REALISTIC ROCK WEIR HYDRAULICS THROUGH COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

Typical engineering designs of rock weirs rely on simplified, one-dimensional empirical equations. For example, nature-like fish passage design guidelines recommend designing the rock weir structures based on one-dimensional submerged broad-crested weir equations developed for solid, nonporous weirs. Not surprisingly, this traditional method fails to predict the real hydraulic conditions through rock weir structures because it does not consider flow through interstitial spaces between rocks and the way interspatial flow alters the head-discharge relationship. Furthermore, no consideration is given in the weir coefficients to the irregularity of the boulders nor the weirs cross-channel shape. To improve the design methodology and to better capture the complex hydraulics past rock weirs, a three-dimensional, high-resolution computational fluid dynamics model is used. Due to the spatially variable water surface elevation and the turbulent nature of the flow, the 3D model captures the free surface with a volume-of-fluid method and turbulence by large eddy simulation. The simulation results show that the flow phenomena and head-discharge relationship are significantly different between broad-crested weirs and rock weirs. Based on the results, we propose a linear decomposition approach to quantify the flow rate through a rock weir structure. The decomposition includes contributing flows from (1) weir flow over the individual rocks, (2) flow through the weir’s notch, and (3) interstitial flow between rocks. In this paper we demonstrate the applicability of the proposed decomposition. More cases will be tested to parameterize the discharge coefficients for different flow conditions and weir geometries.

Keywords: Rock weirs; realistic rock weir modeling; broad-crested weirs; numerical modeling.

1 INTRODUCTION

Channel-spanning rock weirs are widely employed in rivers for purposes including fish passages, irrigation diversions, and floodplain reconnection, among many others. Typical engineering design of rock weirs rely on simplified, one-dimensional equations dependent on empirical constants. For example, nature-like fish passage design guidelines (Towler et al., 2015; Turek et al., 2016) recommend designing the rock weir structures based on one-dimensional, submerged, broad-crested weir equations developed for solid, nonporous weirs (Figure 1). The broad-crested weir equation reported in Towler et al. (2015) takes the form

\[ Q = C_w C_s W_w H_w^{1.5} \]  

where \( Q \) is the volumetric flow rate, \( C_w \) is the weir’s discharge coefficient, \( C_s \) is the submergence coefficient, \( W_w \) is the cross-channel width of the weir measured along the weir crest, and \( H_w \) is the depth of water over the weir crest measured upstream of the weir.

The traditional weir equation does not consider flow through interstitial spaces between rocks and the way interstitial flow alters the head-discharge relationship. Moreover, the recommended empirical constants in Eq. [1] are estimated by empirical equations or selected from tables and charts developed for nonporous weirs. They are rarely measured or calibrated for specific applications.

Specifically, for weir coefficient, nature-like fish passage design guidelines recommend two coefficients to account for (1) the difference between ideal and real flow over a weir using the traditional weir coefficient, \( C_w \), and (2) drowned flow conditions using the submergence coefficient, \( C_s \). The weir coefficient, \( C_w \), is a function of the downstream thickness (or breadth) of the weir crest \( (t_w) \) and the head on the weir \( (H_w) \). Typically, \( C_w \) can be found in tables from previous experimental studies (Brater and King, 1976). The submergence coefficient, \( C_s \), poses difficulties in its selection. Turek et al. (2016) recommends estimating \( C_s \) based on Plate 3-5 of EM 1110-2-1603 Hydraulic Design of Spillways (U S Army Corps Of Engineers and Engineers, 1990). However, as Turek

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et al. (2016) noted, Plate 3-5 was developed from tests of sharp-crested weirs which are characteristically different from rock-weirs that better resemble broad crested weirs. No general empirical relations are available for submergence coefficient of broad-crested weirs (Turek et al., 2016). Furthermore, there is no consideration given in these two recommended weir coefficients to the irregularity of the boulders nor the weirs cross-channel shape.

![Figure 1](image)

**Figure 1.** The schematic diagram of (a) flow over a broad-crested weir and (b) flow over and through a rock weir.

To improve the design methodology and to better capture the complex hydraulics past boulder weirs, a three-dimensional, high-resolution computational fluid dynamics (CFD) model is implemented to study the problem. The numerical model is developed with the open source computational platform OpenFOAM (OpenFOAM, 2019). Due to the spatially variable water surface elevation and turbulent nature of the flow, the 3D model must be capable of capturing these characteristics. The model does so by employing a volume-of-fluid (VOF) method for free-surface tracking and utilizes a large eddy simulation (LES) approach for turbulence. The spatially-varied flow results generated with the model over a refined computational grid allows for detailed analysis of local hydraulics. The objectives of the present study are (1) to identify the weakness of the existing design methodology of rock weirs, and (2) to propose a new methodology to accurately predict the flow through boulder weirs.

## 2 METHODOLOGY

### 2.1 Numerical Model

The hydraulics of boulder weir arrays are similar as a series of step-pool structures, which are characterized by rapidly varied flow at the step crest, a hydraulic jump, and gradually varied flow in the pool (Dust and Wohl, 2012). Obviously, the rapidly changing water surface requires free surface capturing in the CFD model. A two-phase solver, *interFoam*, in OpenFOAM is employed in this work. The *interFoam* solver applies a popular free surface capturing method, Volume-of-Fluid (VOF) (Hirt and Nichols, 1981), in which a scalar volume fraction is used to represent the interface. The same governing equation (i.e. continuity and momentum equations) for the two phases are solved, but they are calculated as weighted averages based on the volume fraction of water, \( \alpha \). For example, a computational cell having a value of \( \alpha = 1 \) is entirely filled with water, a cell with \( \alpha = 0 \) is filled with air, and \( 0 < \alpha < 1 \) represents a cell containing the free surface. To model the interface dynamics, surface tension, \( F_{st} \), is considered. The surface tension \( F_{st} \) (Eq. [2]) can be calculated by surface tension coefficient, \( \sigma \), and the surface curvature, \( \kappa \), represented by the unit vector normal to the interface, \( n \) (Eq. [3]). Thus, to add the effect of surface tension, the momentum equation in VOF method becomes Eq. [4].

\[
F_{st} = \sigma \kappa \nu \alpha \quad [2]
\]

\[
\kappa = -\nabla \cdot n = \frac{\nu \alpha}{|\nu\alpha|} \quad [3]
\]

\[
\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u u) - \nabla \cdot \tau = -\nabla p + \rho g + F_{st} \quad [4]
\]

Due to the turbulent nature of the weir flow, the 3D model must be capable of capturing turbulence fluctuations. With the aim of capturing turbulent details while controlling computational cost, a Large Eddy Simulation approach was used. Due to the requirement of numerical stabilities in modeling complex turbulent structures generated by complex geometries, e.g., complicated angles of rocks, large-scale fluctuations are resolved while subgrid-scale eddies are modeled using the localized dynamic one equation model (Kim and Menon, 1995).

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2.2 Computational Domain

The cases of solid weirs versus boulder weirs were simulated using the CFD model. To reduce the complexity in this proof-of-concept study, the studied cases here are single, straight, unsubmerged weirs without notches. This isolates the role of the interstitial space when compared with solid weirs. The computational domain can be seen in Figure 2. The computational domains with weirs were generated in STL format in order to recreate the irregular and complex geometries of boulders.

Discharge was provided into the computational domain via an upstream tank. Providing discharge this way results in better numerical stability in multiphase simulations versus a plane inlet perpendicular to the primary flow direction. The bottom of the tank was an inlet boundary with constant discharge. The downstream boundary was treated as a free overfall and was at a distance of approximately 9 meters from the weirs to prevent boundary effects in the area of interest. The bed and the sides of the computational domain were walls and treated with a smooth wall function.

Figure 2. (a) Isometric view and (b) plan view of the computational domain and weir geometry for the test cases.

2.3 Test Cases

The weir size reflects field-scale nature-like fishway weirs (Haro et al. 2008), which was 7 m in the cross-channel width (Ww), 0.9 m in downstream thickness (tw), and 0.9 m in depth. Three geometries were considered including (1) solid weir, (2) rock weir with smaller gaps, and (3) rock weir with larger gaps. The rock weir spacing is defined by the center-to-center (c-c) spacing; c-c = 0.9 and 1.0 for the small gap and large gap cases, respectively. The constant discharge for all cases was set to Q = 3 m$^3$/s. The initial mesh was refined specifically near the bed, free surface, and areas near the tops of boulders to ensure high precision near the weir.

3 RESULTS

For the solid weir geometry tested, the weir coefficient, $C_w$, is 2.66, which was iteratively obtained from tabulated values according to the given discharge $Q = 3$ m$^3$/s and the thickness of the weir crest (Brater and King, 1976). Therefore, according to Eq. [1], the theoretical head on the weir, $H_w$, should be 0.440 m. The simulation results indicate that $H_w$ is 0.446 m which agrees well with the empirical formula (0.6% error). This demonstrates the CFD model’s capability to reproduce weir hydraulics for solid, broad-crested weirs.

Figure 3 shows the vertical velocity ($U_z$) on the free surface for the three cases. It is obvious that the flow conditions for the rock weir cases do not match the broad-crested weir case. The interstitial flow between rocks makes the plunging flow less smooth as compared with the solid weir case. This is more obvious in the flow over a larger boulder weir (Figure 3 (c)). These results demonstrate that the hydraulic conditions can be significantly different between solid weirs and rock weirs.
Figure 3. The vertical velocity (Uz) of free surface in three studied cases including (a) solid, broad-crested weir, (b) rock weir with c-c spacing = 0.9 m, and (c) rock weir with c-c spacing = 1.0 m. Velocity units are m/s.

Figure 4 shows the water surface elevation along the longitudinal centerline transect (green plane in Figure 1 (a)). The head on the rock weir is 0.183 m for smaller gaps and 0.026 m for larger gaps. The head results on the rock weirs are not consistent with the weir equation although the solid weir case is, as expected. The difference between rock weirs and the solid weir is greater for the case with larger gap size. Specifically, the percent error in head on the weirs increases from 27.7% for the small-gap case to 44.5% for the large-gap case.

Figure 4. The water elevation along the longitudinal centerline transect.

As shown in Figure 1 (b), the rock weir flow includes three components: (1) weir flow over the boulders, Q_w, (2) flow through the weir's notch, Q_n, and (3) interstitial flow between individual boulders, Q_i. The discharges of these three components are calculated separately from the simulation results. Adding these three components gives the total discharge through the rock weir, Q_t. The discharge results can be seen in Table 1. The total discharge for rock weirs (2.885 m³/s for smaller gaps and 2.962 m³/s for larger gaps) are close to the discharge of solid weir, 2.983 m³/s with only 3.29% error and 0.71% error for the small-gap and large-gap cases, respectively.

The discharge results from the CFD model can be seen in Table 1. In the table, H_w is the head over the weir or rock weir crest, Q_w is the discharge computed from the weir equation as a function of H_w, and Q_wn, Q_im, and Q_tm are the weir, interstitial, and total discharge obtained from model results. The total discharge for the solid weir and rock weir cases are very close as expected. However, for the rock weir case, the discharge computed using the weir equation, Q_w, and the model output weir discharge, Q_wn, do not match (with approximately 22% error). If there was no difference in these values, then the traditional weir equation and corresponding discharge coefficients can be used in determining rock weir discharge. The mismatch indicates that the coefficient in the weir equation is different for rock weirs, thus the head-discharge relationship is not the same as that for a solid broad-crested weir.

Table 1. Discharge results for the test cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Discharge (m³/s)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid weir</td>
<td>2.983</td>
<td>0.71</td>
</tr>
<tr>
<td>Rock weir</td>
<td>2.885 (small)</td>
<td>3.29</td>
</tr>
<tr>
<td>Rock weir</td>
<td>2.962 (large)</td>
<td>0.71</td>
</tr>
</tbody>
</table>
4 CONCLUSIONS

The traditional weir equation and corresponding discharge coefficients cannot adequately predict flow through a rock weir structure. The head-discharge relationship is altered by the presence of interstitial flow between rock elements. A linear decomposition approach is proposed to quantify the flow rate through a rock weir structure. The decomposition includes contributing flows from (1) weir flow over the boulders, (2) flow through the weir's notch, and (3) interstitial flow between individual boulders. However, care must be taken in this approach as the head-discharge relationship over the rock weir crest and likely the rock weir notch will require adjustment of discharge coefficients. Through further realistic CFD simulations and experiments, each of these contributing flows can be assessed individually. The results of parametric study will be assessed further to provide guidance on the altered head-discharge relationship through rock weirs with varying flow and geometric conditions.

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