Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 54(1) (2022) 31-34
DOI: 10.22060/ceej.2021.18314.6830

Undular Flow Conditions and Discharge Coefficients in Rectangular Broad-Crested Weirs

B. Nourani, F. Salmasi*, H. Arvanaghi, F. Rezaei

Department of Water Engineering, Faculty of Agriculture, University of Tabriz, Tabriz, Iran

ABSTRACT: Weirs are common hydraulic structures that can be used in conveyance water canals for increasing the water depth upstream of turnouts or measurement of flow discharge. In this study, the effect of hydraulic parameters and creation conditions of undular flow in the broad-crested weirs were investigated numerically using the finite volume method and the results were evaluated by the experimental method of other researchers. Results indicated that discharge coefficients (Cd) for experimental data are between 0.321-0.332, whereas the Cd for numerical simulation (using ANSYS FLUENT) is between 0.301-0.354. Over the crest where the minimum water depth (dmin) happens, when Fr1 is less than 1.5 (Fr1<1.5), the creation of waves was observed. This type of flow is known as the undular flow. In this situation, measuring water depth over the broad crested weir is not easy and can introduce error for discharge estimation. For preventing of the undular flow, the flow depth cannot be less than a specified value. In this study, this limitation was observed for H/L > 0.1. Thus it can result that long broad-crested weirs (H/L<0.1) are more susceptible than the broad-crested weirs (0.1≤H/L<0.4) in the creation of the undular flows. Additionally, a regression equation for estimation of the Cd in the broad-crested weirs is proposed with reasonable accuracy.

Review History:

Received: Apr. 23, 2020
Revised: Sep. 10, 2020
Accepted: Aug. 26, 2021
Available Online: Aug. 31, 2021

Keywords:

Broad-crested weir
Discharge coefficient
Undular flow
Finite volume method

1- Introduction

Weirs are used to achieve aims such as regulating the upstream water surface level in a hydraulic structure for turn out or measuring discharge. Weirs allow water to pass through a structure with known dimensions and determine the discharge as a function of flow depth. Therefore, one of the simple and accurate methods of measuring discharge in open channels is the use of weirs. The geometry of broad-crested weirs can influence the flow conditions and discharge capacity. Numerous experimental and numerical studies have been conducted on the flow over broad-crested weirs, including, and not limited to, Singer [1], Hager and Schwalt [2], Ramamurthy et al. [3]. Shaima et al. [4] simulated the water surface profiles in broad-crested weirs in *2D* and *3D* mode using *FLUENT* software and compared the results with the results of the experimental model. The results indicated that the relative error (*RE%*) and the root mean square error (*RMSE*) for the *2D* numerical model were 2.5 and 0.6, respectively, and for the *3D* numerical model were 2.1 and 0.5, respectively. That study also showed that the results of the *3D* model are almost similar to the *2D* model, but the *3D* model requires a lot of time to simulate a similar condition. Nourani et al. [5] numerically simulated the flow in triangular plan weirs using *ANSYS FLUENT* software. In that study, the *k-ε* (*Re-normalization group, RNG*) turbulence model was used to solve the Reynolds Average Navier-Stokes (*RANS*) equations. The results showed that this model in providing flow simulation on triangular plan weirs provides logical and acceptable answers. Effects of upstream face slope and radius of curvature of weir upstream corner in rectangular broad-crested weirs on the undular flow were investigated by Madadi et al. [6]. That study established that curvature and slope have similar effects on wave elimination. The experimental results showed that the wave was not generated above the weir with 21° upstream face.

Undular flow in broad-crested weirs can occur under conditions where the water head on the weir is less than a certain value. This condition causes sinusoidal waves and oscillating currents on the crest. According to the literature, the conditions for creating a wave current on broad-crested weirs have not been fully and comprehensively investigated. Therefore, in this study, in addition to investigating the hydraulic parameters of the flow in this type of weirs, the simulation of how and conditions of creating the undular flow is investigated using a numerical model by applying *ANSYS FLUENT* software.

2- Methodology

The use of computer models for flow investigation in hydraulic structures has become widespread with the

*Corresponding author's email: Salmasi@tabrizu.ac.ir

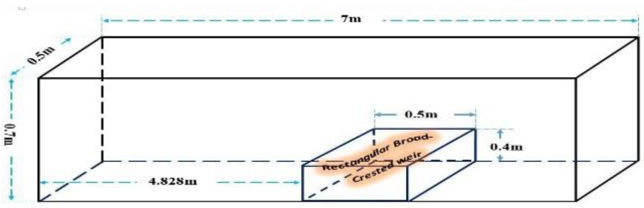

Fig. 1. Characteristics of flume and weir geometry in Hager and Schwalt [2] experimental study and numerical model in the present study

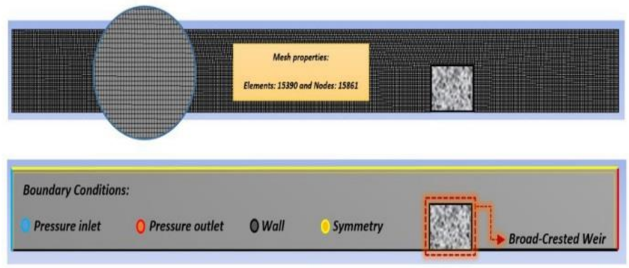

Fig. 2. Mesh properties and boundary conditions in numerical simulations

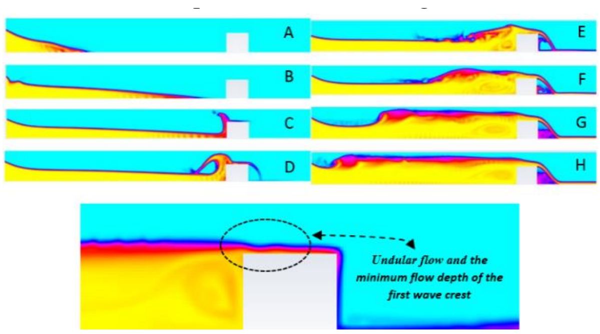

Fig. 3. Illustrations of the entry flow in the flume and creation of undular flow waves on the weir crest

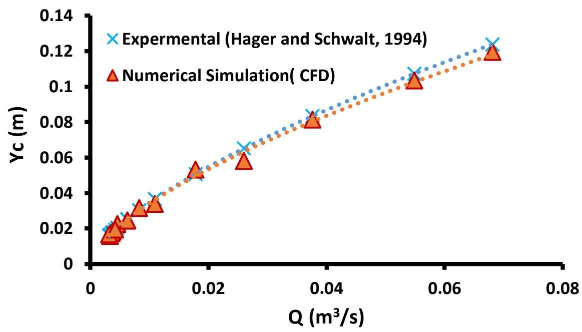

Fig. 4. Comparison of the relationship between flow discharge versus critical depth with experimental and numerical results

development of numerical methods. In this study, in order to investigate the hydraulic properties of the flow in broad-crested weirs, a numerical simulation is used. To simulate the flow over weir, a rectangular flume with length, height and width of 7.0 m, 0.7 m and 0.5 m was considered. The crest of the weir was placed at a distance of 4.83 m from the entry of the flume fixed in all simulations (Figure 1). These conditions correspond to the conditions of the physical-hydraulic model of Hager and Schwalt [2]. In this study, the $k-\varepsilon$ (*RNG*) turbulence model was applied in computational fluid dynamic (*CFD*) simulations by using *ANSYS FLUENT* software. The boundary conditions (BCs) for flume bottom, weir body, flume top, inlet and outlet were selected as wall, symmetry, pressure-inlet and pressure-outlet, respectively. It should be noted that all simulations were implemented in such a way that the number of elements is greater than or equal to 15390 for this computational domain (Figure 2).

3- Results and Discussion

According to the study of Govinda Rao and Muralidhar [7], one of the special features of broad-crested weirs is the creation of sinusoidal waves on the crest of the weir with the ratio of the depth of flow to the length of the crest less than 0.1 (H/L <0.1). The main cause of this type of undular flow is viscosity, which reduces the flow velocity in long weir crest. Chanson [8] introduced the possibility of creating wave on a rectangular broad-crested weir at low flow discharges for a Froude number (F_r) of less than 1.5 (F_r<1.5) at the location where the lowest depth occurs. According to Figure 3, near the upstream corner of the weir crest, after setup the steady conditions, a wave has formed due to the low ratio of the depth of flow to the length of the crest.

Figure 4 shows the relationship between flow discharge versus depth at the control section (or critical depth) for experimental and numerical models. As can be seen, with increasing critical depth on the crest of weir, the discharge flow over the weir increases exponentially. It is also observed that there is a good agreement between experimental and numerical results. Also, in this study, with the obtained results, a regression equation was extracted for the discharge coefficients (C_d) of broad-crested weirs (Eqs. 1-3).

$$C_d = 0.385(\frac{H}{L} - 0.07)^{0.018} - 0.028 \quad (1)$$

$$Q = C_d b\sqrt{2gH_1^3} \quad (2)$$

$$Q = (0.385(\frac{H}{L} - 0.07)^{0.018} - 0.028)b\sqrt{2gH_1^3} \quad (3)$$

4- Conclusions

In this study, using available experimental data, first numerical simulations were performed using the *FVM* with *ANSYS FLUENT* software and then, in addition to investigating the flow discharge in these types of weirs, the creation of undular flow was studied. The following outcomes are provided:

1. The mean *RE%* between the experimental data and the numerical simulation method is 4%.

2. For preventing undular flow, the flow depth cannot be less than a specified value. This limitation was observed for H/L>0.1. Thus it can result that long broad-crested weirs are more susceptible than the broad-crested weirs to the creation of undular flows.

3. The changes of the discharge coefficients with respect to the H/L parameter under conditions of H/L>0.1 are gradual and almost linear.

4. A regression equation was also extracted to estimate the discharge coefficient of broad-crested weirs. The results indicated that this extracted equation can be used to estimate the flow discharge with acceptable accuracy.

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HOW TO CITE THIS ARTICLE

B. Nourani, F. Salmasi, H. Arvanaghi, F. Rezaei, Undular Flow Conditions and Discharge Coefficients in Rectangular Broad-Crested Weirs, Amirkabir J. Civil Eng., 54(1) (2022) 31-34.

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