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A probabilistic framework for comparison of dam breach parameters and outflow hydrograph generated by different empirical prediction methods

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ABSTRACT

This study presents a probabilistic framework to simulate dam breach and evaluates the impact of using four empirical dam breach prediction methods on breach parameters (i.e., geometry and timing) and outflow hydrograph attributes (i.e., time to peak, hydrograph duration and peak). The methods that are assessed here include MacDonald and Langridge-Monopolis (1984), Von Thun and Gillette (1990), Froehlich (1995), 2008). Mean values and percentiles of breach parameters and outflow hydrograph attributes are compared for hypothetical overtopping failure of Burnett Dam in the state of North Carolina, USA. Furthermore, utilizing the probabilistic framework, the least and most uncertain methods alongside those giving the most critical value are identified for these parameters. The multivariate analysis also indicates that lone use of breach parameters is not necessarily sufficient to characterize outflow hydrograph attributes. However, timing characteristic of the breach is generally a more important driver than its geometric features.

1. Introduction

Dam breach is a serious concern all over the world due to its severe damages in the downstream areas. According to the National Inventory of Dams (NID), there are up to 15,000 high-hazard potential dams in the US alone (US Army Corps of Engineers (USACE, 2013). A population growth of 130 million within the US by 2050, can lead to reclassifying many low or significant hazard dams to high-hazard potential as this population is expected to move into the undeveloped areas downstream of the aging dams (American Society of Civil Engineers (ASCE, 2013). According to the Association of State Dam Safety Officials (ASDSO), repair costs of US dams are estimated to be $57 billion, and a $21 billion investment is needed to repair aging high-hazard potential dams (ASCE, 2013). With the ASCE "D" grade rating of the nation's dams, the continued aging of US dams and the increase in the number of high-hazard potential dams, evaluation of the dam failure hazards is very crucial for proactive risk management and planning.

A dam may fail due to different causes with overtopping and piping as main failure modes (Singh and Scarlatos, 1988; USACE, 1997). Overtopping failure has been found to be the most crucial cause mainly with respect to time of failure (Tsakiris and Spiliotis, 2013). There are approximately 57,000 dams in the US with overtopping hazard potential (Ralston, 1987) and it is also the leading reason of dam failure worldwide (Wu et al., 2011). Overtopping failure of a dam can be due to various reasons such as deficient design of outlet capacity, primary outlet failures, and large inflow events due to extreme rainfall. Global changes including climate change and urbanization have increased the risk of extreme hydrologic events such as flood (Gilroy and McCuen, 2012; Hirabayashi et al., 2013; Mallakpour and Villarini, 2015), which is likely to alter the dam overtopping risk. Hence, it is essential to analyze overtopping failure risk with more caution.

The first step in evaluation of dam failure flood risk is estimation of breach outflow (Ahmadisharaf et al., 2013). In spite of the recent research advances, breach prediction is still a substantial source of uncertainty in dam break risk assessment (Morris et al., 2009b). Dam breach outflow is often determined as a function of breach

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parameters, including geometry and timing. The prediction of breach characteristics is multifaceted because it needs the estimation of complex interactions between soil, water and structure (Wu et al., 2011). Breach features can be predicted through breach models, which are commonly classified into three groups: empirical, analytical, and physically-based (Morris et al., 2009b). This paper focuses on empirical methods. Until now, several empirical methods have been developed to estimate breach parameters, which mostly rely on simple regression analysis. Wahl (1998, 2004) and Brunner (2014) provided an excellent literature review on prediction methods in this context. In general, no single breach model can be recommended (Morris, 2000) and thus it is required to estimate breach parameters based on different available approaches. There have been few studies on comparison of breach prediction methods such as Wahl (2004), Gee and Brunner (2007) and Yochum et al. (2008). All of these studies have employed a deterministic framework and not incorporated data or model uncertainties.

Like any physically based phenomena, empirical methods to predict breach geometry and timing, have uncertainty and thus influence the estimated breach outflow. This uncertainty is attributed to various factors, including: poor documentation of historical failure events; lack of knowledge; inherent variation in the erodibility of cohesive materials; the effects of variability of embankment design; configuration; and geometry (Wahl et al., 2008; Wu et al., 2011). Bearing in mind these various sources of uncertainty and huge damages of dam break events, it is very crucial to analyze the uncertainty of breach parameters for reliable outflow estimation.

One of the complexities in quantifying the uncertainty of the breach outflow hydrograph is that the outflow is affected by multiple uncertain variables, in which the nature and range of their uncertainties are not independent (Zhong et al., 2011). There have been few studies that analyzed the uncertainties of breach parameters. Wahl (2004) evaluated several empirical breach prediction methods and their uncertainties in terms of average breach width, formation time and peak outflow. In that study, the methods were applied on a hypothetical erosion seepage failure and suggested breach parameter ranges were presented. However, a similar study for overtopping is not found in the literature. Additionally, uncertainties in breach hydrograph attributes such as time to peak and duration, which are crucial in determining the time-variant flood parameters (e.g., velocity, duration and arrival time), the worst flooding scenario (e.g., estimation of evacuation ability and population at risk (PAR)) (Morris, 2005; Dang et al., 2011; Qi and Altinakar, 2011a, 2011b; 2012; Ahmadisharaf et al., 2015), have not been assessed. The sole estimation of peak outflow for assessing downstream flood risk can be another source of uncertainty, as it requires a breach hydrograph, which should be fitted to the estimated peak that would likely increase the flow computation error (Morris et al., 2009b). It is also noted through the literature review that uncertainty analyses have been typically performed deterministically. Deterministic frameworks have inherent limitations and may not reveal the worst case scenario and thus may not be an appropriate strategy for uncertainty analysis. Furthermore, uncertainty analysis by using a deterministic framework may not adequately reveal the inter-relationships between the independent variables (Peng and Zhang, 2012). Applying probabilistic frameworks are more desirable, in which the risk is quantified and the impact of various uncertainties is incorporated and uncertainty of input parameters is propagated to the output by using probability distributions (Zhong et al., 2011). Froehlich (2008) stated the need for thorough uncertainty analysis of breach parameters by incorporating their inherent randomness. Monte Carlo (MC) sampling strategies and specifically Latin Hypercube sampling (LHS) (McKay et al., 1979) are valuable tools in this context. Therefore, probabilistic dam breach methods are needed to better understand the risks and to evaluate the uncertainty of the breach outflow hydrograph.

One concern about using a probabilistic dam breach model is the high computational time needed by flood models (in particular, two-dimensional models) to route multiple breach hydrographs through the downstream valley (Morris, 2005). However, recent advances in computational capabilities of flood models with tremendous speedup (e.g., Flood2D-GPU by Kalyanapu et al. (2011)) can assist modelers in efficiently using probability-based analyses. Considering these advances in flood modeling, breach outflow hydrograph estimation needs to be improved by incorporating the uncertainties using probabilistic frameworks.

This study presents a probabilistic framework to evaluate the impact of employing different dam breach prediction methods on breach timing and geometry as well as outflow hydrograph. The unique aspects of this research are: i) application of a probabilistic dam breach framework for comparison of different breach prediction methods; ii) evaluation of different breach prediction methods on a hypothetical overtopping failure; iii) analysis of the uncertainties of all the breach outflow hydrograph attributes (including time to peak and duration) and not only peak; v) multivariate analysis to analyze the sensitivity of outflow hydrograph attributes to breach parameters. Four empirical breach prediction methods are assessed here, including MacDonald and Langridge-Monopolis (1984), Von Thun and Gillette (1990), Froehlich (1995, 2008). A probabilistic LHS-based framework is employed to propagate the uncertainty of inputs to outputs. Resulting mean values and percentiles are compared for breach parameters including average breach width and formation time and hydrograph attributes. In addition, the least and most uncertain methods alongside those giving the most critical value are identified for these parameters. Multivariate analysis is finally carried out to investigate the sensitivity of breach hydrograph attributes to average breach width, formation time and bottom elevation of final breach. This investigation is illustrated through the hypothetical overtopping failure of Burnett Dam, which is one of the high-hazard potential dams in the state of North Carolina.

2. Methodology

The methodology section is organized into the following subsections: 1) dam breach prediction methods: description of the four methods used here to predict breach geometry and timing; 2) dam breach outflow equations: description of the methodology applied to determine dam breach outflow hydrograph; 3) development of the probabilistic dam breach model: description of the probabilistic dam breach model development, characterizing uncertainty of input elements and uncertainty propagation; and 4) comparison metrics: description of the measures used to compare the results of breach parameters and outflow hydrograph.

2.1. Dam breach prediction methods

The following sub-section describes the four chosen dam breach prediction methods. It is to be noted that these four methods are chosen as they suggest equations for both average breach width and formation time, and are often applied in-practice (Brunner, 2014).

2.1.1. MacDonald and Langridge-Monopolis (1984)

MacDonald and Langridge-Monopolis (MLM) in 1984 studied 42 dam failure events and proposed equations to estimate eroded volume and breach formation time for earthfill and non-earthfill