Numerical investigation of flow characteristics in different types of chute spillway aerators

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Abstract

Aeration of chute spillways, as an effective method for reducing erosive damage caused by cavitation, plays an important role in protecting chute structures. The degree of protection achieved through aeration largely depends on the design of the aerator and the distribution of air concentration within the flow. In the present study, the characteristics and performance of various chute aerators were simulated using Computational Fluid Dynamics (CFD) with the ANSYS Fluent software. The considered models included offset aerators, ramp aerators, combined ramp–offset aerators, as well as bottom and sidewall ramp aerators. For the hydraulic analysis of the flow, the RNG k–ε turbulence model and a multiphase flow approach were applied. The results revealed that the spacing between aerators in bottom and sidewall ramp aerators is greater than that of ramp, offset, and combined ramp–offset aerators. This is attributed to the formation of a cavity region along the bottom and sidewall, which enhances turbulence and promotes better air–water mixing within the flow. Moreover, the combination of bottom and sidewall ramps produced more effective aeration compared to other configurations. By forming cavity zones along both the bottom and sidewall, this configuration improves both the efficiency and uniformity of air concentration. In this case, the length of the cavity region was approximately 50% greater than that observed when using a bottom ramp alone.

Keywords

Aerator, Bottom ramp and side wall, Cavitation, Cavity region length, Turbulence model

1.Introduction

Chute aerators are installed on the bottom or sidewalls of a spillway to prevent cavitation damage during a high-speed flood discharge. Typically, a combination of lateral and bottom aerators offers effective aeration protection near the chute wall by entraining air bubbles [1]. An aerator's effectiveness can be estimated by considering the air entrainment rate, which is influenced by factors such as the geometry of the aerator and the conditions of the discharge flow. There are three commonly utilized aerator geometries: (1) deflector, (2) offset, and (3) a combination of both. The introduction of air into the water flow primarily occurs through an air supply system connected to the open atmosphere. This system typically includes two lateral ducts and a transverse groove, enabling the transverse distribution of air beneath the water jet [2, 3].The volume of air mixed into a flow serves as a measure of aeration efficiency. In laboratory experiments, Chanson [4] demonstrated that the demand for air is primarily influenced by the geometry of the aerator, the flow discharge, and the sub-pressure within the cavity. Following model tests on a bottom-inlet aerator with varying flow rates and angles (θ), Aydin [5] proposed empirical formulas to estimate air entrainment. Lian et al. [6] assessed existing empirical methods for estimating air demand and developed a new predictive approach. Aydin and Ozturk [7] conducted a numerical study that showed computational fluid dynamics (CFD) modeling offers accurate predictions of air entrainment in aerators, aligning well with both field observations and empirical equations. Wei et al. [8] utilized a numerical model to simulate air demand in a tunnel aerator, achieving an average deviation of 25% from experimental results. Tullis and Larchar [9] examined how factors such as gate geometry, gate opening, water head, and tailwater submergence affect air demand.

2. Methodology

The dimensions of the solution domain consisted of a length of 5.0 m, a height of 0.45 m, and a width of 0.2 m. The aerator is located at a distance of 0.5 m from the upstream, and also, the numerical simulation data were validated using the experimental results Bai et al.[10]. The basis of all numerical methods in hydraulic engineering is the solution of the governing equations of flow, including

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the continuity equations and the momentum equations, which are known as the Navier-Stokes equations. For an incompressible flow with constant viscosity, these equations are written in the form of Eqs. (1) and (2), respectively [11, 12]:

$$\frac{\partial}{\partial x_i}(\overline{x_i}) = 0 \tag{1}$$

$$\rho\left(\frac{\partial \overline{u_i}}{\partial t} + u_j \frac{\partial \overline{u_i}}{\partial u_j}\right) = B_i - \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u_i}}{\partial x_j} - \rho \overline{u_i u_j}\right) \tag{2}$$

Where u_i and u_j the velocity vector components in the spatial direction i, j, and B_I are the volumetric force in the direction i, p represents the pressure, μ is the fluid viscosity and P is the fluid density.

The upstream boundary condition consists of an inlet for the flow velocity that depends on the water depth, as well as an inlet for the air pressure set to atmospheric pressure. The upper boundary and aerator are defined as pressure inlet conditions. The downstream boundary is positioned 4.5 m downstream of the deflector in the region where the water flow is supercritical. At this location, the boundary is perpendicular to the base of the chute and encompasses both the water flow and the air. In this instance, the downstream boundary is a pressure outlet, indicating that water and air can discharge from the channel without restriction. Where boundaries are not explicitly mentioned, they are considered walls, and a no-slip condition is applied. The BCs are shown in Fig.1.

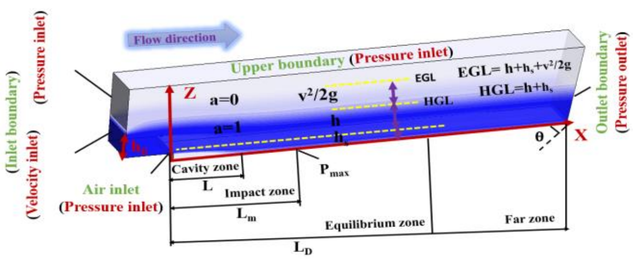

Fig. 1 Apply boundary and initial conditions for numerical simulation in the present study

3. Results and Discussion

The cavity length below the aerator, which is influenced by aerator distance and air supply, has a significant effect on air entrainment and cavitation protection. The distance between aerators depends on the minimum air concentration, the rate of air detrainment along the chute, and the specific chute geometry and flow conditions. Table 1 illustrate the distance between the aerators (L_a) and the average air concentration (C) at the area where the second aerator is located. The distance of the aerators is obtained based on the average air concentration during the chute spillway. To determine the optimal distance of the aerators and increase the efficiency of aeration, an average air concentration between 8% and 12% was considered. In Fig. 2, the length of the aerator area L_i, and the distance between the two aerators is L_a, which equals 1.5 m; the water flow rate is assumed to be 0.255 m3/s. It can be seen that the length of L_1 is 1.2 m and the length of L_2 is 1.1 m. The reason for the slight change in L_2 is that the initial aeration happens on the first ramp, and the aeration efficiency on the second ramp is slightly reduced. As a result, the suitable distance between two ramps can be obtained from numerical simulations. This means that the distance between two consecutive ramps should be determined so that the aeration efficiency of the next ramp is appropriate. In this aerator, the aeration efficiency or air concentration coefficient ($\beta = Q_a/Q_w$) for the first ramp is 2.8%, and for the second ramp is 2.5%.

4. Conclusion

This study presents an examination of aerated flow downstream of a chute aerator. A 3D numerical model was developed to determine the distance between two aerators with different types of chute aerators. These models include ramps, offsets, ramps with offsets, and bottom-and-side wall ramps. The simulations captured the air concentration distributions at various locations such as the cavity, the impact area, and the equilibrium area. Also, it was found that the air concentration is affected by various factors, including ramp length, ramp angle, offset height,

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and upstream Froude number. Furthermore, bottom and side wall ramp aerators provide improved aeration because they create a cavity zone in both the bottom and side wall chute. Therefore, the length of the cavity zone is longer than and the aeration efficiency increases. In addition, the optimal spacing of the various chute spillway aerators was determined to prevent cavitation damage downstream of the spillway and to ensure that the required air concentration is maintained throughout the chute.

Table 1 Flow characteristics in ramps aerators

Lr (m)	Φ (degree)	Q_w (m^3 /s)	Q_a×10^{-3} (m^3 /s)	β %	F_r	C%	L (m)	L_a (m)
0.04	15	0.255	0.21	0.84	6.6	9	0.8	1.4
0.04	15	0.383	0.315	0.83	9.9	11	1.5	1.8
0.08	15	0.255	0.42	1.65	6.6	8	1.2	1.5
0.08	15	0.383	0.632	1.65	9.9	8.5	2.4	2.1
0.12	15	0.255	0.63	2.47	6.6	10	1.5	1.6
0.12	15	0.383	0.945	2.47	9.9	9	2.7	2.2
0.04	10	0.192	0.104	5.5	4.97	9	0.5	1
0.04	10	0.255	0.14	0.55	6.6	9.5	0.8	1.2
0.08	10	0.255	0.275	1.08	6.6	10	0.9	1.3
0.08	10	0.383	0.413	1.08	9.9	11	1.6	1.9
0.12	10	0.255	0.413	1.62	6.6	12	1	1.6
0.12	10	0.383	0.62	1.62	9.9	8	2	1.8

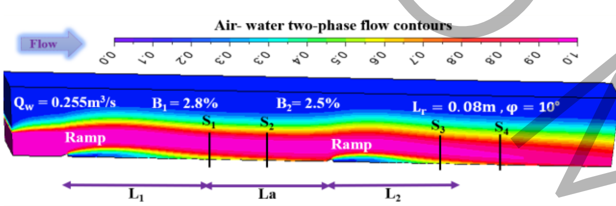

Fig. 2 Distance between two aerators in the chute spillway

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