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Technical Note

Empirical and semi-analytical models for predicting peak outflows caused by embankment dam failures

Bo Wang, Yunliang Chen, Chao Wu, Yong Peng*, Jiajun Song, Wenjun Liu, Xin Liu

State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China

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ABSTRACT

Prediction of peak discharge of floods has attracted great attention for researchers and engineers. In present study, nine typical nonlinear mathematical models are established based on database of 40 historical dam failures. The first eight models that were developed with a series of regression analyses are purely empirical, while the last one is a semi-analytical approach that was derived from an analytical solution of dam-break floods in a trapezoidal channel. Water depth above breach invert (H_w), volume of water stored above breach invert (V_w), embankment length (E_l), and average embankment width (E_w) are used as independent variables to develop empirical formulas of estimating the peak outflow from breached embankment dams. It is indicated from the multiple regression analysis that a function using the former two variables (i.e., H_w and V_w) produce considerably more accurate results than that using latter two variables (i.e., E_l and E_w). It is shown that the semi-analytical approach works best in terms of both prediction accuracy and uncertainty, and the established empirical models produce considerably reasonable results except the model only using E_l. Moreover, present models have been compared with other models available in literature for estimating peak discharge.

1. Introduction

The safety for modern dams has attracted more concern than early dams because the surrounding areas for modern dams were more densely populated and industrialized and these dams were generally larger than early dams. The analysis of modern dam safety was initiated in the 1970s. During 1972 and 1977, four notable dam failures occurred in the United States (i.e., Buffalo Creek, Canyon Lake, Teton, and Kelly Barnes); and two were in China (i.e., Banqiao Reservoir, and Shimantan Reservoir). Compared with other types of dams (i.e., gravity dams, buttress dams, barrages, and arch dams et al.), an embankment dam termed an “earthfill” or “rockfill” dam has attracted more attention because an embankment dam is the most common type of dam in use. For example, nearly 86% (about 75,000) of more than 87,000 dams located in the United States and its territories are embankment dam (USACE, 2013). Another reason is that embankment dam has higher risk of failure. For instance, during 1954–2006, 93% of the 3498 dam failures occurred in China are embankment dams (Xie and Sun, 2009). So, it is essential for risk assessment to accurately and quickly estimate the peak outflows from a potentially breached dam since it is a vital basis for both hazard classification and emergency planning.

Among the numerous models which are developed to estimate the peak outflows caused by dam failures, empirical and semi-theoretical models that were based on the case-study data, have attracted much attention (e.g., Kirkpatrick, 1977; SCS, 1981; Hagen, 1982; Bureau of Reclamation, 1982; MacDonald and Langridge-Monopolis, 1984; SCS, 1985; Costa, 1985; Evans, 1986; Froehlich, 1995; Webby, 1996; Walder and O’Connor, 1997; Pierce, 2008; Macchione, 2008; Macchione and Rino, 2008; Xu and Zhang, 2009; Pierce et al., 2010; Thornton et al., 2011; Gupta and Singh, 2012; Hooshyaripor et al., 2014; De Lorenzo and Macchione, 2014; Azimi et al., 2015; and Froehlich, 2016; Wang et al., 2016). It is noted that these models are parametric and to usually use the data of historical dam failures to develop empirically linear, curvilinear or multiple regression relationships relating the peak discharge to one or more parameters of dam and reservoir characteristics (i.e., dam height H_d, water depth above breach invert at time of failure H_w, volume of water stored above breach invert at time of failure V_w, reservoir storage V_s, or the produce of ($V_s \times H_d$) or ($H_w \times V_w$)). Recently, more features of dam (i.e., embankment length E_l, average embankment width E_w) have been involved into the prediction models in conjunction with H_d, and V_s to determine the peak discharge (i.e., Thornton et al., 2011; Gupta and Singh, 2012; Froehlich, 2016). However, these models have a common defect that the empirical relationships were derived from a limited case-study database and show insufficient accuracy. Wahl (2004) reviewed the models of predicting peak outflows developed between 1977 and 1997, and concluded that

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* Corresponding author.
E-mail addresses: wangbo@scu.edu.cn (B. Wang), pengyongscu@foxmail.com (Y. Peng).

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the uncertainty bands were about ± 0.5 to ± 1 order of magnitude except that the relation by Froehlich (1995) which had an uncertainty of ± 1/3 order of magnitude. The uncertainty band used by Wahl (2004) is defined as ± 2 S_e (i.e., standard deviation) that approximately represents a 95% confidence band. It is noted that Xu and Zhang (2009) incorporated dam erodibility and failure mode in the prediction model in addition to H_w and V_w. Wahl (2014) evaluated the method by Xu and Zhang (2009) and showed that this method produced reasonable results of peak breach outflow rates for medium- and high-erodibility dams, but it is not clear whether it is applicable for low-erodibility dams due to insufficient data available.

The semi-theoretical models of Walder and O'Connor (1997) and Macchione (2008) were developed based on the continuity equation applied to reservoir, which describes the emptying of the reservoir due to the discharge outflowing through the breach. A constant downcutting rate for the breach deepening over the entire development of the breach was simply assumed in the Walder and O'Connor (1997) method and its value is very difficult to be determined (Froehlich, 2017). This issue may be solved using the breach formation time formula proposed by Froehlich (2008). Differently to the constant downcutting rate used by Walder and O'Connor (1997), in the model of Macchione (2008) a time-variable rate of breach opening, depending on the eroding flow capacity, was introduced to address the dam erosion. Based on the model of Macchione (2008), Macchione and Rino (2008) proposed an analytical method for predicting the whole outflow hydrograph for overtopping failures. In addition, De Lorenzo and Macchione (2014) proposed some formulas for peak discharge both for overtopping and piping failures obtained by regression analysis of the numerical results provided by the model proposed by Macchione (2008). The formula of Froehlich (2016) is based on a semi-theoretical approach that reduces the maximum possible peak discharge through an instantaneous partial breach of prescribed dimensions that forms in the shape of a trapezoid.

Assuming the final geometry of the breach as a trapezoidal shape, Wang et al. (2016) developed a semi-analytical model of predicting floods peak discharge caused by embankment dam failures, which was based on an analytical solution of dam-break floods in a trapezoidal channel. The method by Wang et al. (2016) has a high coefficient of determination and a small standard error among the considered 15 models. However, a coefficient determined by the data of historical dam failures in their model was taken as a constant due to the limit of the case-study data (i.e., only 27 dam breach cases were used in Wang et al., 2016). The objectives of present study are to: (1) develop new empirical relationships based on regression analysis of the case-study database and (2) propose a new method of determining the coefficient in the method by Wang et al. (2016) to improve the predictive capability by using a larger database of historical dam failures.

2. Database

Wahl (1998) presented a database containing 108 cases, 43 of them contained data describing H_w and V_w or H_d and V_s as well as reported peak outflow through the dam breach Q_p. Macchione (2008) presented a database of 15 cases with earthfill dam failure, providing data describing the main characteristics of the reservoir, dam, and breach (i.e., maximum storage volume, surface area of reservoir, average value of upstream and downstream embankment slopes, overall outflow volume from the breach, water depth of reservoir before failure, observed breach top widths and breach average widths, and the observed peak discharges). Xu and Zhang (2009) compiled a database composed of 75 cases with earth and rockfill dam failure, 39 of them containing data describing H_w, V_w and Q_p. Pierce et al. (2010) compiled a database of 87 cases by combining the Pierce (2008)'s database (44 cases) with the Wahl (1998)'s data (43 cases). 38 of them reported embankment length (E_l), average embankment width (E_w), or both of them. Gupta and Singh (2012) employed a database of 35 dam-break cases to develop an expression including H_w, V_w, E_l, and E_w for predicting peak outflow. However, the data used were not presented in that paper. Hooshyaripor and Tahershamsi (2012) presented a dataset composed of 93 embankment failure cases which contains data involving H_w, V_w and Q_p. Froehlich (2016) compiled a database containing 41 cases with H_w, V_w and Q_p as well as 40 cases including E_l, and E_w.

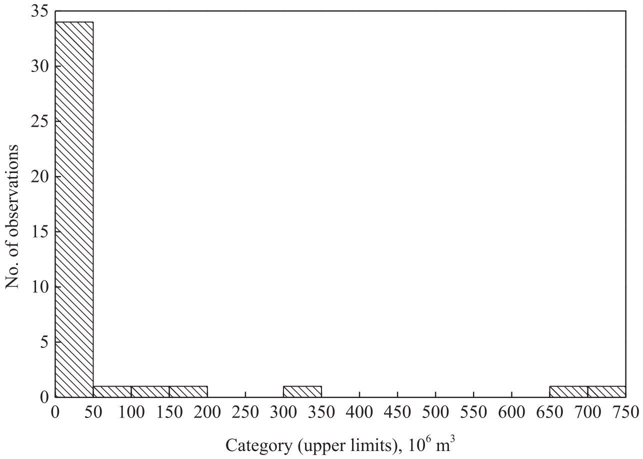

Fig. 1. Probability distribution of volume of water above breach bottom.

In present study, the dam-breach case data involving all four variables (i.e., H_w, V_w, E_l, and E_w) and reported peak outflow Q_p have been used to develop an empirical models of predicting peak discharge. The database used in this study is comprised of 40 dam failure cases, all of them are from the work of Froehlich (2016).

Probability distributions of various parameters involved in this database are presented in Figs. 1–6. These diagrams show that the distributions are right-skewed and scattered especially in the cases of V_w, Q_p and E_l. Moreover, the mass of the distributions are concentrated on the left. V_w, reported here is in the range of 0.0133 – 701 million m^3. V_w with less than 50 million m^3 are accounted for 85%. Q_p, ranges from 30 to 65,120 m^3/s; and 75% of them is less than 5000 m^3/s. E_l is in the range of 40 and 4100 m. While for 30 of 40 breached embankments, E_l is less than 500 m. E_w is in the range of 9.63 and 250 m, and only three cases have E_w with larger than 100 m. Two parameters (H_w and H_b) of measuring flow potential energy have similar distribution. The number of cases with $H_w < 40$ and $H_b < 40$ are 39 and 38 respectively. Based on the findings of International Commission on Large Dams (1974), the embankment failures were classified into two modes (Froehlich, 2016): overtopping and internal erosion. Among the breached embankments showed in Table 1, one half (18 cases) failed due to overtopping, and another half failed due to internal erosion (22 cases).

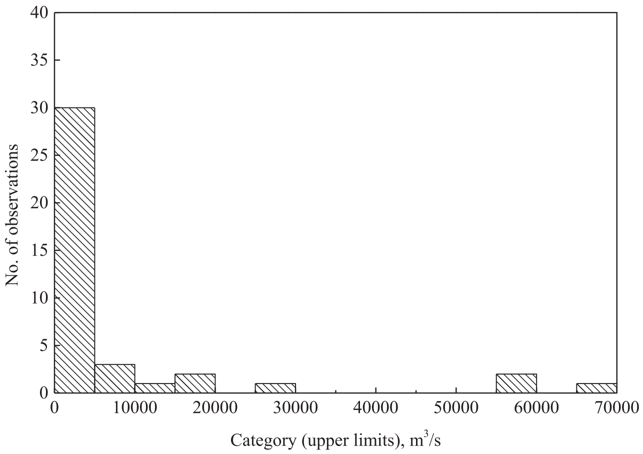

Fig. 2. Probability distribution of observed peak outflows.