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Derivation of discharge coefficient of a pivot weir under free and submergence flow conditions

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ABSTRACT

A pivot weir is a measuring and regulating structure that benefits fixed weirs and can be used to set the level of water from long distances in modern irrigation networks utilizing a mechanical lift. Earlier studies have shown that the discharge coefficient of a pivot weir is mostly based on experimental results and few studies have used theoretical approaches to estimate this coefficient. In this paper, analytical equations are proposed to estimate the discharge coefficient of a pivot weir and the results are compared with those of experimental approaches. The equations proposed in this study are based on the Bernoulli and momentum equations for both free and submerged flow conditions. The correction coefficients in the proposed equations have been determined using experimental data. The results show that the proposed equations offer less complexity and higher accuracy when estimating the pivot weir discharge coefficient than the results of earlier studies. Furthermore, these equations can be used as full range standard equations because of their theoretical basis.

1. Introduction

A pivot weir is an overflow structure that includes a hydraulic system. It is widely used in irrigation canals to measure, control, regulate and stabilize the upstream water surface of sub-channel flow. This structure can be set at different levels for a variety of upstream discharge rates and depths. The ability to maneuver and change pivot weir performance by remote control is among the advantages of this structure.

The hydraulic performance of pivot weirs structure has been the subject of limited study. Schoder and Turner (1929) studied the geometric conditions of the pivot weir edge [10]. Villemonte (1947) proposed an equation to estimate the reduction factor of discharge in a sharp-edged vertical submerged weir [13]. The viscosity and surface tension as effective parameters in the estimation of the pivot weir discharge coefficient were studied by Kindsvater and Carter [7].

Studies on pivot weir discharge coefficients under free and submerged flow conditions were carried out by Wahlin and Replogle [14]. They provided an experimental equation (Eq. (1)) to estimate discharge coefficient of pivot weir as follows:

$$Q = C_a C_r C_e \frac{2}{3}\sqrt{2g}\,[(h_1 + K_h)(b_c + K_b) - 2A_s \cos\theta]\sqrt{h_1 + K_h} \tag{1}$$

where b_c is the weir crest width, A_s is the cross-section area, h_1 is the upstream head, g is the acceleration of gravity, θ is the weir angle to the horizon and C_a,C_r,C_e,K_h, and are experimental coefficients as defined by Wahlin and Replogle [14]. It can be seen that in order to define this equation, numerous experimental parameters are necessary.

Ferro (2000, 2001) provided a new method for estimating the discharge coefficient for sluice gates based on incomplete self-similarity theory [4,5]. Prakash et al. (2011) derived an experimental relation for the discharge coefficient of a pivot weir based on the weir slope in a laboratory environment. Their proposed relation showed 4.37–9.69% error when compared to the results of laboratory experiments for different angles. They concluded that an increase in the angle of the pivot weir will increase the discharge coefficient [9].

Nikou et al. (2016) derived an analytical method for estimating the discharge coefficient of a pivot weir for both free and submerged flow conditions using only the Bernoulli equation. The validation of this relation with experimental data showed ± 20% error, which indicates insufficient accuracy in estimating the discharge coefficient [8]. Di Stefano et al. (2016) conducted research using previous experimental results to estimate the weir discharge coefficient in order to provide a general discursive equation for estimating the discharge coefficient for complex types of weir. The validation of this equation with the experimental results shows a ± 10% relative error [3].

Bijankhan et al. (2017) collected several stage discharge relationships for weirs and their dimensional analysis in a review paper [1]. A review of previous studies shows that most researchers used experimental equations to estimate the pivot weir discharge coefficient with a

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List of symbols

Q	discharge of flow
C_d	discharge coefficient
b, b_c	width of the weir
h	depth of water on the weir
C_c	contraction coefficient
F	force
μ	dynamic viscosity
σ	surface tension
ρ	density of water
k_e, k_m	correction coefficients in Bernoulli's and momentum equations
y_0	upstream water depth
y_t	downstream water depth
C_r, C_a, K_h, and K_b	empirical coefficients
P	weir height
g	acceleration due to gravity
L	length of weir
a,s,η	dimensionless parameters
θ	angle of the diversion weir
γ	specific gravity of water

focus on vertical sharp-edge weirs. These investigations impose numerous experimental coefficients in a hypothetical regression form for estimating the discharge coefficient. The downside of such assumption is that assuming a regression form is not always realistic and may not provide acceptable accuracy.

Although the equations from previous studies are applicable for a range of measurements, the authors believe that proposing a formula based on appropriate theoretical principles results in a more acceptable degree of effectiveness for the parameters introduced in the equation. Furthermore, they are less influenced by the measurement range and are closer to reality.

In this study, an analytical method is considered for estimating the discharge coefficient relationship. For this purpose, Bernoulli and momentum equations have been used. After some simplification, the discharge coefficient can be estimated. The simplification is carried out by introducing two calibration coefficients which were obtained using experimental data. These final proposed equations are validated with complementary experiments. To the knowledge of the authors, this is the first time that this procedure has used equations with less complexity, higher accuracy and more generality for both types of flow on pivot weirs.

2. Dimensional analysis

Previous studies have shown that the overflow discharge from a pivot weir is primarily a function of flow depth and the geometric conditions of the channel. The basic parameters for overflow discharge of a pivot weir under free-flow conditions can be expressed as follows:

$$Q = f(y_0, L, b, B, \mu, g, \rho, \theta, \sigma) \tag{2}$$

The overflow discharge under submerged conditions is a function of following parameters:

$$Q = f(y_0, L, b, B, \mu, g, \rho, \theta, \sigma, y_t) \tag{3}$$

The parameters in Eqs. (2) and (3) are shown in Fig. 1. In this figure, y_0 is the upstream water depth, L is the length of the weir, B is the width of the main channel, b is the width of the sub-channel, y_t is the downstream water depth, ρ is the density of the water, μ and σ are the dynamic viscosity and surface tension, respectively, and θ is the angle of the weir.

Discharge coefficient)C_d(is used to introduce the effects of the velocity head in the approach channel, the viscous effects, turbulence and non-uniform velocity distribution under the discharge-estimating equation (Eq. (8)). Using the Buckingham Π theorem and choosing B and $P = L\sin\theta$ as repeating variables, and by neglecting the effects of surface tension and viscosity under turbulent flow conditions and considering sufficient depth on the weir, the discharge coefficient of the free flow based on Eq. (2) can be shown as follows:

$$C_d = f(y_0/P, b/B, \theta) \tag{4}$$

Under submerged flow conditions, it can be written as:

$$C_d = f(y_0/P, b/B, s = y_t/y_0) \tag{5}$$

3. Methodology

3.1. Bernoulli equation under free-flow conditions

Fig. 1 shows the longitudinal section of flow over a pivot weir. Under free-flow conditions, the downstream water depth is less than the height of the weir (*P*) and it is possible to use the Bernoulli equation

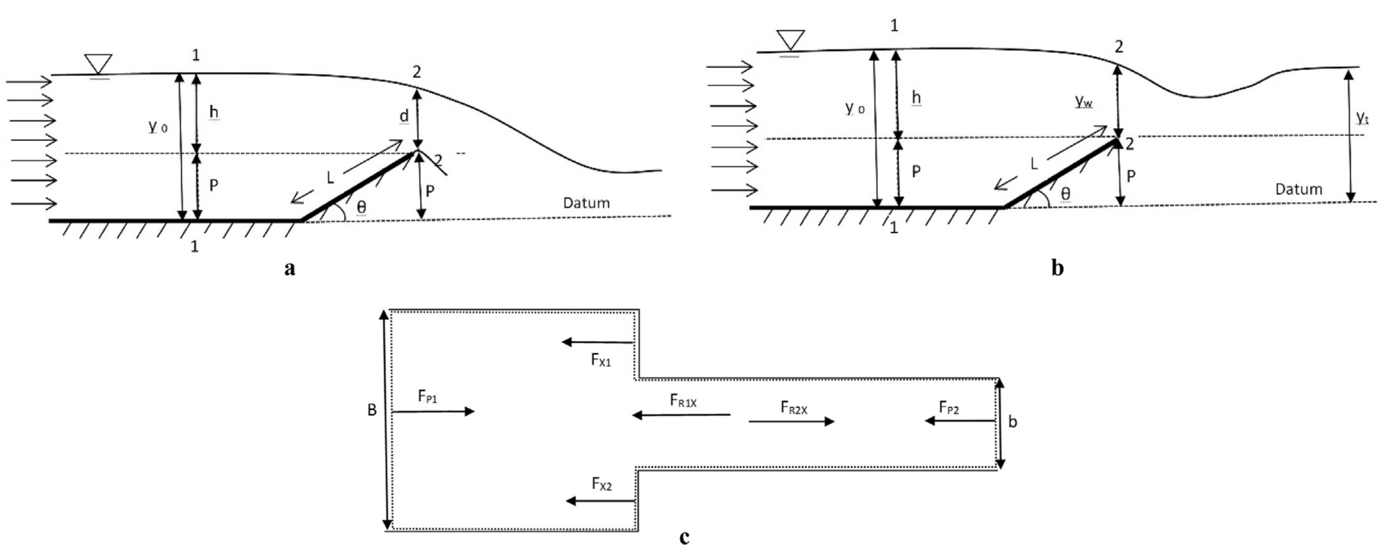

Fig. 1. Pivot weir specifications and parameters: (a) free-flow section view; (b) submerged flow section view; (c) plan view.