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Numerical study of characteristics and discharge capacity of piano key weirs

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ABSTRACT

A comprehensive numerical investigation was performed to better understand the flow patterns of Piano Key weirs (PKW) for different upstream heads, based on the volume-of-fluid model. The results of numerical simulation indicate that, the efficiency of side crests are limited by following factors: the change of side crest flow direction caused by the effect of the longitudinal flow velocity along the inlet keys, submerged flow regime in outlet keys, interference between nappes, and the head loss along the inlet keys, under the conditions of high upstream head, which eventually leads to the decrease in discharge efficiency with an increase in the upstream head. An orthogonal analysis revealed that, the weir height, inlet/outlet key width ratio, significantly affect the piano key weir discharge efficiency. New formulas with obvious physical significance and high accuracy for the piano key weir discharge were then derived and verified, which improve the accuracy of the design and structural optimization of the piano key weir.

1. Introduction

Piano key weirs (PKW) have obvious advantages in terms of increasing spillway discharge capacity. As a new form of labyrinth weir structure [1], the PKW was first designed by Lempérière [2], which is similar to the design principle of the labyrinth weir, the PKW prolongs the weir crest through the action of several side weirs, and thus significantly increases the discharge capacity compared with traditional weirs under the same upstream head condition. However, unlike normal labyrinth weirs, the PKW has a long crest but a small bottom. The use of overhang structure limits the footprint of the structure. The PKW can thus be placed directly on a dam crest, making it a useful device for dam rehabilitation [3,4].

The characteristics, design methods, operation and management of the PKW have been widely studied by many research institutions, including Electricité de France [5], École Polytechnique Fédérale de Lausanne [6], the University of Liège [7], and Utah State University [8]. Theoretical, experimental, and observational studies on PKWs have been carried out. By 2014, several PKW projects had been accomplished for dam rehabilitation in France [9]. Meanwhile, the PKW has also been studied for new dam projects in Asia and Africa since 2010 [10].

Since the discharge capacity is related to the maximum reservoir water level and the capacity of the reservoir directly, it is crucial to predict the discharge capacity when designing a PKW. Although many PKW projects have been completed, their discharge characteristics and optimization have been mostly studied by conducting model tests before engineering implementation.

A lot of research has explored methods of calculating the discharge of a PKW. Michael Pfister et al.[3] described the discharge capacity of the PKW by defining a discharge ratio coefficient, which is closely related to the geometric parameters of the PKW. Ribeiro et al. derived the discharge ratio coefficient through fitting analysis. Kabiri-Samani et al. [11] proposed a standard weir equation for both free and submerged flows over PKWs, by empirical fitting. Machiels [12,13] conducted a large number of experiments using 39 PKW models to investigate the effect of a single parameter on the hydraulic characteristics of the PKW. The discharge of the PKW was divided into three parts: the discharge released on the upstream crest of the outlet key, the downstream crest of the inlet key, and the side crest between the inlet and outlet keys. Machiels' formulas thus have obvious physical significance. However, the calculation results greatly differ from the experimental results obtained by Lempérière, for not considering the head loss and energy conversion in the inlet key.

In order to accurately predict the head-discharge curve and improve the efficiency of PKW design, this study explored the hydraulic characteristic of PKWs in-depth, then provided new reliable discharge calculating formulas with obvious physical significance and high accuracy.

2. Structure of a PKW

The complex geometry of a PKW involves a large set of parameters. To unify the notation, a specific nomenclature has been developed. A

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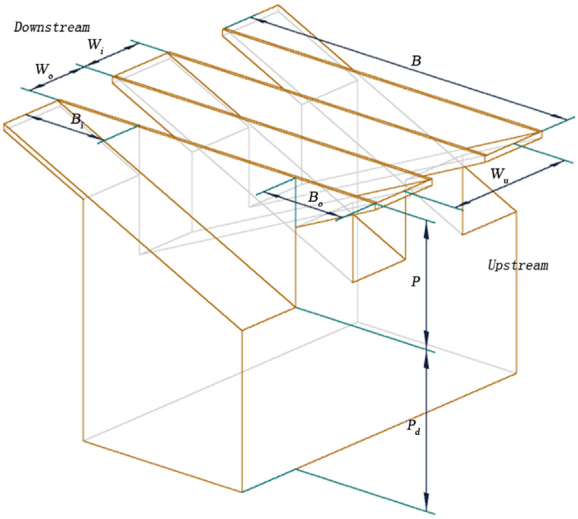

Fig. 1. Three-dimensional sketch and main geometric parameters of a type-A piano key weir (PKW).

PKW unit is the basic structure of a PKW, which consists of an inlet key, two side walls and two halves of outlet keys. According to the convention [14], the parameters relying to the basic structure are as follow: the total width of the PKW *W*, the total developed crest length *L* and the number of PKW units N_u. The main geometric parameters of a PKW unit are the weir height *P*, the width of the PKW unit *W*u, the side crest length *B*, the inlet and outlet key widths W_i and W_o, and the upstream and downstream overhang lengths B_o and B_i, as shown in Fig. 1.

A number of studies have explored the optimal values of geometric parameters affecting the PKW efficiency. The research of Ouamane and Lempérière [2] showed that the *L*/*W* ratio is the main parameter controlling the discharge capacity, which was confirmed by Ribeiro et al. [6]. Furthermore, Lempérière et al. [15] stated that an *L*/*W* ratio of 5 is a reasonable compromise between weir efficiency and structural complexity.

3. Discussion on the discharge coefficient

The discharge of PKWs could be expressed by common weir flow formula Eq. (1),

$$Q = C_d W \sqrt{2gH^3} \tag{1}$$

where *Q* is the discharge of a weir, *H* is the upstream water head, C_d is the discharge coefficients of a weir, and *g* is the gravitational acceleration.

According to Lempérière's test results [2], we could calculate the discharge coefficient curve of a PKW inversely, as shown in Fig. 2. The discharge coefficient curves of sharp-crested weir [16], and ogee-crested weir [17] are also displayed in Fig. 2.

From Fig. 2, the discharge coefficient of the PKW decreases sharply with the increase in the upstream head H, whereas discharge coefficients of sharp-crested weir, and ogee-crested weir increase slightly. Under low head conditions, compared with sharp-crested weirs and ogee-crested weirs, the discharge of PKW is 4–5 times larger. However, under the condition of high upstream head, the discharge of the PKW is merely 1–2 times the discharge of sharp-crested weirs and ogee-crested weirs, the advantage of the PKW is thus seriously limited.

In order to reveal the mechanism of this phenomenon, numerical model study was carried out.

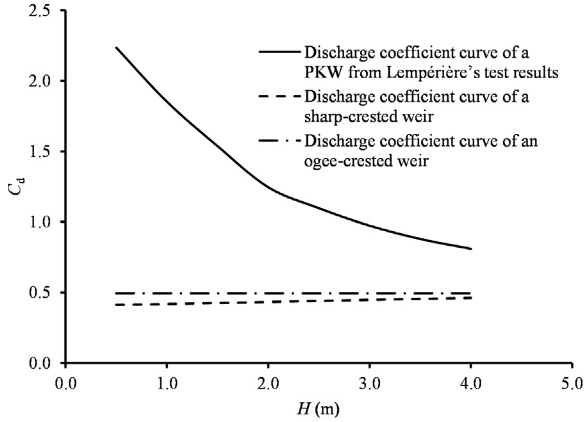

Fig. 2. Discharge coefficient curves of the PKW [2], sharp-crested weir [16], and ogee-crested weir [17].

4. Numerical simulation method

4.1. Numerical model

In this study, Flow-3D is selected as the computational fluid dynamics solver. The volume-of-fluid (VOF) method [18] was used to simulate the flow fields over PKWs.

Employing the VOF method, empty cells are given a value of zero, full cells are given a value of 1, and cells that contain the free surface are given a value representing the ratio of the fluid volume to cell volume. The water surface is then described as a first-order approximation according to the fluid-to-cell volume ratio and the location of the fluid in the surrounding cells. Using the true VOF method, Flow-3D is able to track free surfaces in both time and space.

Flow-3D uses the Reynolds-averaged Navier-Stokes equations and turbulence model to solve for fluid flow [19].

$$\text{Continuity:} \quad \frac{\partial}{\partial x_i}(u_i A_i) = 0 \tag{2}$$

$$\text{Momentum:} \quad \frac{\partial u_i}{\partial t} + \frac{1}{V_F}\left(u_j A_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{1}{\rho}\left(\frac{\partial p}{\partial x_i}\right) + g_i + f_i \tag{3}$$

In these equations, u_i is the fluid velocity components in the *x*, *y* and *z* directions; A_i is fractional areas of cell faces open to flow; V_F is the volume fraction of fluid in each cell; ρ is the density of the fluid; *p* is pressure; g_i is the acceleration of gravity; f_i is the viscous acceleration, and can be solved for using one of many available turbulence models, such as the standard k - ε model.

The standard k - ε model [20] was selected to account for turbulence and possible hydraulic jumps.

4.2. Numerical model and boundary conditions

First, a PKW numerical model was established, which has the same size as that in the experiment of Lempérière et al. Table 1 demonstrates the values of the geometrical parameters of the model.

Grids of average 10-cm computational cells was set in each numerical simulation. Cells were square and refined near critical structures.

The inflow boundary was set as a specific fluid height for each simulation. The top boundary was set as a pressure boundary with zero gauge pressure. No-slip wall boundaries were set along the whole surface of the PKW structure. To ensure the flow became stable, each numerical simulation was run for 30 s. The fluid was considered incompressible, and the standard density and viscosity of water at 20 °C were used in all calculations. The structures were assumed to have smooth surfaces such that wall friction was neglected, and constants