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Prediction models for discharge estimation in rectangular compound broad-crested weirs

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ABSTRACT

Experimental results of the flow of water over 9 different rectangular compound broad-crested weirs with varying lower weir crest width and step height were analyzed to develop prediction models for discharge estimation. The compound cross sections were formed by a combination of three sets of step heights and three sets of lower weir crest widths in a horizontal laboratory flume of 11.0 m length, 0.29 m width and 0.70 m depth. Flow depths at the approach channels were measured for a wide range of discharges. The dependence of the discharge coefficient (C_d) and approach velocity coefficient (C_v) on different parameters of the model was investigated. Multiple regression equations based on three dimensionless ratios R_2, R_3 and R_4 for C_d and three dimensionless ratios R_1, R_2, and R_4 for C_v were developed. Two derived prediction models can be used for the prediction of discharge over rectangular compound broad-crested weirs for free flow regime. The predictive capabilities of these models were evaluated using the experimental data obtained. By using the general equations of C_d and C_v, one can estimate the flow discharge in rectangular compound broad-crested weirs when the head at the upstream head measurement section, $h_{1,}$ is given with an absolute mean error of less than 5%.

1. Introduction

Most flow measurement structures in open channels are operated by producing flow at critical-depth or critical flow through a control section of known dimensions. For this flow condition, the discharge through the critical section is a function of the upstream potential energy and the section shape, as indicated by the water level upstream from the structures. There are many critical-flow devices such as broad-crested weirs, sharp-crested weirs and long-throated flumes, and various investigators have done many studies related to these types of flow measuring structures of open channels [1–8].

In practice, a compound weir composed of triangular, trapezoidal and/or rectangular parts in the cross section is a common device for flow control in mountainous gullies and canals. From the discharge equations developed for a compound triangular sharp-crested weir that was composed of two triangular parts it was concluded that the proposed equations could provide a good estimation of the discharge coefficient for the upper part of the weir providing that the discharge coefficients from single V-notch weirs are previously known [9–11]. The studies conducted by Göğüş and Al-Khatib [12], Özkandemir [13], Göğüş et al. [14] and Al-Khatib et al. [15] are the ones related to hydraulic properties of weirs and flumes of rectangular compound cross sections.

According to the United States Bureau of Reclamation (USBR) [16], broad-crested weirs are specially shaped weirs that can be designed to fit more complicated channel cross sections better than other weirs, and the shape of the control section can be selected considering the range of variations of the discharge and head. Other advantage is that some types of broad-crested weirs can easily pass sediment and floating debris better than sharp crested weirs, especially those having sloped upstream transitions or round noses at the upstream sections. In addition, submergence does not affect the operation of the broad-crested weirs up to about 90% with sloped downstream transitions and up to about 80% with vertical downstream drops.

The purpose of this study is to document the stage–discharge relationship on a broad-crested weir with a rectangular compound cross section, to experimentally analyze the effect of geometry (step height, z, and lower weir crest width, b) on the discharge coefficient and approach velocity coefficient of the models tested and finally to develop prediction models to estimate the discharge.

1.1. Theoretical considerations

An equation for the flow rate, Q, can be obtained by applying the energy equation between the head measurement section and the control section, when the fluid is considered frictionless or

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Nomenclature

A^*	imaginary wetted area at control section if water depth were equal to h_1;
A_c	cross-sectional area at control section;
A_1	cross-sectional area of flow at head measurement section;
B_o	top width of head measurement section and weir model cross section;
b	lower weir crest width of model;
C_d	discharge coefficient;
C_v	approach velocity coefficient;
g	acceleration of gravity;
H_1	total energy head at upstream head measurement section;
h_1	head at upstream head measurement section;
L	length of weir crest in direction of flow;
MSE	mean squared errors;
MSPR	mean of the squared prediction errors;
n	dimensionless power depending on shape of broad-crested weir;
P	height of weir crest (sill);
Q	volumetric rate of flow;
Q_m	measured discharge;
Q_p	predicted discharge;
R-square	determination coefficient;
R_1	$\sqrt{\propto} C_d A^*/A_1$;
R_2	y_f/h_1;
R_3	h_1/L;
R_4	B_o/b;
r_1	rounding at entrance of lateral contraction resulting from lower weir crest part of weir crest cross section;
r_2	rounding at entrance of weir at top of step of weir crest cross section;
V_c	average critical flow velocity at control section;
VIF	variance inflation factors;
V_1	average flow velocity at upstream head measurement section;
W	coefficient depending on the size and shape of the weir;
y_c	critical water depth at control section;
z	step height of model cross section; and
α	energy correction coefficient

ideal (Fig. 1). A number of assumptions are made in the derivation of this theoretical discharge, and therefore, this discharge equation must be adjusted for real fluids by introducing a coefficient for the broad-crested weirs regardless of the throat cross section as stated below:

$$Q = C_d W H_1^n \tag{1}$$

where Q=volumetric flow rate; W=coefficient depending on the size and shape of the weir; H_1=total energy head at the head measurement section and n=dimensionless number depending on the shape of the cross section of the control section, which is equal to 3/2 for rectangular cross sections. Here, C_d=discharge coefficient introduced to correct for a number of assumptions which are: the flow streamlines are parallel, hydrostatic pressure distribution over the crest prevails, boundary layer thickness is overlooked compared to the flow depth over the crest velocity distribution at the head measurement and control sections are uniform [17–21].

For practical purposes, it is difficult to measure the total energy head, H_1, directly in open channels. Therefore, it is a common practice to relate the flow rate to the upstream sill-referenced head, h_1, in the following form:

$$Q = C_d C_v W h_1^n \tag{2}$$

where C_v=approach velocity coefficient, which corrects for neglecting the velocity head at the head measurement section.

Regarding the present study, for the model tested at the laboratory (Fig. 1), the head–discharge relationships for broad-crested weirs of rectangular compound cross section can be presented for two different cases, as shown in Fig. 2. Details of the derivations are presented by different authors [13,20–22].

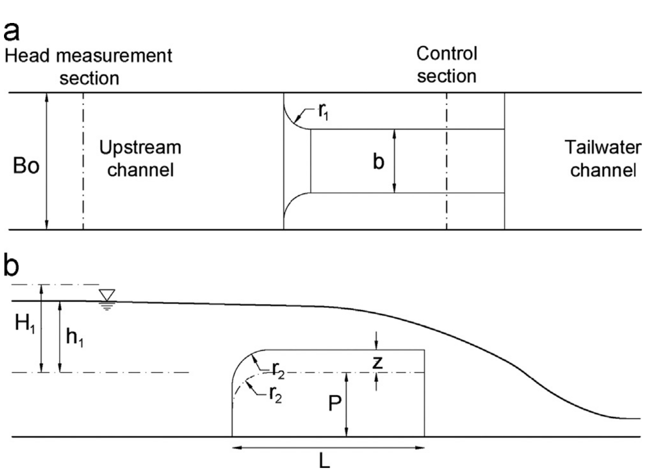

Fig. 1. Definition sketch of models used in theoretical analysis: (a) plan view; (b) longitudinal profile.

Case 1. ($h_1 \le z$ and $y_c \le z$)

In this case, the flow occurs only through the lower weir crest part of the compound cross section and the weir works like a simple traditional broad crested weir. In this case, the total energy of the flow at the upstream of the weir will be less than 1.5z. For this case, the stage–discharge relationship, C_d and C_v can be obtained as [12,18,19,22].

$$Q = \frac{2}{3} C_d C_v b \left(\frac{2}{3} g\right)^{1/2} h_1^{2/3} \tag{3}$$

where

$$C_d = \frac{3}{2} \frac{Q}{b\left(\frac{2}{3}g\right)^{1/2} H_1^{2/3}} \tag{4}$$

$$C_v = \left(\frac{H_1}{h_1}\right)^{3/2} \tag{5}$$

where g=acceleration of gravity

Case 2. ($h_1 > z$, $y_c > z$)

In this case, the depth at the control section i.e., the critical depth is greater than z and the flow occurs through the compound cross section and $H_1 > 1.5z$. Applying the energy and continuity