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A simplified physically-based breach model for a high concrete-faced rockfill dam: A case study

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Abstract

A simplified physically-based model was developed to simulate the breaching process of the Gouhou concrete-faced rockfill dam (CFRD), which is the only breach case of a high CFRD in the world. Considering the dam height, a hydraulic method was chosen to simulate the initial scour position on the downstream slope, with the steepening of the downstream slope taken into account; a headcut erosion formula was adopted to simulate the backward erosion as well. The moment equilibrium method was utilized to calculate the ultimate length of a concrete slab under its self-weight and water loads. The calculated results of the Gouhou CFRD breach case show that the proposed model provides reasonable peak breach flow, final breach width, and failure time, with relative errors less than 15% as compared with the measured data. Sensitivity studies show that the outputs of the proposed model are more or less sensitive to different parameters. Three typical parametric models were compared with the proposed model, and the comparison demonstrates that the proposed physically-based breach model performs better and provides more detailed results than the parametric models.

Keywords: Concrete-faced rockfill dam; Physically-based breach model; Parametric breach model; Sensitivity analysis; Gouhou CFRD

1. Introduction

The concrete-faced rockfill dam (CFRD) is a type of dam widely used throughout the world for different purposes, with sizes ranging from small irrigation projects to large reservoirs on major rivers. The CFRD design is considered to have a high degree of fundamental safety, especially against strong earthquake shaking, and to be appropriate for high dams (Li and Yang, 2012; Cen et al., 2016; Chen et al., 2016). It also has substantial advantages over the clay-core rockfill dam design (Sherard and Cooke, 1987), e.g., lower cost and easily available materials. This has led to the selection of the CFRD design for very large reservoirs, for which low-level release facilities are neither feasible nor necessary (Sherard and Cooke, 1987; Modares and Quiroz, 2016; Gurbuz and Peker, 2016). At present, with the development and utilization of water resources, an array of high CFRDs with heights greater than 200 m are being built or planned in China (Chen, 2015; Zhou et al., 2015a; Du et al., 2015). These high dams and large reservoirs will bring tremendous financial benefits, but hidden safety issues should be given more attention (Zhou et al., 2015b; Jia et al., 2016; Yang et al., 2016; Niu et al., 2016). Although the CFRD has many advantages, there have also been some failure cases due to overtopping or seepage erosion (Wahl, 1998; Xu and Zhang, 2009; Xu, 2010). For several decades now, a series of physically-based breach models for earth dams have been put forward (ASCE/EWRI Task Committee on Dam/Levee Breaching, 2011; Chen, 2012; Xie et al., 2013; Zhong et al., 2016). Unfortunately,

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there have been few records made of CFRD breach modeling, except for some parametric models.

Investigation of CFRD failure cases around the world has revealed that only the Gouhou CFRD breach case in China has detailed records. Based on the survey data and model tests, the Gouhou CFRD breach may have begun with a piping failure. The subsequent breaching process can be delineated as follows: At first, a large amount of water leaked at the junction of a concrete slab and the bottom of a wave wall (Fig. 1). Then, the drained water scoured the downstream slope and caused sloughing. Under the effects of piping, scouring, and sloughing, the wave wall collapsed, and then overtopping dominated (Liu et al., 1998). Owing to the support of the concrete slab, the water head of overtopping flow increased slowly at the initial stage. With the erosion of dam materials, the breach crest diminished, and the length of the concrete slab suspended in air increased. The concrete slab broke off when it could no longer support the self-weight and water loads, and the discharge increased rapidly after the breaking of the concrete slab (Li, 1995; Chen et al., 2012). Then, the breach continued to deepen and widen until the remaining dam was stabilized under various loads.

In this study, based on the survey data and model tests of the Gouhou CFRD breach case, a simplified physically-based breach model for the Gouhou CFRD was developed. Considering the dam height, the initial scour position on the downstream slope was simulated using a hydraulic method. The broad-crested weir equation was used to simulate the breach flow discharge. The backward erosion was considered the key mechanism of breaching of compacted rockfill materials, which was reflected with a time-averaged headcut migration rate from an empirical formula of the energy method. The moment equilibrium method was adopted to simulate the ultimate length of the concrete slab.

2. Numerical model for Gouhou CFRD breach

2.1. Water balance equation

The water balance equation for the reservoir can be described as

$$\frac{\mathrm{d}V}{\mathrm{d}t} = A_s \frac{\mathrm{d}z_s}{\mathrm{d}t} = Q_{in} - Q_b - Q_{spill} - Q_{sluice} \tag{1}$$

where V is the volume of water in the reservoir, t is time, A_s is the surface area of the reservoir, z_s is the water surface elevation, Q_{in} is the inflow discharge, Q_b is the breach flow, Q_{spill} is the flow through spillways, and Q_{sluice} is the flow through sluice gates.

2.2. Breach flow

The overtopping flow at the breach can be calculated using the broad-crested weir equation:

$$Q_b = k_{sm}\left(c_1 B_b h^{1.5} + c_2 m h^{2.5}\right) \tag{2}$$

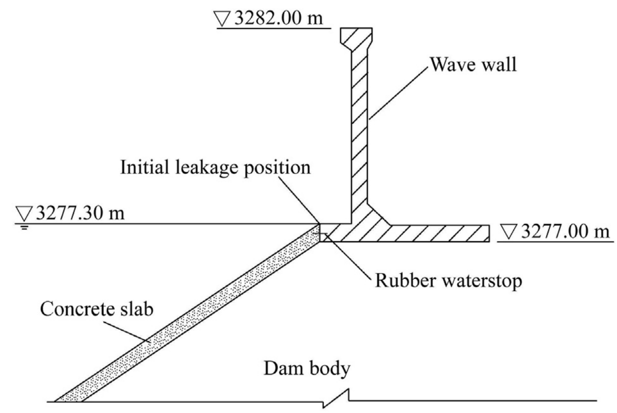

Fig. 1. Initial leakage position of Gouhou CFRD.

where B_b is the breach bottom width; $h = z_s - z_b$, where z_b is the elevation of the breach bottom; m is the slope of the breach; $c_1 = 1.7$; $c_2 = 1.3$; and k_{sm} is the submergence correction for tailwater effects on weir outflow.

2.3. Initial scour position

Visser (1998) pointed out that, on account of the steepness of the downstream slope of the dam, flow accelerates from point F at the top of the downstream slope to point P on the downstream slope, where the normal flow velocity is reached if the slope is long enough (Fig. 2). Beyond point P, breach flow remains uniform with its velocity and water depth being normal values, and it is defined as the initial scour position. The distance l_n between F and P can be approximated with the following expression:

$$l_n = \frac{2.5\left(Fr_n^2 - 1\right)d_n}{\tan\beta} \tag{3}$$

where β is the inclination angle of the downstream slope, d_n is the normal water depth, and Fr_n is the Froude number at point P. Fr_n is calculated as follows:

$$Fr_n^2 = \frac{U_n^2 B_{tn}}{g d_n B_n \cos\beta} \tag{4}$$

where U_n is the cross-sectional averaged normal flow velocity, B_{tn} is the breach width at the dam crest under the normal flow conditions, B_n is the breach width at the downstream slope, and g is the gravitational acceleration.

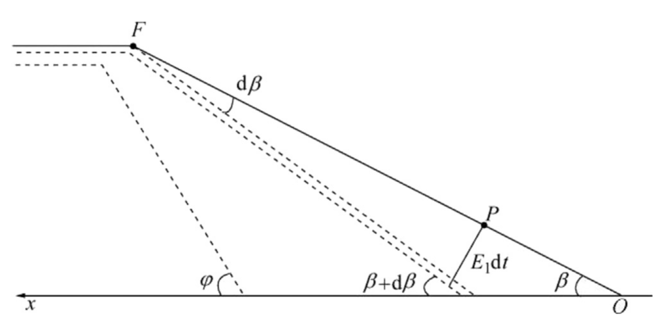

Fig. 2. Lowering of dam crest and steepening of downstream slope.