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A simplified physically-based model for core dam overtopping breach

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ABSTRACT

Based on the breach mechanism of the core dam due to overtopping failure, a simplified physically-based model has been proposed in this study. A hydraulic method was used to predict the initial scour position for high dam. A time averaged erosion equation was adopted to simulate the backward erosion of dam's shoulder. The broad-crested weir equation was adopted to calculate the breach flow discharge. Furthermore, the sliding or overturning failure was adopted as the key mechanism for the core, which was judged based upon numerical analysis. The results showed that the model allowed for one-side and two-side erosions, as well as for the dam base erosion. An iterative method is developed to simulate the coupling process of soil and water at each time step. The failure of Banqiao dam was used as an illustrative example, as detailed data about its failure is available in literature. Nine core dam breach cases, caused by overtopping, were studied to verify the model. Meanwhile, three typical parametric breach models were chosen to compare the results with those obtained from the proposed model. The back analysis and comparison results demonstrated that the proposed physically-based model not only provided satisfactory results, but also performed better and produced more detailed results than the parametric model. Moreover, the calculated results indicated that the overturning failure was the dominating failure mode for the core failure.

1. Introduction

Earth-rock dams use simple and locally available materials and have the advantages of simple construction technology and effective cost. They are the most widely used dam types [1–3]. Although artificially filled dams bring tremendous benefits to human beings, they are always accompanied by the risk of a dam's breach. The causes of failure include overtopping, piping, and foundation and structural defects. Among them, overtopping is the leading cause of failure in earth-rock dams [4]. Costa [5] reported that approximately 34% of the dam failures were caused by overtopping. According to the statistical data of Dam Safety Management Center of the Ministry of Water Resources, P. R. China [6], there have been 3530 dam breach accidents in China between 1954 and 2014, out of which, more than 50% were caused by the overtopping.

Consisting of earth and rockfill materials, core dams have become an increasingly popular dam type. Many core dams are being built or are planned to be built. However, it is worth mentioning that, there have been 183 core dam failures in China between 1954

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and 2014. These failures represented 5.2% of the total dam failures. In August 1963, two medium-sized reservoirs, Liujiatai and Zuocun core dams, which had the maximum dam heights of 35.8 m and 35.0 m, respectively, failed due to overtopping in "63.8" flood in Hebei province, China. The flood caused a lot of property loss along with 948 casualties [7]. In August 1975, Banqiao reservoir dam with the height of 24.5 m failed in "75·8" flood in Henan province, China. The dam's breach resulted in catastrophic downstream flooding and caused over 26,000 fatalities [7,8].

The overtopping failure of core dams differs from that of homogeneous earthen dams [9–14]. When water overflows or waves overtop a composite dam with an internal core, erosion starts on the downstream slope in the form of either surface erosion or headcut migration until the core is reached. With the increase in erosion of the downstream dam shell, the downstream side of the core is gradually exposed and becomes hollow. The erosion may affect the stability of core. Eventually, the co-action of upstream water and soil pressure leads to the failure of core. The likely failure mechanism of core includes sliding and overturning. The failed materials may be washed out rapidly by the breach flow, while the breach may be further lowered and widened.

The mathematic models for dam breaches are classified as parametric, simplified physically-based or detailed physically-based models [4]. Parametric models usually utilize empirical correlations, while simplified physically-based models are solved either analytically or numerically. The detailed physically-based models need to be solved numerically. It is worth mentioning that, the detailed physically-based breach models encounter difficulties owing to a lack of understanding of sediment transport under embankment breach flow conditions, which are not well developed and understood in modeling core dam breach. With regards to the parametric models, the breach parameters, such as peak breach flow, final breach width, and failure time have been studied in detail. USBR [15,16], Froehlich [17,18], and Xu and Zhang [19] are the representative models, which can provide outputs from derived regression equations based on databases of historical dam failures. The parametric models play important roles in feedback analysis of a dam's failure, though they still have several shortcomings. Additionally, their most important shortcoming is that the empirical equations neglect the breaching processes, while only a few of them consider the effects of soil properties.

Because the parametric models do not consider the breach processes, and the detailed physically-based breach models are not well developed at present, the breach models widely used in practices are the simplified physically-based models, which are developed using some simplifications and assumptions for the breach processes. However, most of the dam breach models are developed for homogeneous earthen dams, while less consideration is given to the core dam. Among the few available models, NWS BREACH model [20], HR BREACH model [21,22] and DLBreach [23] are the representative models. However, these models mainly focus on dams with relatively small heights.

In order to better understand the breach process of core dam's overtopping, a simplified physically-based breach model that considers the core dam with a large height is put forth in this study. For the modeling purpose, the breaching process is divided into three stages. In Stage 1, the initial scour position on the downstream slope is determined according to the breach flow condition. Then, the downstream slope steepens to a critical slope angle under the action of breach flow, while the backward erosion occurs at the dam shell before the core is exposed (see Fig. 1; a–c). In Stage 2, with the erosion of rockfill materials, sliding or overturning failure occurs at the exposed core due to significant erosion in the lower shoulder (see Fig. 1; d–f). In Stage 3, after the core failure, the breach deepens and widens under the action of breach flow. Finally, the breach process comes to an end when either the headwater is depleted or the tailwater is raised (see Fig. 1; g–i). The technical details of the proposed model are given in the following section.

2. A simplified physically-based model for clay core dam's overtopping breach

2.1. Breach flow routing

The volume of water in the reservoir changes due to the inflow from upstream and outflow from the breach. The change in the level of water in reservoir during the breaching is given by Eq. (1).

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

where t is the time (h), z_s is the water level in the reservoir (m), A_s is the surface area of the reservoir (m^2), Q_{in} is the inflow discharge

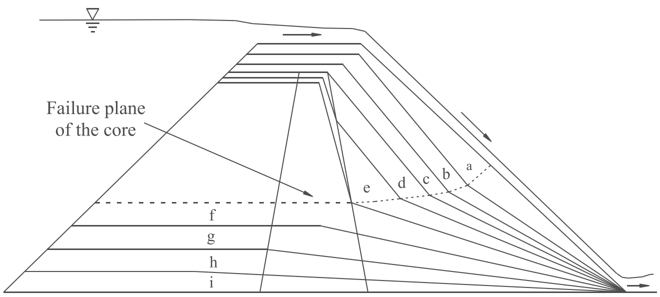

Fig. 1. Breach process for the clay core dam due to overtopping failure.