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Free-flow discharge estimation method for Piano Key weir geometries

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ABSTRACT

Currently, many existing spillways located throughout the globe require rehabilitation due to dam safety issues. Consequently, there is an increasing need for design tools that facilitate better, more economical spillway designs. Piano Key weirs (PK weirs), the focus of this study, represent one option to address spillway deficiencies. Two design approaches used by practitioners for estimating PK weir discharge were examined: (1) empirical prediction methods ranging from simple to sophisticated and (2) computational fluid dynamics. This evaluation included five published empirical design methods and CFD simulations featuring two different turbulence models (*i.e.,* LES and RNG k-ε). The results indicate that, depending on geometry, differences exceeding 30% can exist between predictive method and experimental results. Also, CFD discharge results were relatively independent of turbulence closure schemes and showed very good agreement with experimental data (mean relative errors of 3–4%). Finally, recommendations are presented to designers that include a new empirical equation for Type-A PK weir geometries and rectangular labyrinth weirs.

1. Introduction

Through inspection or engineering study, a spillway may be identified as deficient in one or more of the following areas: hydraulic capacity, structural integrity, operation, performance, and maintenance. Currently, many existing spillways located throughout the globe require rehabilitation due to dam safety issues. For example, in the USA the Association of State Dam Safety Officials (ASDSO) estimates that over 1600 state-regulated, High-hazard potential dams are in need of rehabilitation at a total cost of more than $18.2 billion (ASDSO, 2015). Certainly, there is motivation for continued development of various hydraulic design tools that facilitate better, more cost-effective designs to address these deficiencies.

An approach to overcoming capacity-deficient spillways is to increase the crest length of the control section, or add a passive-control auxiliary spillway. However, increasing the width of the spillway or adding overtopping protection may be prohibitive due to site conditions and anticipated construction costs. As a result, extended crest lengths are often achieved by folding the weir into more compact three-dimensional weir shapes such as: arced, duckbill, and minimum energy loss (MEL) weirs; box-inlet drop spillways; and labyrinth weirs (Crookston and Tullis, 2013a,b). A recent development is the Piano Key Weir (PK weir) that further reduces the spillway footprint (relative to labyrinth weirs) via ramps, overhangs, and placement of longitudinal weir walls in parallel (see Fig. 1). Numerous research and case studies have been performed during the past 15 years with recent projects being completed in Europe, Asia, and Australia (Erpicum et al., 2013, 2011). A PK weir may be used with embankment dams, placed on an abutment or crest of a gravity dam, or in natural channels as a run-of-river structure. Due to their hydraulic performance, labyrinth and PK weirs have been used to replace structurally deficient spillways, gated systems, and to improve operations and maintenance.

2. PK weir head-discharge predictive methods

2.1. Empirical methods

The geometry of a PK weir is perhaps infinitely variable. However, there are four general types (Pralong et al., 2011a) with the Type-A PK weir being more common. Standardized geometric sub-identifiers include the ratio of the inlet (W_i) and outlet (W_o) key widths, ramp slopes (S_i, S_o), length of overhangs (B_i, B_o) relative to the PK weir base (B), and appurtenant features such as crest shape, parapets, and fillets. For specific projects, discharge estimation via physical modeling is preferred but not always feasible. Therefore, alternative means for estimating a discharge rating curve have been developed. Considerable literature is available, with a summary of notable PK weir design methods derived from systematic studies presented in Table 1.

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Nomenclature

a, b, c, d	empirical coefficients for Eq. (2)
B	PK weir total streamwise length
B_b	PK weir base streamwise length
B_i	inlet key overhang length
B_o	outlet key overhang length
c	Smagorinsky coefficient
C_d	dimensionless discharge coefficient
ε_{Cd}	relative error of simulation results for C_d
ε_Q	relative error of simulation results for Q
g	gravitational constant
h	piezometric head relative to the weir crest elevation
H	total upstream head of a weir relative to the normal weir crest elevation
k_T	maximum turbulence mixing length (MTML)
L	total weir centerline crest length
l	LES turbulence model kinematic eddy viscosity sub-grid length scale
N	number of PK weir cycles or total number of data
ν_T	LES turbulence model kinematic eddy viscosity used to represent the effects of turbulence
O	observed or experimental results
P	weir height
Q	weir discharge
$Q_{PK\text{-}weir}$	PK weir discharge
Q_{lin}	linear weir discharge
S	simulation results
$\bar{S}$	LES turbulence model kinematic eddy viscosity strain rate tensor component
S_o	outlet key slope
S_i	inlet key slope
T_s	wall thickness of weir
V	velocity
W_i	inlet key transverse length
W_o	outlet key transverse length
W_u	PK weir unit or key width

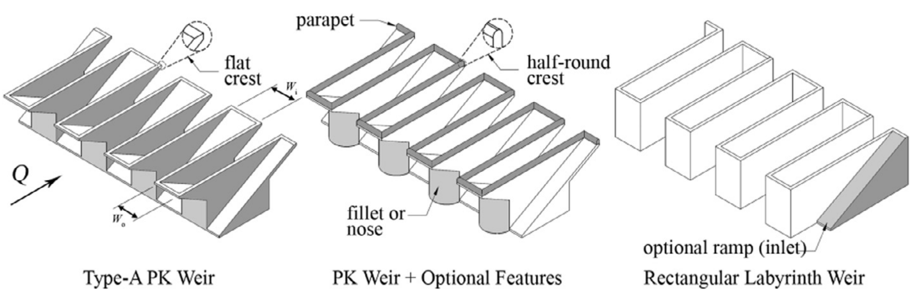

Fig. 1. PK weir geometries tested by Anderson (2011).

Lemperiere (2009) presents a simplified empirical equation for unit discharge as a function of weir height and driving head. Anderson (2011) and Anderson and Tullis (2013) developed a design method (additional details in subsequent section) for a variety of 4-unit PK weir and rectangular labyrinth (RL) weir geometries (see Fig. 1) of common scale. Their approach is similar to the published labyrinth weir design methods of Crookston and Tullis (2013a,b) and Tullis et al. (1995) that utilize geometry-specific, H/P-dependent discharge coefficient (C_d) data. Kabiri-Samani and Javaheri (2012) presented experimental data for “thin-wall” PK weirs with similar W_i/W_o and $B_{i,o}/B$ geometries as Anderson and Tullis (2013). Leite Ribeiro et al. (2012) used half-round crest shapes and greatly expanded design parameter ranges with H/P values approaching 3.0. This method is based on the flow magnification ratio ($Q_{PK\text{-}weir}/Q_{lin}$) where the PK weir discharge ($Q_{PK\text{-}weir}$) is divided by the discharge of a linear weir (Q_{lin}), (discharge coefficient of 0.42) of an equivalent channel width. This method elegantly incorporates the influence of variations in $L, W, P, H, W_i/W_o, B_o, B_i, B,$ and parapet effects via four correction factors. Machiels et al. (2014, 2015) provides an alternative approach by partitioning the PK weir discharge into upstream, downstream, and sidewall sections with corresponding analytical equations. Although the most complicated and calculation intensive design method of those highlighted herein (Table 1), it also provides a considerable amount of flexibility with respect to PK weir geometric design variability. However, they reported an accuracy of 10% between their empirical predictions and experimental results.

Table 1
Summary of notable PK weir design methods and corresponding parameter ranges.

Study	W_i/W_o	$B_{i,o}/B$	H/P	Crest type
Lempériére (2009)	1.25	0.5	0.27–1.3	Sharp
Anderson and Tullis (2013)	0.67–1.50	0.00–0.25	0.05–0.9	Flat, half-round
Kabiri-Samani and Javaheri (2012)	0.33–1.67	0.00–0.26	0.10–0.6	Sharp
Leite Ribeiro et al. (2012)	0.50–2.00	0.20–0.40	0.08–2.8	Half-round
Machiels et al. (2014, 2015)	0.46–2.18	0.00–0.45	0.06–3.2	Flat

2.2. Equation for Anderson and Tullis (2013) method

The Anderson and Tullis (2013) design method uses a standard form of the weir equation, Eq. (1), to estimate PK weir discharge:

$$Q = \frac{2}{3} C_d L \sqrt{2g} H^{3/2} \quad (1)$$

where Q is the volumetric discharge, L is the total crest length (sum of all the sidewall and upstream, and downstream apex weir crest segments illustrated in Fig. 1), g is the gravitational acceleration constant, and H is the total upstream head (piezometric + velocity head) measured relative to the weir crest. Various configurations of the basic PK weir geometry [Fig. 1(a)], were developed by adjusting the W_i/W_o ratio. Additional PK weir geometries were created by adding optional features [see Fig. 1(b)] such as noses (or fillets) to the upstream faces, parapets, and/or improved crest shapes (half-round). The RL weir [Fig. 1(c)] geometries were tested with and without optional floor ramps. The 13 different PK and RL weir geometries evaluated by Anderson (2011) and Anderson and Tullis (2013) are summarized in Table 2 and illustrated in Fig. 2. However, neither their method nor Anderson (2011) provide empirical equations to designers to estimate C_d. Therefore, to facilitate this analysis and aid designers, a new statistically best-fit trend line equation is presented as Eq. (2), which is based upon the Anderson and Tullis (2013) design method and additional geometries tested by Anderson (2011), written as:

$$C_d = 1/[a + bH/P + c/(H/P)] + d \quad (2)$$

where the empirical coefficients a, b, c, and d are summarized in Table 2