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Numerical simulation of the hydraulic performance of triangular and trapezoidal gabion weirs in free flow condition

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ABSTRACT

During the recent years, gabion weirs have attracted the attention of many researchers due to their compatibility with the environment, positive effects on river's water quality and simple design and implementation. In this research, the hydraulic parameters of flow around the triangular and broad-crested gabion weirs with various side slopes were numerically investigated. The numerical results were validated using the data obtained from laboratory experiments. Overall, a number of 256 different models were studied numerically. Results indicated that decreasing the average diameter of particles may result in the reduction of the discharge coefficient (C_d), through flow discharge and the energy dissipation of flow over the models up to 27%, 34%, and 8% respectively. Also, it was concluded that the upstream slope of triangular weirs and downstream slope of broad-crested gabion weirs have more significant impact on the performance of gabion weirs. Finally, mathematical relationships are correlated using Nonlinear Multivariate regression analysis in order to estimate the discharge coefficient and through flow discharge of these structures.

1. Introduction

Weirs are such structures that can be usually used in order to measure and control the water flow in open channels. Generally, weirs are constructed of a concrete rigid body; however, the porous structures, such as, gabions are nowadays preferred. Physical and chemical materials, such as, sediments and suspended organic matters can pass downstream through the porous body of these structures which will result in the reduction of the sedimentation behind the weirs. Also, the flow turbulence through these porous mediums may increase the flow aeration and may lead to the river water refinement. Thus, it could be inferred that the gabion weirs are structures with minimum negative impact on the environment [1].

The hydraulic performance of broad-crested rigid weirs has been considered in various studies including Göğüş [2], Hager and Schwalt [3], Ansar and Gonzalez-Castro [4], Li and Garga [5], etc. The effect of upstream and downstream slopes of broad-crested weirs is studied by Sargison and Percy [6]. They concluded that increasing the upstream slope decreases the discharge coefficient. Sarker and Rhodes [7] used a commercial 3-D CFD software and a 1D in-viscid flow method to simulate rapidly varied flow over a rectangular rigid weir. They stated that the 3D software has accurately estimated the water surface profile, while the 1D method estimated the water surface profile with large errors. Habili et al. [8] compared the hydraulic characteristics of finite-crested length weir with quarter-circular crested weirs. They concluded that the discharge coefficient for finite crest length weir is significantly smaller than that for quarter-circular crested weir due to the obviation of the formation of separation zone. Madadi et al. [9] studied the effect of the upstream slope of the trapezoidal weirs on the discharge coefficient. The results showed that by decreasing the upstream face slope, the dimensions of the flow separation zone reduces which may enhance the performance of weir.

In comparison with the broad-crested and trapezoidal weirs, Crump weirs have been paid less attention; however following researches could be cited in this field. Azimi et al. [10] studied the hydraulic performance of the triangular and broad-crested solid weirs with either the upstream, downstream or both ramps. Their results indicated that by increasing the downstream slope, the discharge coefficient of triangular weirs increases, while the discharge coefficient decreases with increasing the upstream slope. In addition, in a solid broad-crested weir, the discharge coefficient (C_d) for an embankment weir (weirs with both upstream and downstream ramps) is relatively higher than that for broad-crested weirs with one side ramp. They concluded that the effect of the downstream slope on the discharge coefficient is less than the upstream slope due to the formation of flow separation zone at the upstream edge of the weir. Also, the difference between the Cd curves

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of weirs with either the upstream ramp, downstream ramp or embankment weirs decreases by increasing the upstream water level. Furthermore, some researchers including Abou-Seida and Quraishi [11], Fritz and Hager [12], Keller [13], and Crump [14] have investigated the hydraulic performance of solid Crump weirs in different geometries. Many experimental studies have been performed to investigate the hydraulic performance of broad-crested weirs and the following head-discharge formulation is proposed:

$$Q = CB\sqrt{g}h^{1.5} \quad (1)$$

where, $C = \frac{2\sqrt{2}}{3}c_d$ is the discharge coefficient, B is the channel width and h is the water head over the weir [1]; considering the triangular weirs have no general head-discharge relationship, in this study, the Eq. (1) is arbitrarily opted as the basic head-discharge equation for the triangular weirs.

Several researchers have studied the flow field through and around the porous and solid weirs experimentally and numerically. Wang et al. [15] investigated the hydrodynamics of trapezoidal embankment weirs with upstream and downstream slopes of 1:2 (V:H) using particle image velocimetry (PIV) technique. Investigated parameters include flow regimes, velocity fields and discharge coefficient. They concluded that the flow structure is largely dependent on tailwater level as well the upstream Froude number. Azimi et al. [16] utilized the K-ε turbulence model as well as the VOF scheme to simulate the flow patterns in a triangular channel along a side weir. Results showed that the numerical model estimated the free surface profile and the flow characteristics accurately. Kells [17,18] studied the spatially varied flow over the rockfill dams. Results indicated that the ratio of through to overall flow is ranged between 0.25 and 0.5. Michioku [19] indicated that the through flow discharge of porous weirs is a function of upstream and downstream water levels, porosity, the weir's height, and its length. Chanson [20] noted that the interactions of through flow with the over flow are valuable topics for future studies which have received little attention. Leu et al. [21] studied the velocity distribution and turbulence intensity around the solid and porous structures at submerged flow conditions. They investigated the fluctuations of velocity magnitude and the turbulence intensity around the rigid and porous weirs and showed that the vertical velocity distribution above the porous bodies are smoother than that for rigid structures considering the slip flow velocity at the flow-structure interface. In addition, increasing the mean diameter of particles may lead to the increase of the stream-wise velocity component, turbulence intensity, turbulent kinetic energy, and the Reynolds shear stress. Shahamiri and Wierzba [22] utilized a one-dimensional modeling method to simulate the reactive process inside a porous medium. Mohammadpour et al. [23] utilized the Reynolds-averaged Navier-Stokes equations, the VOF method, and three variants of the K-ε turbulence models to solve the flow field around the broad-crested gabion weirs. The results indicated that the standard k-ε model provides more accurate prediction compared to other turbulence models.

Analyzing the flow through a porous weir requires the flow hydrodynamics of both inside a coarse-grained porous media and the rapidly varied free-surface flow above the weir [19]. On the other hand, measuring the properties of through flow requires expensive experimental instruments which are not usually available. Even in many circumstances, using such devices would be impossible due to the irregular internal structure of the real porous mediums. Considering the existence of the difficulties and special instruments and methods required for the laboratory measurement of the discharge passes through the porous media especially at the presence of a simultaneous over flow discharge, only few studies have considered this area. Regarding the above-mentioned reasons, investigation of the flow behavior around and inside a porous media using numerical simulations might be a logical and beneficial method. Also, reviewing literature reveals that fewer scholars have addressed the characteristics of narrow crested weirs compared to the Broad-crested ones. So, the main objective of this research is to investigate the hydraulic performance and the flow behavior around and inside the porous body of triangular and narrow-crested gabion weirs with varying side slopes (trapezoidal weirs) numerically. A series of laboratory experiments were performed on the hydraulic behavior of the narrow-crested gabion weirs where the obtained experimental data were used for calibration and validation of the results of a 3D numerical model. Totally, 256 three-dimensional simulations were performed and the effect of porosity and side slopes of triangular and trapezoidal weirs on water surface profile, through flow discharge, discharge coefficient (Cd), and the energy dissipation of theses weirs were studied. Moreover, the interactions of through flow with the passing overflow were investigated and their effects on the hydraulic behavior of porous weirs are discussed in details. Finally, nonlinear multivariate regression analyses were performed to present some equations to estimate the discharge coefficient and the through flow discharge for each model. A general overview of the results indicate that, although some of the results fall within the broad crested domain ($0.1 < H/L_{crest} < 0.35$), but the majority of results represent the narrow crested domain ($0.35 < H/L_{crest} < 1.5$). Therefore, all trapezoidal and rectangular weirs are called narrow-crested throughout the paper.

2. Modeling and simulations

2.1. Experimental setup

Experiments were conducted in a laboratory flume with 0.3 m width, 0.5 m height and 10 m length. A rectangular model of the gabion weir with 0.3 m crest's length, 0.16 m height and 0.15 m stream-wise crest's width was placed in the channel at a distance of 4 m from the entrance of the flume. Three different particle sizes were used in order to investigate the effect of porosity and particle diameter on the hydraulic performance of the weir. Fig. 1 shows the laboratory flume and the weir model. Flow rate measurements were performed using an ultrasonic flow-meter with ± 1% of measurement accuracy. The upstream water level for each model was recorded in 6–9 different discharges using a point gauge with ± 0.2 mm of reading accuracy. This gauge was located at a distance of 1.5 m prior to the weir on the flume centerline. Also, photographs taken from the flow on the weir during the experiments were used to extract the water surface profiles which were considered for model validation. Hence, 26 laboratory experiments were performed in three different weir porosities. The temperature of water in all experiments was almost equal to 25 °C. The distribution of the particles diameters was uniform with $\sigma = \sqrt{d_{84}/d_{16}}$ equal to 1.27, 1.11 and 1.07 for mean diameters equal to 34, 23 and 19 mm respectively. Also, the Reynolds number was sufficiently high in all experiments, so the flow regime could be considered fully turbulent.

2.2. Simulated models

Side slopes of 45° (1) and 60° (2) were added to the upstream and

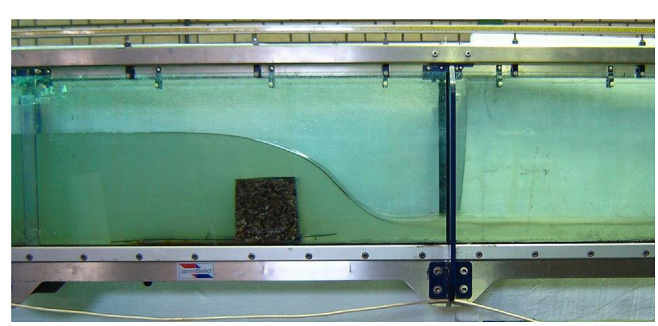

Fig. 1. View of the laboratory flume and the Broad-crested gabion weir used in this study.