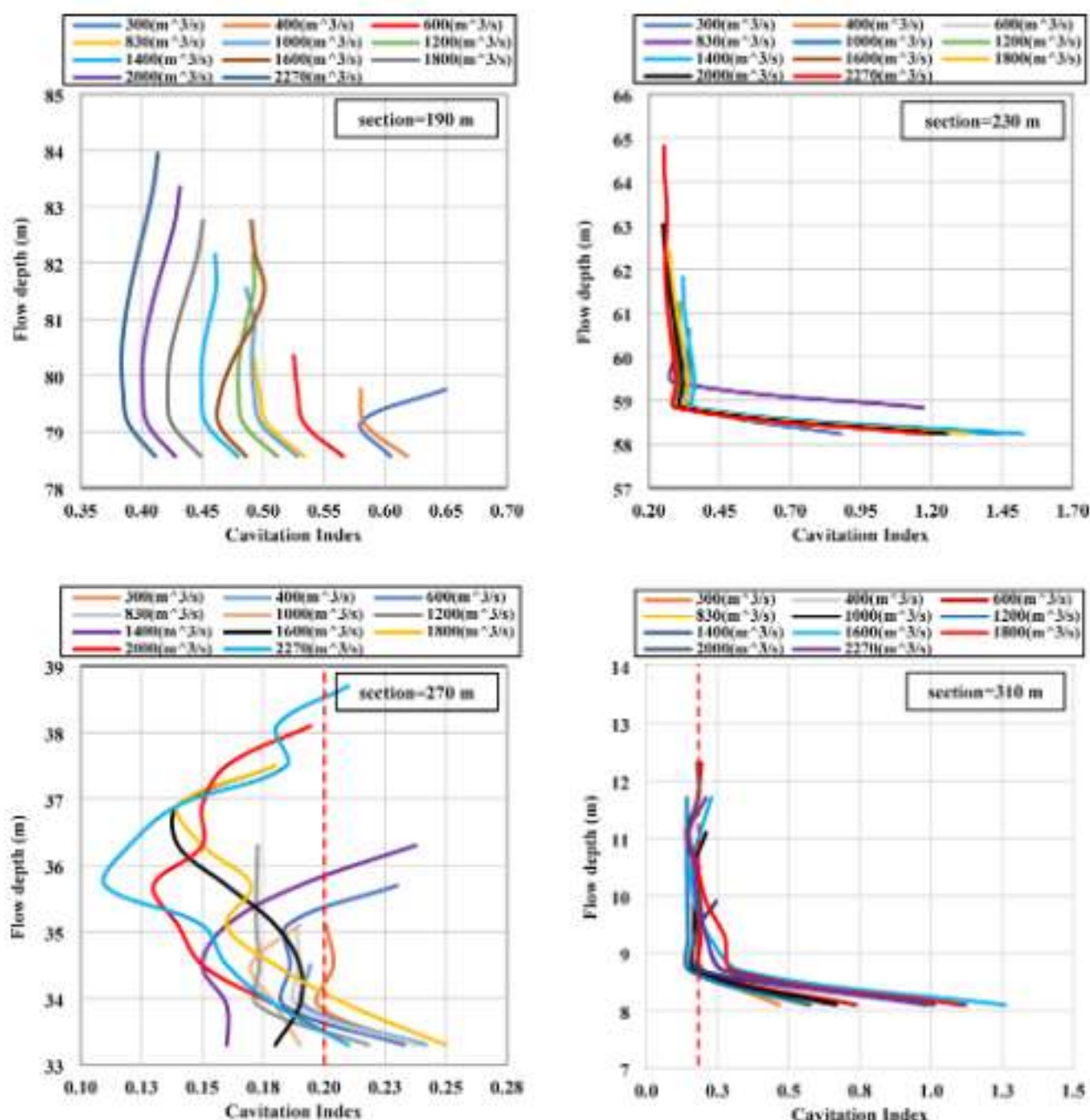


Fig. 16 (continued)

at the 270 m section for the various discharges were 0.19, 0.19, 0.18, 0.19, 0.17, 0.17, 0.15, 0.14, 0.14, 0.15, and 0.14, respectively. At the 310 m section, the corresponding values were 0.18, 0.17, 0.17, 0.15, 0.16, 0.14, 0.16, 0.16, 0.15, 0.14, and 0.14 all below the critical threshold of 0.2. Finally, the results for the 350 m section showed that this section is only safe from cavitation at inflow discharges of 300 and 400 m^3/s , while for all other discharges, the cavitation index falls below the critical value of 0.2. Variations in flow depth

directly influence the flow velocity and pressure distribution along the spillway, which consequently affect the cavitation index values. In general, a reduction in flow depth increases flow velocity and decreases local pressure, thereby reducing the cavitation index and increasing the likelihood of cavitation occurrence.

Based on the results of the cavitation index along the spillway floor and sidewalls for different inflow discharges, it can be concluded that the occurrence of cavitation within

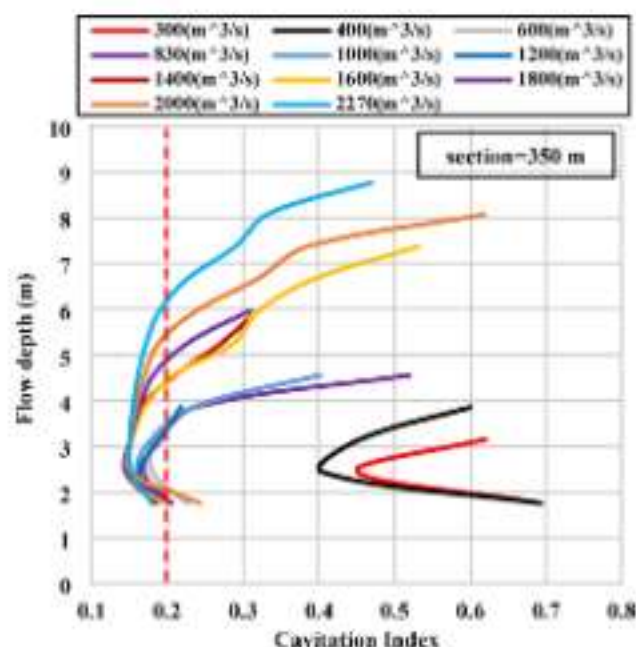


Fig. 16 (continued)

the spillway channel particularly in the downstream portion of the chute and the upstream section of the stilling basin is highly probable. Specifically, the cavitation index along the floor falls below the critical threshold of 0.2 for the probable maximum flood (P.M.F) discharge, from the 210 to the 340 m section from the spillway crest. Similarly, the sidewalls, from the 270 m mark to the end of the spillway channel, are also subject to cavitation under these flow conditions.

Conclusions

Evaluation of flow velocity, pressure, and cavitation index along the spillway for various inflow discharges

The analysis of flow velocity values along the longitudinal direction of the spillway under different inflow discharges revealed the following:

1. In the converging channel section, due to the low bed slope, the flow velocity remains relatively uniform. As the flow moves downstream, static energy is gradually converted into dynamic energy. Owing to the low velocity in this section, the flow pressure remains hydrostatic, and increases in discharge lead to increased flow pressure.
2. As the flow passes over the ogee and chute spillway sections, the increased bed slope leads to higher velocities and, consequently, reduced pressures.

3. In the steep chute section, a significant acceleration in flow occurs. At the downstream end of the chute, flow velocity reaches its peak, while pressure drops to its minimum value.
4. Upon entering the stilling basin, flow velocity decreases, and dynamic energy dissipates. For instance, under a discharge of 300 m³/s, the flow velocity decreases from 34.25 to 10.22 m/s, and for a discharge of 2270 m³/s, it reduces from 44.16 to 24.89 m/s. Due to flow turbulence caused by hydraulic jump, pressure values in this section exhibit greater fluctuations. The minimum recorded pressure was -10.63 kPa at 300 m³/s, while the maximum pressure reached 180.20 kPa at 2270 m³/s.

The assessment of the cavitation index on both the spillway floor and sidewalls for various inflow discharges indicates the following:

1. The spillway floor, even at the minimum design discharge of 300 m³/s, experiences cavitation in the downstream portions of the chute.
2. For discharges of 300 and 400 m³/s, the cavitation index along the floor drops below the critical threshold of 0.2 between the 260 m and 335 m sections from the spillway crest.
3. As discharge increases, the onset of cavitation shifts further upstream. Specifically, for discharges of 600 and 830 m³/s, cavitation occurs from 240 to 340 m; for discharges of 1000–2000 m³/s, from 225 to 350 m; and for the probable maximum flood (P.M.F) discharge of 2270 m³/s, from 210 to 350 m.
4. The cavitation index on sidewalls, measured at sections 55.5, 70, 110, 150, 190, 230, 270, 310, and 350 m from the crest, shows that sidewalls in the ogee, chute, and upper chute sections are safe from cavitation. However, the lower chute and stilling basin sidewalls exhibit cavitation risks, with values dropping below the critical index.
5. The downstream end of the chute and the beginning of the stilling basin are prone to cavitation at all inflow discharges, with the cavitation index dropping to as low as 0.14. The far end of the stilling basin, however, remains safe from cavitation under discharges of 300 and 400 m³/s.

Based on the results for flow velocity and pressure, it can be concluded that when flow velocities exceed 30 m/s, flow pressure significantly drops, increasing the likelihood of cavitation within the channel. Cavitation index values along the spillway floor and sidewalls confirm that the downstream end of the chute and the upstream portion of the

stilling basin are highly vulnerable to cavitation. To mitigate this phenomenon, it is recommended to implement air entrainment systems along the floor and sidewalls before the 210 m section. Introducing air into the flow creates a cushioning effect between the flow surface and channel boundaries, increasing pressure and thus preventing vaporization of water and the subsequent onset of destructive cavitation.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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