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LABORATORY AND HEC-RAS SIMULATIONS OF A SINGLE-STEP WEIR

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ABSTRACT

The River Analysis System (HEC-RAS) software was used to simulate the free flow over the broad-crested single-step weir. The software was used to compute the water surface profile, determine the location of the hydraulic jump, and establish the head-discharge relationship for the weir. The simulation results were verified by a series of laboratory measurements using a horizontal flume 5 m long, 0.45 m deep and 0.30 m wide. The tested weir had the following dimensions: total length was 48 cm; length of the downstream step of the weir was 24 cm; total height was 24 cm; height of the downstream step of the weir was 12 cm. Different inflow rates were applied to the weir for tail water depths of 6, 8, 10, 12 and 14 cm under free flow conditions. It was found that HEC-RAS could capture the overall features of the flow profile over the weir with reasonable accuracy. HEC-RAS could also determine the location of the hydraulic jump. It also produced a head-discharge relationship well close to the measured data. Besides, HEC-RAS was found easy to use for this specific flow problem and performed the computations in a short time.

Keywords: single-step weir, HEC-RAS, water surface profile, head-discharge relationship, hydraulic jump, free flow.

1. INTRODUCTION

Today with the improved numerical algorithms and the increasing computing power, using software became essential for solving hydraulic problems. The software can be used as an effective tool for many purposes, such as to evaluate the designs of existing and proposed structure, predict structure performance under different flow conditions, and perform hydraulic calculations for the entire flow field at a cost and time less than physical modelling.

A large number of computer models are available for simulating the hydraulic problems. The models are usually different in their complexity and reliability. It is therefore important that engineers have sufficient knowledge of the abilities and limitations of the models so as to select the suitable software for solving specific flow problems.

One of the most common computer models is the one-dimensional River Analysis System (HEC-RAS) developed by Hydrologic Engineering Center of the US Army Corps of Engineers (USACE). This model can perform computations on 1-D steady and unsteady river hydraulics, sediment transport, and water temperature analysis. Effects of bridges, culverts, spillways, drops and weirs may also be considered in the computations (USACE, 2010).

For the purpose of this study, the studies that have evaluated the performance of HEC-RAS are reviewed herein. HEC-RAS is a very commonly used program, but its performance has rarely been evaluated. Gonzalez (1999) used HEC-RAS to determine the maximum capacity of a floodway channel of a river. It was noticed that HEC-RAS required few input data, but presented a simplified view of the flow pattern with complex channel geometry. Cook (2008) also used HEC-RAS in floodplain mapping and hydraulic modelling of two river reaches. It was found that the simulation in HEC-RAS was easy and quick. Siddique-E-Akbor *et al.* (2011) used HEC-RAS for estimating river water levels in deltaic environments. It was noticed that HEC-RAS had a general tendency to overestimate water levels during high flows and underestimate during low flows. Toombes and Chanson (2011) tested the capability of HEC-RAS to simulate gradually and rapidly varied flows. Two physical models were made to verify the simulation results. The first was a streamlined weir and the second was a channel controlled with upstream and downstream gates. As to the weir flow problem, it was found that HEC-RAS achieved good flow profiles across the weir at low flows. For the high-flow case, significant differences were observed over the weir. However, profiles upstream and downstream of the weir were predicted with good accuracy. For the channel flow problem, the HEC-RAS results were shown to be in good agreement with the measurements. It was concluded that HEC-RAS could model subcritical and supercritical flows, and predict the location of a hydraulic jump with reasonable accuracy.

The preceding review shows that HEC-RAS has mostly been used to model floodplains and channels and it has rarely been evaluated to describe weir flow problems (to the best of author's knowledge).

In the present study, the one-dimensional steady-flow module of HEC-RAS was used to develop the water surface profile, determine the location of the hydraulic jump, and produce the head-discharge relationship for the broad-crested single-step weir.

The performance of this numerical model was evaluated using a series of laboratory experiments that incorporated different free flow situations. The effects of variation of parameters such as the flow rate and the tailwater depth were investigated. It was a major purpose of the present study to discover the advantages and limitations of HEC-RAS for simulating the flow over a stepped hydraulic structure.

2. THE SINGLE-STEP WEIR

Stepped weirs differ slightly from vertical weirs. The addition of stepped downstream faces allows for some

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energy to dissipate at each level. Stepped weirs are appropriate for small structures in waters without heavy sediment loads. Where larger structures are required or bearing capacity of soils is limited, sloped weirs are most appropriate (gabions.net).

The free flow over the single-step weir is shown in Figure-1. The head-discharge relationship for a single-step broad-crested weir with rectangular control section is given by (Hussein *et al*., 2010):

$$Q = \frac{2}{3} C_d B \sqrt{\frac{2}{3} g} \, H^{\frac{3}{2}} \tag{1}$$

$$C_d = 1.02 \left(\frac{H}{P}\right)^{0.05} \left(\frac{L_1}{L}\right)^{0.41} \tag{2}$$

where

- L total length of the weir (m)
- L_1 length of the downstream step of the weir (m)
- P total weir height (m)
- P_1 height of the downstream step of the weir (m)
- Q total flow rate (m^3/sec)
- C_d discharge coefficient
- B width of the channel (m)
- g acceleration due to gravity (m/sec^2)
- H total head over the crest of the weir (m)

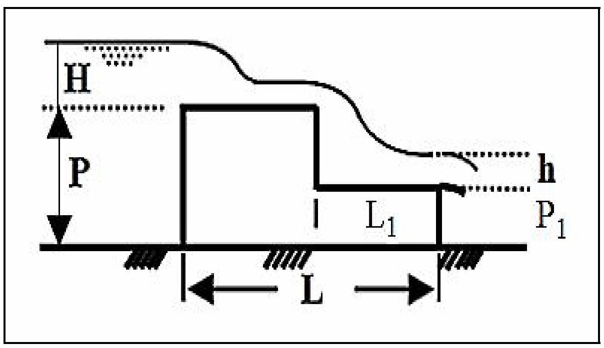

Figure-1. Free flow over single-step weir.

3. THE EXPERIMENTAL WORKS

The single-step weir model was installed in a horizontal rectangular flume. The flume was 5m long, 0.3m wide and 0.45m deep. Water entered into the flume from the head tank and dropped freely in a sump tank at the other end of the flume. The experimental arrangement is shown in Figure-2. A ruler for measuring the tailwater depth was put at the downstream end of the flume. An electro-magnetic flow meter was used to measure the inflow rate. The water surface elevations were measured by using two manual point gauges. The datum was set at the bed level of the flume.

Figure-2. The experimental arrangement.

The tested weir, shown in Figure-3, has the following dimensions: L = 48 cm, L_1 = 24 cm, P = 24 cm, P_1 = 12 cm.

Figure-3. The tested single-step weir.

The weir was setup inside the flume using Plexiglas plates of 6 mm thickness. The parts of the weir were joined together and to the flume bed and sides by silicone sealant. The centerline of the weir was placed at 2.61 m from the upstream end of the flume.

The weir was operated under various free flow conditions. Different flow rates were investigated for tailwater depths, d_{tw} = 6, 8, 10, 12 and 14 cm.

4. DESCRIPTION OF THE RIVER ANALYSIS SYSTEM (HEC-RAS)

The steady-flow module of HEC-RAS can model the flow surface profiles for supercritical, subcritical, and mixed flow regimes in a single river reach or a system of channels (USACE, 2010).

The water surface profile between two cross sections is computed based on the solution of the energy equation, which is defined as:

$$Z_{b1} + d_1 + \alpha_1 \frac{V_1^2}{2g} = Z_{b2} + d_2 + \alpha_2 \frac{V_2^2}{2g} + h_e \tag{3}$$

where

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Z_{b1}, Z_{b2} = bed elevation at the cross sections (m)
d_1, d_2 = depth of flow at the cross sections (m)
V_1, V_2 = average velocity of flow at the cross sections (m/sec)
α_1, α_2 = velocity weighting coefficients at the cross sections
h_e = energy head loss (m)

The above terms are illustrated in Figure-4. This equation is solved with an iterative procedure called the standard step method. Energy equation is valid for uniform and gradually varied flow situations. These situations signify that the streamlines are parallel, that is, the pressure distribution over the channel section is hydrostatic, and that the channel is prismatic with a small bed slope.

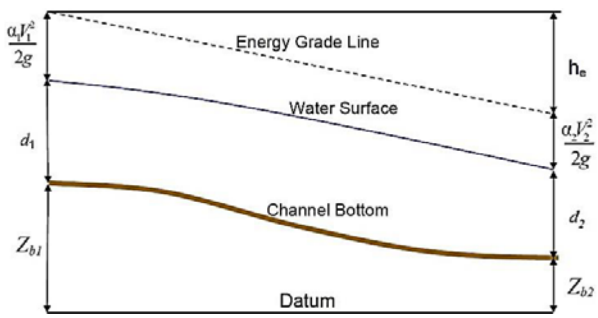

Figure-4. Terms of the energy equation (USACE, 2010).

The energy head loss includes friction losses and contraction or expansion losses. The equation for the energy head loss is as follows:

$$h_e = L\bar{S}_f + C\left|\alpha_1\frac{V_1^2}{2g} - \alpha_2\frac{V_2^2}{2g}\right| \quad (4)$$

where

L = discharge weighted reach length (m)
$\bar{S}_f$ = representative friction slope between two cross sections
C = contraction or expansion losses coefficient

The discharge weighted reach length is calculated as:

$$L = \frac{L_{lob}\,\bar{Q}_{lob} + L_{ch}\,\bar{Q}_{ch} + L_{rob}\,\bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \quad (5)$$

where L_{lob}, L_{ch} and L_{rob} are the reach lengths for flow in the left overbank, main channel and right overbank, respectively; and $\bar{Q}_{lob}$, $\bar{Q}_{ch}$ and $\bar{Q}_{rob}$ are the average flow rates between two cross sections for the left overbank, main channel and right overbank, respectively.

The friction slope for the reach is computed using the average conveyance equation as:

$$\bar{S}_f = \left[\frac{Q_1 + Q_2}{\frac{A_1 R_1^{\frac{2}{3}}}{n} + \frac{A_2 R_2^{\frac{2}{3}}}{n}}\right]^2 \quad (6)$$

where

n = Manning's roughness coefficient (sec/m$^{1/3}$)
Q_1, Q_2 = discharge at cross sections (m^3/sec)
A_1, A_2 = flow area of cross sections (m^2)
R_1, R_2 = hydraulic radius of cross sections (m)

Flow contraction or expansion due to changes in the channel cross section is a common cause of energy losses between two cross sections within a reach. HEC-RAS assumes that a flow contraction occurs when the velocity head increases in the downstream direction; and an expansion occurs when the velocity head decreases (USACE, 2010).

5. RUNNING THE HEC-RAS PROGRAM

Work with the HEC-RAS program was started by creating a project. Then two types of data were needed to be entered into the project:

5.1. Geometric data

The schematic of the channel to be modelled was drawn. Then data of the cross sections along the channel were entered. These data include the station and elevation coordinates, reach length, channel width at the sections, Manning's coefficient, and contraction/expansion coefficient.

In the present study, 74 cross sections were created for the flow problem to perform the simulation process with the desired accuracy. Manning's n coefficient was set within the allowable range (0.009-0.013) (Chow, 1959) for the channel used in the laboratory work.

5.2. Steady flow data

These data include the number of flow profiles to be computed for the weir, the flow rates, and the boundary conditions. The laboratory data of the flow rates, the flow depths, and the tailwater depths were used as boundary conditions in the simulations.

Once the necessary data were entered, the program became ready to run a steady flow simulation. There were three options for the computation of the flow surface profile in the program: subcritical, supercritical, and mixed flow regime. The flow profile over the single-step weir is characterized by a flow change from subcritical to supercritical due to the geometry of the weir, and from supercritical to subcritical due to the hydraulic jump. Therefore, the mixed flow regime was adopted. After the computations were finished, the generated water surface profiles could be viewed in different tabular and graphical forms within the HEC-RAS program.

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6. CALIBRATING THE HEC-RAS PROGRAM

The ability of the HEC-RAS model to predict the characteristics of flow over the single-step weir was tested by comparing the numerical simulation results against the corresponding data from the laboratory experiments. The accuracy of HEC-RAS results was increased by calibrating the program.

The controlling parameter affecting the performance of the HEC-RAS model was the Manning's roughness coefficient. The value of this coefficient was adjusted to fix unstable runs until the computed water surface profiles best represented the observed flow conditions.

7. COMPARISON OF THE COMPUTED AND THE OBSERVED DATA

In order to discover the advantages and limitations of the software for modelling this specific flow problem, a detailed evaluation is performed as follows:

7.1. Water surface profile

The water surface profiles generated by HEC-RAS are compared to the corresponding observed profiles. A sample of the data is shown in Figure-5.

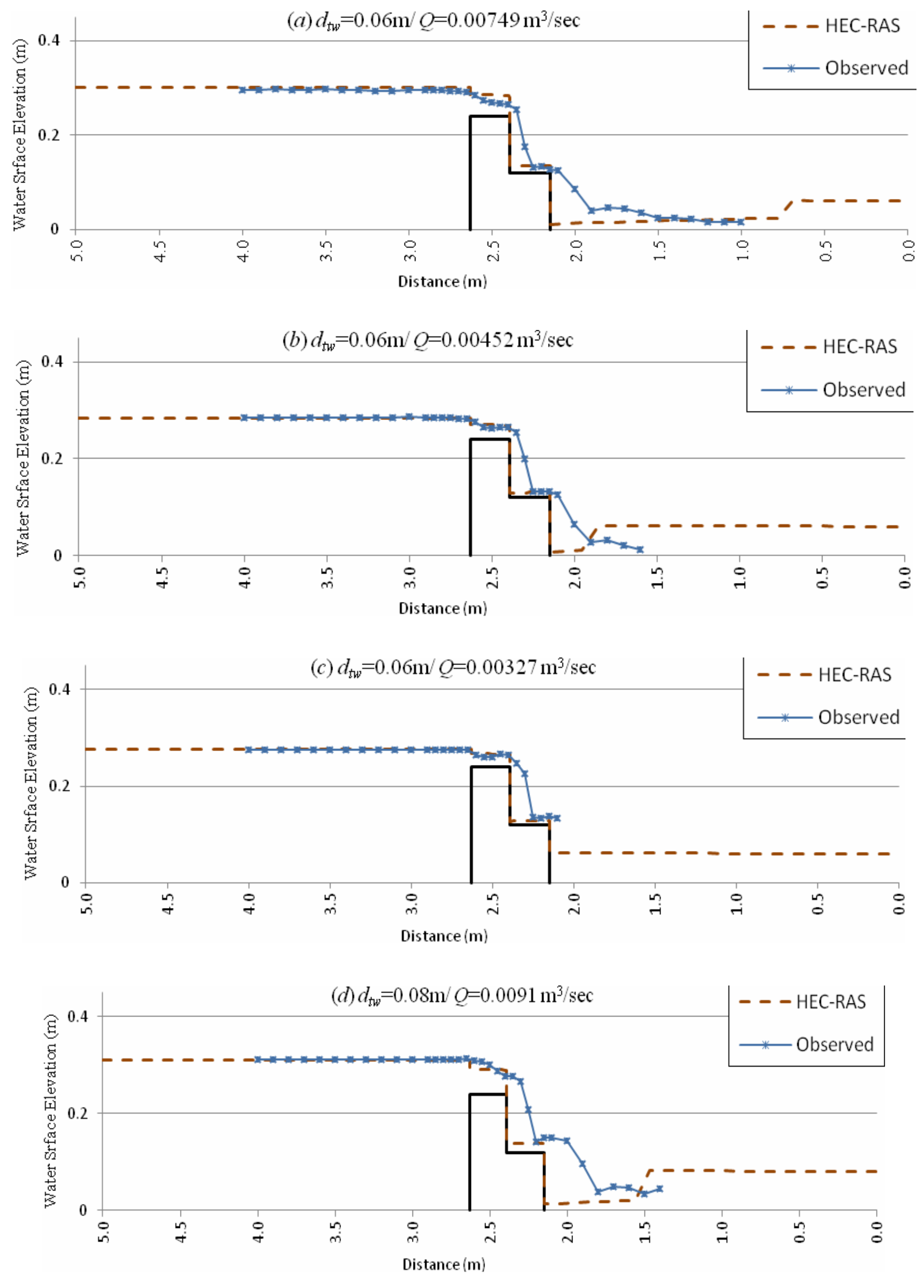

Figure-5(a). Computed and observed water surface profiles over a single-step weir.

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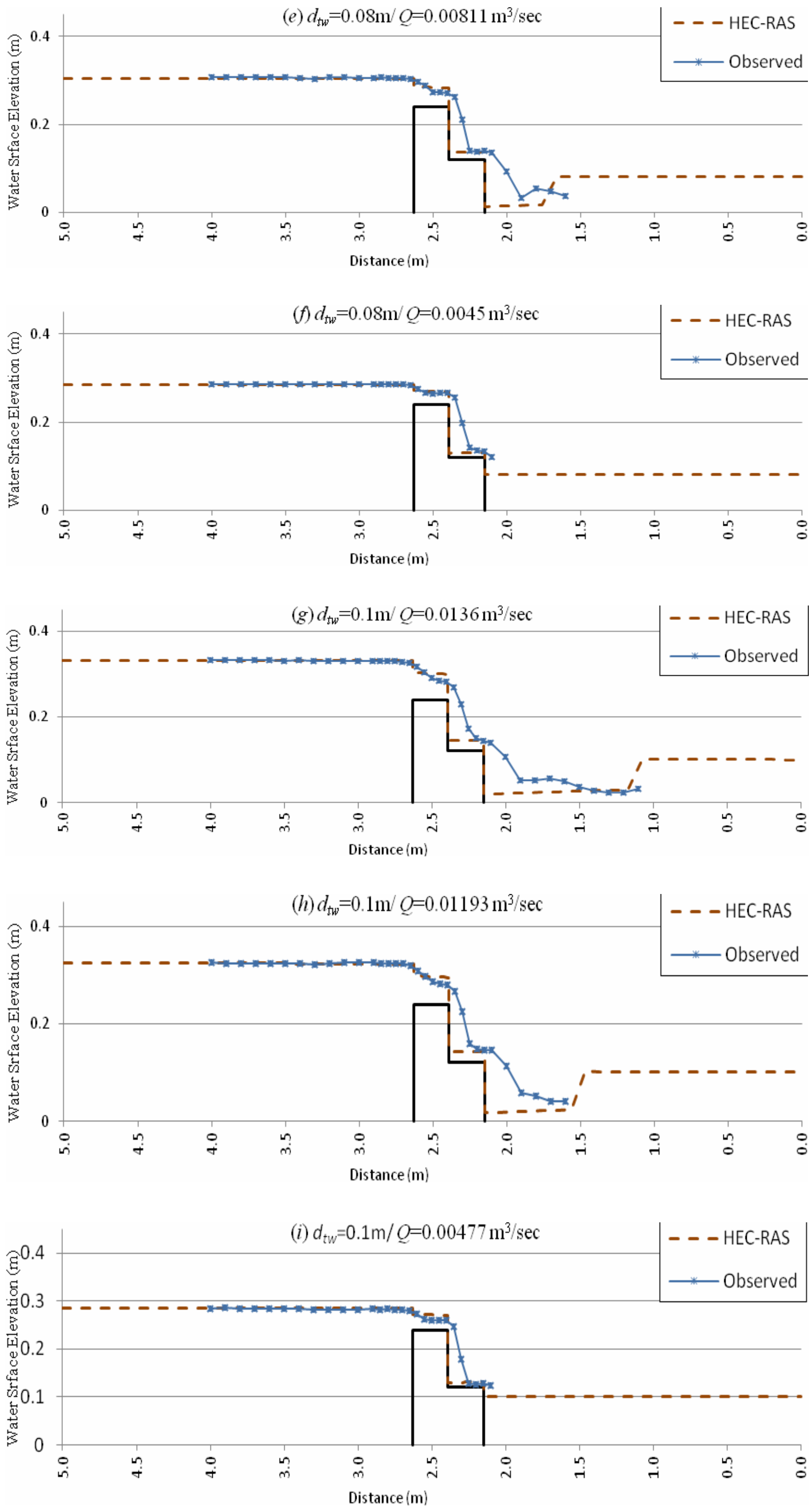

Figure-5(b). Computed and observed water surface profiles over a single-step weir (continued).

It may be seen from the above figures that HEC-RAS well predicted the water surface profile upstream of the weir. The HEC-RAS profile is also in good agreement with the observed profile over the upper part of the weir.

However, it may also be observed that HEC-RAS could not simulate the curvature of the water profile at the hydraulic drops where the water falls from the upper part of the weir to the lower part, and also from the lower part of the weir to the channel bed. HEC-RAS could neither describe the impact of jet occurring after these hydraulic drops. This behaviour is believed to be due to the marked curvature of the streamlines, and the difficulty of forming a smooth transition.

7.2. Location of the hydraulic jump

HEC-RAS proved its ability to predict accurately the occurrence of the hydraulic jump on the horizontal bed of the channel, except when the jump occurs at the toe of the weir at low flow rates. HEC-RAS represents the jump as a straight line.

However, reviewing the second case of Figure-5.a shows that HEC-RAS made an improper prediction of the jump location. The reason behind this unstable performance is not clear. The prediction of the water level in this case is still correct.

7.3. Head-discharge relationship

The head-discharge relationship is established by plotting the total head over the weir crest against the discharge. The experimentally observed results and the predicted head-discharge relationship for the weir are shown in Figure-6.

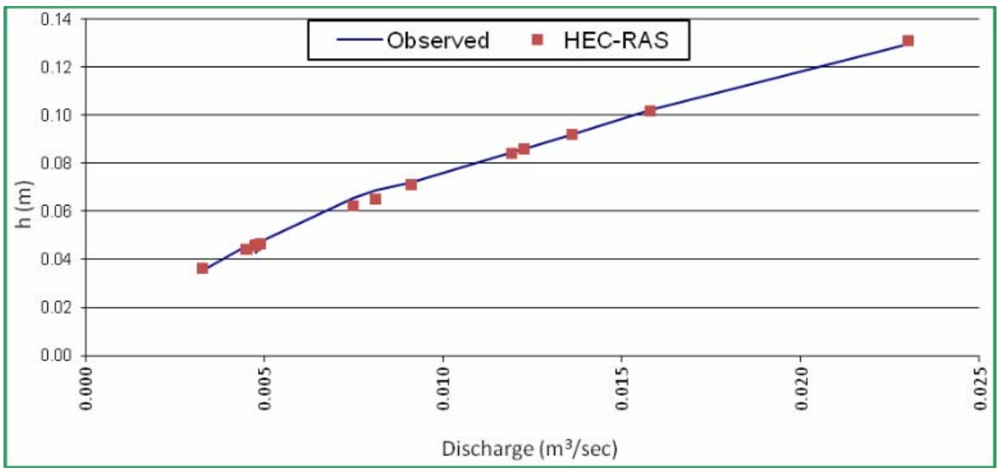

Figure-6. The observed and predicted head-discharge relationship of a single-step weir.

The figure shows that the results produced by HEC-RAS are in good agreement with the laboratory results. Thus, HEC-RAS possess considerable accuracy in estimating this relationship for such stepped hydraulic structure.

7.4. Computational time

The theoretical bases and the solution techniques of the HEC-RAS model are determining factors of the time of computations. In the present simulations, HEC-RAS spent a maximum time of less than (30) seconds to compute the water surface profiles over the weir.

This significantly short run time is owed to the governing equations and solution approaches followed by HEC-RAS. The 1-D steady-flow component of HEC-RAS is based on the energy equation, which involves a number of simplifying approximations that help reduce computational complexity. Furthermore, the energy equation is solved by the standard step method, which is a relatively simple iterative approach applied easily to 1-D grids and, hence, contributes to the short computation time.

7.5. Ease of use

In addition to the run time, inputting data and displaying the results are other parts of the simulation process. From this perspective, HEC-RAS with its simple interface windows was found easy to create and modify the geometric data file for this specific flow problem.

Besides, it is apparent from the running procedure of HEC-RAS, illustrated previously, that it requires no initial conditions and also demands few boundary conditions data, resulting in significant savings in effort and time.

However, HEC-RAS offers simple and not quite descriptive graphs, but it offers tabular forms that are quite flexible for viewing the results.

8. CONCLUSIONS

The1-D steady-flow HEC-RAS module was used to describe the water surface profile, determine the location of the hydraulic jump, and produce the head-discharge relationship for the single-step weir. Performance of the numerical model was evaluated by free flow laboratory tests on the weir.

From analysing and comparing the HEC-RAS results to the observed results, the following conclusions may be drawn:

a) HEC-RAS could compute the water surface profile upstream of the single-step weir very well.
b) HEC-RAS could simulate accurately the water surface profile over the upper part of the single-step weir.
c) HEC-RAS could not simulate the curved flow past the vertical faces of the single-step weir.
d) HEC-RAS could not simulate the impact of jet past the vertical faces of the single-step weir.
e) HEC-RAS could accurately determine the location of the hydraulic jump on the channel bed when the jump was not at the toe of the weir.
f) HEC-RAS presented precise results of the head-discharge relationship for the single-step weir.
g) HEC-RAS is easy and friendly to use. It demands few boundary conditions data and required no initial conditions. The geometric data file for this specific flow problem was also found easy to create and modify.
h) HEC-RAS computes the one-dimensional free-flow surface profiles very quickly. The computation time was less than a half minute.

However, the performance of the steady-flow module of HEC-RAS on the single-step weir is expected to be the same for a multi-step weir flow problem.

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