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Solution method of overtopping risk model for earth dams

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ABSTRACT

Hydrologic risk analysis relies on a series of probabilistic analyses, and it is a complex problem in estimating the probability distributions of multiple independent and random variables. The goal of this study is to presents the procedure and application of a probability-based risk analysis methodology to evaluate earth dam overtopping risk that induced by concurrent flood and wind. The uncertainty arising from initial water surface level, flood, wind velocity, and dam height are discussed in this research. The improved Monte Carlo simulation and mean-value first-order second-moment method are used to solve the proposed dam overtopping risk model, respectively. The nonparametric kernel density estimation method, which can better learn the complex multimodal characteristic of probability density function than that of traditional parametric estimation method, is employed to improve the probability density function of initial water surface level. The latin hypercube sampling is introduced to generate uniform random number, which improves the efficient and stability compared with simple random sampling. Afterward, an application to the Dongwushi Reservoir in China illustrates that the dam overtopping risk computed using the improved Monte Carlo simulation is lower than that using mean-value first-order second-moment method. Furthermore, the sensitivity analysis show that initial water surface level is more sensitive to overtopping risk than wind velocity.

1. Introduction

Dam safety is a major concern to the general public. In recent years, many countries have experienced frequent floods that may have overtop dams. Such deficiencies can cause dams to break and extreme floods to occur downstream. This leads to various problems such as loss of social capital, large scaled economical expenses, and the loss of life seriously (Jiang, 1999; Kwon and Moon, 2006; Yanmaz and Gunindi, 2008; Hsu et al., 2011). In the case of modification of the structure, including repairs and reconstruction of the dam, economic feasibility and social goals need to be addressed. When evaluating the priority of the dam rehabilitation, a risk-based analysis is a potentially useful approach. Moreover, overtopping is one of the most important risk factors inducing dam failure. According to the International Commission on Large Dams (ICOLD, 1973), overtopping causes about 35% of all earth dam failures; seepage, piping, and other causes make up the rest. Accurate assessment of overtopping risk will provides useful information for managers in decision making such as formulating the emergency preparedness planning. For these reasons, dam overtopping risk analysis is very important to satisfy dam safety needs.

In recent years, numerous studies have attempted to find and explore the possibility of a risk-based analysis in dam safety. Von Thun (1987) studied the risk analysis method with U.S. Bureau of Reclamation (USBR) in order to estimate dam risk and risk expense and two conferences were held in 1985 (McCann, 1985; Haimes and Stakhiv, 1986). Cheng (1982, 1993) estimated the dam overtopping risk considering the uncertainties of hydrology and hydraulics using the advanced first-order second-moment (AFOSM) method and fault tree analysis; Langseth and Perkins (1983) proposed the procedure of dam risk analysis; Kwon and Moon (2006) studied the dam overtopping risk using probabilistic concepts and the improved Monte Carlo simulation was used to solve the hydrologic dam risk model; Kuo et al. (2007) used five uncertainty analysis methods to calculate the overtopping risk and the results were compared with each other. Sun and Huang (2005) established the overtopping risk model induced by concurrent flood and wind by considering the uncertainties of flood, wind wave, storage capacity of reservoir and discharge capacity; Mo et al. (2008) established the overtopping risk model under the joint actions of flood and wind wave, and the Integrate-FOSM method was used to calculate the overtopping risk.

In light of the above mentioned methods, the general approach for dam safety evaluation is to estimate a probability distribution associated with extreme precipitation and runoff. Dam overtopping risk analysis depends on a series of probabilistic analyses of rainfall-runoff and uncertainty analyses of their associated input

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variables such as initial water surface level, flood, and wind velocity. This is a complex problem in that the probability distributions of multiple independent and derived random variables need to be estimated to estimate the probability of dam overtopping. Typically, the parametric density estimation (PDE) methods and the Monte Carlo simulation (MCS) of models are used to derive some of the distribution. Often, the true distribution is always unknown in practice and the arbitrary choice of or preference for a given distribution increases the estimation uncertainty. Often, the distributions used to model some of the random variables are usually inappropriate relative to the expected behavior of these variables (Kwon and Moon, 2006).

In this research, a dam overtopping risk model is presented. The improved Monte Carlo simulation (MCS) method and mean-value first-order second-moment (MFOSM) method are introduced to solve the overtopping risk model. The nonparametric kernel density estimation (NKDE) approach is proposed to estimate the probability density function of input variables. This method can apply better than traditional PDE because it does not require assumptions of the underlying model structure, and does not need to estimate the parameters (Faucher et al., 2001). In addition, the latin hypercube sampling (LHS) technology for uncertainty analysis of the dam overtopping risk is also introduced to improve the sampling efficiency and stability. Finally, the proposed model and the solution method are applied to the analysis of the safety of Dongwushi reservoir in China.

2. The overtopping risk model for an earth dam

2.1. Overtopping risk modeling induced by concurrent flood and wind

Overtopping can be defined as when flood outlet works are not able to release water fast enough and the water level rises above the allowable safe height of the dam. To evaluate the overtopping risk associated with dam failure, we need to establish a method to transform the water surface level into overtopping probability. Assume that H_C is the dam height, H_0 is the initial water surface level, H_F and H_W is the increasing water surface level by the flood, wind respectively. Then, overtopping will happen when (Cheng, 1982; Sun and Huang, 2005; Ma, 2004)

$$H_0 + H_F + H_W \geqslant H_C \tag{1}$$

Assume that H_F, H_W, H_0 are independent variables, and they are all the function of time. Then, $H_0 + H_F + H_W$ can be expressed by a stochastic process of $H(t)$. Flood and wind can be considered as an annual periodic random process. However, the largest effective wind during flood season within a year is used in earth dam overtopping risk evaluation. Flood discharge and storage capacity are constant random process. Therefore, $H(t)$ can be considered as an annual periodic random process. The dam overtopping risk can be defined as the probability that the water surface level of reservoir exceeding the dam height. Then, the formulation associated with MCS for dam overtopping risk analysis induced by concurrent flood and wind can be represented as follows.

$$P_{FW} = P(H(t) \geqslant H_C) = P(H_0 + H_F + H_W \geqslant H_C) \tag{2}$$

The flowchart for dam overtopping risk analysis is illustrated in Fig. 1. As shown in Fig. 1, the procedure of this research includes three major steps (Kuo et al., 2007, 2008; Hsu et al., 2011): (1) Identifying and assessing the important factors which may affect reservoir routing or overtopping. Fault tree analysis is adopted to assess the main important factors which may affect the risk of overtopping, and concluded with the following important uncertainty factors: initial water level, rainfall, T-year return period flood, wind velocity, dam height, and reservoir release, etc. (2) Data collection and analysis for reservoir routing and uncertainty analysis. Collecting the records of annual peak discharges and conducting a hydrological frequency statistical analysis to obtain return periods of discharges; using reservoir routing to calculate the highest water level during a flood; and defining the performance function and assigning distributional properties of uncertainty factors. (3) Performing reservoir routing incorporating uncertainty analysis and dam overtopping risk analysis. The uncertainty variable sets generated in step 2 are used in reservoir routing model that considers rainfall-runoff analysis, wind wave setup and run-up. The overtopping risk model are then analyzed to evaluate dam overtopping probability.

2.2. Uncertainty analysis

Uncertainty is also called stochastic, which is a concept of stochastic mathematics. In this paper, the uncertainties of flood, wind wave, initial water surface level, and dam height are studied.

2.2.1. Flood

Flood of certain frequency is a stochastic event and it often follows distribution of P-III type. The increased water surface level H_F induced by flood can be calculated using water balance method (Li and Long, 2006):

$$Q(t) - q(h, c) = dV/dt = F(Z)dZ/dt = F(Z)f(Z, t) \tag{3}$$

where $f(Z, t)$ is the derivative of water surface level Z with respect to time t; $Q(t)$ is reservoir inflow at time t; $q(h, c)$ is reservoir outflow at time t, of which h represents weir water head and c is hydraulic parameter; V is reservoir volume; $F(Z)$ is the relation function between water surface level and surface area.

From Eq. (3), it can be seen that H_F is influenced by the uncertainty factors of $Q(t)$, $q(h, c)$, and $F(Z)$. The location of peak flow during flood process is uncertain due to stochastic of rainfall distribution. The peak flow and large flood volume also don't happen simultaneously, i.e., the biggest peak flow does not always happen when the flood volume is largest. Thus, different rainfall may form different inflow flood hydrograph. The stochastic characteristic of $Q(t)$ can be obtained by studying the rainstorm distribution or existing materials of inflow flood hydrograph of study area. Uncertainty of $F(Z)$ are induced by survey calculating error, collapse of reservoir banks, and sediment deposition. $q(h, c)$ is also relative to human operation and management besides h and c.

2.2.2. Wind wave

Wind velocity and wind direction can be considered as a stochastic process. So, the increased water surface level e and wave run-up h_p induced by wind are also random variables. Only the wind blowing to the dam during flood process, which is called "effective wind", contributes to dam overtopping risk. Probability of maximum wind velocity W during certain time usually follows extreme type I distribution. The distribution function and distribution density function can be expressed by (SL274-2001, 2001)

$$\begin{cases} F(w) = \exp\{-\exp[-(w-\mu)/\alpha]\} \\ f(w) = (1/\alpha)\exp[-(w-\mu)/\alpha]\exp\{-\exp[-(w-\mu)/\alpha]\} \end{cases} \tag{4}$$

where α and μ are distribution parameters, and they have the following relationship with mean value $M(w)$ and mean square deviation $\sigma(w)$.

$$\begin{cases} \sigma(w) = 1.2826\alpha \\ M(w) = 0.5772\alpha + \mu \end{cases} \tag{5}$$

According to "Design code for rolled earth-rock fill dams" (SL274-2001, 2001), the increased water surface level induced by wind e can be calculated by the following equation.