Rockfill Dams Overtopping Risk Analysis

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Abstract

In hydraulic structures which are located in a natural environment, there is the possibility of system failure with increasing external forces acting on the structures. Stability and crest settlement of rockfill dams is a major factor in design which in some cases is very important (after construction and impoundment). Particle breakage in rockfill dams is the main cause of vertical deformations. Particle breakage changes resistance and deformation behavior of rockfill materials and this affects the performance of dams. For embankment dams the highest risk of damage is caused by water overtopping over the dams. The purpose of this research is to study rockfill dams settlement and freeboard height reduction that affect performance of dams, especially during the heavy flooding. Increasing in the probability of dams overtopping results in total destruction of the dam. In this research the overtopping risk analysis method has been studied and the effective parameters on overtopping risk analysis and the effect of particle breakage on overtopping risk of rockfill dams was investigated.

Keywords: particle breakage, rockfill dams, overtopping risk, Mahabad dam.

PREFACE

The risk concept has a long history and has been a main aspect of life since the beginnings of human experience. Applications of risk and safety analysis have been developed simultaneously by expanding various facets of technology in all branches of science, such as engineering and environment.

The main intentions of risk and safety analysis are to identify existing system threats and predict possible outcomes in the future to provide clearer ideas for making the best possible decisions. In other words, risk analysis not only provides quantitative support for decision makers, but also helps to find the most effective options for decision-making. For instance, engineers could never have designed systems such as great bridges, dams, sewer systems, and so on, without some form of risk assessment.

1. INTRODUCTION

1.1. DAM SAFETY

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 [1,2]. 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 [3]overtopping causes about 35% of all earth dam failures; seepage, piping, and other causes make up the rest. Accurate assessment of overtopping risk will provide 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 [4] studied the risk analysis method with U.S. Bureau of Reclamation (USBR) in order to estimate dam risk and risk expense. Cheng [5] 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 [6] proposed the procedure of dam risk analysis; Kwon and Moon [7] 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. [8] used five uncertainty analysis methods to calculate the overtopping risk and the results were compared with each other. Sun and Huang [9] 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. [10] 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.

1.2. PARTICLE BREAKAGE IN ROCKFILL

Behavior of granular media is related to mineralogical composition, particle grading, size, shape, fragmentation and stress conditions. Breakage of the constituent components (grains) of a soil structure due to imposed stresses, called "particle breakage", has arisen in many soil-rockfill masses such as rockfill dams and breakwaters as well as in many conventional laboratory tests under normal pressures. The related phenomenon has been studied in various laboratory tests, e.g., triaxial, consolidation and uniaxial [11,12,13,14], which showed that many engineering characteristics of granular materials such as strength (stress–strain behavior), deformability, pore pressure distribution and permeability are greatly influenced by the level of breakage of materials [11,15]. Marsal [13], perhaps the first to deal with the concept of crushing of particles, verified the breakage phenomena of particles in rockfill materials in a large-scale triaixal test, summarizing his study as follows: "It seems that phenomenon of fragmentation is an important factor that impacts shear resistance and potentiality of compaction of grain materials and this phenomenon is effective on aforesaid parameters in different conditions of implementing stresses such as confining pressure stage or stage of divertive loading in triaxial test." Among other researchers [11,12,16], Varadarajan et al [17] presented the ratio of principal stresses ($\sigma1/\sigma3$) imposed on different rock materials at failure in triaxial tests. Also, many researchers demonstrated that particle breakage led to a reduction in void ratio, leading to compaction of the material. Marsal [13] believed that changes in void ratio were due to new arrangement of particles after breakage. Lade and Yamamuro [11] and Yamamuro and Lade [12] concluded from testing sand under different confining pressures (from 0.5 to 70MPa) that breakage of particles played the major role in changing the volume of the material.

Particle breakage index can be divided into different categories based on four methods. The first one is the PSD method, which is based on the differences of PSD before and after test. This method produced a single index, such as B15 [18], B10 [19], Bg [13] and Bt [20], and a global index, such as Br [21], BrE [22]. The second one is fine content (FC) method ($d < 0.075$ mm) [23]. The third one is area method [24,25,26], which is based on the increasing particle area during test and the last one is the discrete element method (DEM) [27,28,29,30], which simulates particle breakage by a discrete element software. The greater confining pressure, the more contact force among particles, which leads to the greater particle breakage. In addition, greater coefficient of uniformity Cu means more intermediate particles, and the PSD curve is distributed in a wider range, resulting in more contacts among particles. A decrease in the force of each particle due to increasing contacts causes decrease in the particle breakage.

The breakage is usually expressed quantitatively by the Breakage Index, Bg [13]. The value of Bg is calculated by sieving the sample using a set of sieves before and after testing. The percentage of particles retained in each sieve is determined at both stages. Due to the breakage of particles, the percentage of particles retained in the large size sieves will decrease and the percentage of particles retained in the smaller size sieves will increase. The sum of the decreases will be equal to the sum of the increases in the percentage retained. The decrease (or increase) is the value of the breakage factor, Bg. generally, the friction angle decreases with decreasing Bg . The effect of confining pressure on Bg is more significant for the high compacted materials.

1.3. MAHABAD DAM

The Mahabad storage dam specification presented in Table 1.

Table 1 . Mahabad dam specification

Type of dam	ECRD
Dam height	47.5 m
Crest length	700 m
Crest width	8 m
Dam body volume	1.66 M$\boldsymbol{m^3}$
Reservoir capacity	197.8 Mm^3
Power capacity	6 Mwat
Year of construction	1970

2. THE OVERTOPPING RISK MODEL FOR ROCKFILL DAM

2.1. OVERTOPPING RISK MODELING INDUCED BY CONCURRENT FLOOD AND WIND

Overtopping can be defined as when flood outlet works are notable 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 [31,32]

$$H_0 + H_f + H_w \geq H_c \tag{1}$$

Assume that H_0, H_f, H_w 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 and rockfill 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(Monte Carlo Simulation) for dam overtopping risk analysis induced by concurrent flood and wind can be represented as follows.

$$P_{FW} = P\big(H(t) \geq H_C\big) = P(H_0 + H_f + H_w \geq H_c) \tag{2}$$

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 [33,34]
(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.

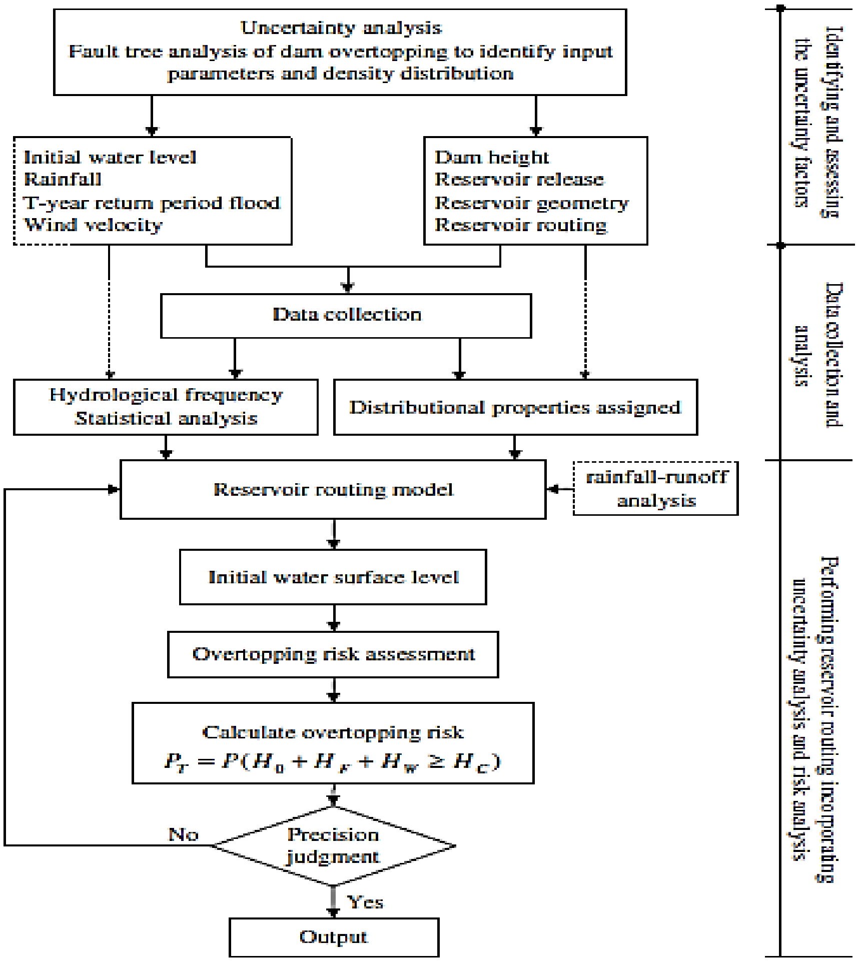

Fig1. Flowchart for calculating overtopping risk[35]

Overtopping happens when the flood outlet cannot release water fast enough and water rises above the dam and spills over (Fig. 2).

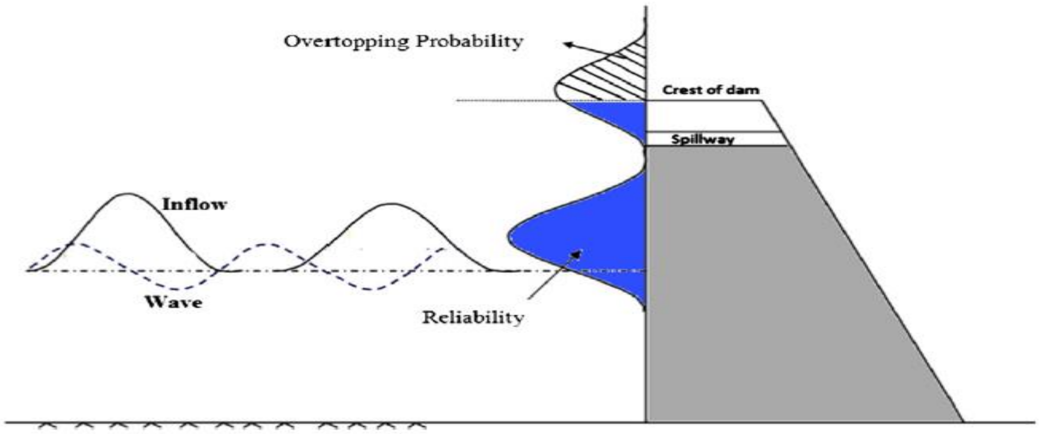

Fig 2. Overtopping risk concept based on probabilistic approach[36]

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[37]. For flood probability is assumed to follow distribution: Gumbel Max, General Extreme Value, Log-Logistic, Gamma, Log-Gamma, Pearson 5, Log-Pearson 3, Normal.

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[38]. For wind wave probability is assumed to follow distribution: Gumbel Max, General Extreme Value, Weibull, Gamma, Log-Gamma, Normal, Log-Normal, Pearson 5, Log-Pearson 3.

2.2.3. INITIAL WATER SURFACE LEVEL

Uncertainty of initial water surface level is caused by operation, management, and so on. It is difficult to estimate the probability distribution to reflect the property of initial water surface level.

2.2.4. DAM HEIGHT

Uncertainty of dam height is induced by measure, construction error, and so on. Generally, dam height is assumed to follow normal distribution. The designed dam height is set to mean value, and the standard deviation is usually small [39]. Settlement and displacement inside the rockfill support shells during construction and operation not exceeding 0.6% to 0.8% and 0.1% and 0.2% respectively of the height of the dam. Relevant literature suggests settlement generally ranges between 1% and 3% during construction and between 0.2% and 1% during operation. Horizontal displacements are generally less than half of settlement. Settlement at a given time varied parabolically, with maximum settlement near the middle third of the dam; this is expected, since settlement is a function of the thickness of the compressible layer and the overburden[40].

3. SOLUTION METHOD OF DAM OVERTOPPING RISK MODEL

3.1. IMPROVED MONTE CARLO SIMULATION

The MCS method does not need to consider the complex interactions among random factors. The method is a statistical sampling technique that generates random variables according to the distributional property and provides numerical evaluations of the probabilistic features of the system response. The procedure for calculating dam overtopping risk by MCS is as follows: (1) generate random number corresponding to the probability distribution of each random variable; (2) substitute the random number into performance function and evaluation the system response; and (3) the dam overtopping risk is obtained after many times repeated test [41]. In MCS, it is important to generate random number that following the given probability distribution. Generally, simple random sampling is used to generate random number, and the sampling efficiency is low and unstable. It firstly generates random number between 0 and 1, and then generates sample value from the distribution function of random variables using reverse method and calculates the failure probability. Nevertheless, LHS method is an improvement of simple random sampling, and it is a statistical sampling method which has sample recording ability. The probability distribution of each variable is subdivided into N ranges with an equal probability of occurrence (1/N). Random values of the basic variable are efficiently simulated such that each range is sampled just once without repetition. LHS can be defined as follows [42,43]:

$$x_{i,j} = F_j^{-1}(\frac{1}{n}\left[P_{i,j} - r_{i,j}\right]) \tag{3}$$

where $r_{i,j}$ is the random number between 0 and 1 that follows the uniform distribution, and $P_{i,j}$ is random permutation.

The parametric method is usually used in dam overtopping risk evaluation. It reflects the linear relationship while neglects the important nonlinear characteristic of variables. Recently, nonparametric kernel density estimation (NKDE) method has gained popularity in a variety of fields. This method has the advantage of not requiring assumptions about the distribution. The shapes of nonparametric density functions are directly determined by the data which avoid the difference between simulated probability density distribution and real distribution [43].Kernel density estimation (KDE), a commonly used nonparametric density estimation method, is introduced by Rosenblatt [44]. By assuming that x is the real data where $x_1, x_2, \ldots, x_n$ are independent identically distributed real observations, K(.) is a kernel function, n is the sample size, and h is a bandwidth parameter assumed to tend to zero as n tends to infinity. The nonparametric density function can be defined as [43].

3.2. MEAN-VALUE FIRST-ORDER SECOND-MOMENT METHOD

MFOSM is an approximately analysis method and it assumes that the uncertainty features of a random variable can be represented by its first two moments [33]. This method is based on the Taylor series expansion of the performance function Z = g(x_1, x_2, …,x_n) linearized at the mean value μ_{xi} of the random variables. For most practical applications, information on higher-order moments and cross-product moments is not easily available. So, the first-order approximation of Z is used.

3.3. LATIN HYPERCUBE SAMPLING (LHS)

There are some reduction variance techniques to increase the precision of the Monte Carlo simulation outcome without needing to increase the sample size [45]. Some of the most important methods of variance reduction are antithetic variates technique, control variates, importance sampling technique, Latin hypercube sampling (LHS), correlated sampling, and stratified sampling technique [45]. LHS is one of the main variance reduction techniques that can increase the efficiency of the output statistics parameters. In this method, the range of each variable is divided into n non-overlapping intervals with the equal probability 1/n. Then, a random variate is selected from each range with regards to the desire probability distribution [45].

4. THE RESULTS OF OVERTOPPING RISK ANALYSIS IN EMBANKMENT DAMS IN WORLD

Goodarzi et al[36] studied overtopping risk analysis about the Meijaran dam in Iran. From these results it can be concluded that rising water levels in the reservoir would result in the increasing overtopping probability based on both the MCS and LHS techniques. For instance, the probability of overtopping in T = 20-year from H0 =46 to H0 =49 increased from 5.28E_10 to 1.82E_07 based on the MCS and LHS methods, respectively. On the other hand, the results revealed that wind speed could have a great impact on reservoirs situated in windy areas. Dam overtopping probabilities at T =20-year, T = 2-year and H0 =49 were found to be 56.14% and 55.49% greater than the risk in the same condition without considering the wind effect.

Goodarzi et al [46] studied overtopping risk analysis about the Doroudzan dam in Iran. Based on the achieved results, by increasing the initial water level in each step, the probability of overtopping (in a constant return period) was raised for both uncertainty approaches adopted in this study. To show the effect of increasing initial water level in the reservoir on the risk of overtopping, the percentage of increasing risk in different water levels, On the other hand, the results revealed that wind speed could have a great impact on reservoirs situated in windy areas, and the probability of overtopping has been increased by increasing wind speeds in different return periods. Based on the results LHS method, the overtopping risk summary, the inclusion the uncertainty of key variables results in an expanded range of overtopping risks in different return periods, and provide significant information for decision makers to identify the critical parameters needed to effectively monitor, and detect the events that indicate a developing failure mode.

Chongxun et al[47] studied overtopping risk analysis about the Chengbihe reservoir in China. The results indicate that increasing the reservoir level by 0.40 m can increase storage by 16 million m3 and lead to a corresponding mean annual direct economic profit of about 100 million CNY while at the same time protecting the reservoir dam from overtopping.

Sun et al [37] studied overtopping risk analysis about the Dongwushi reservoir in China. The application results show that the dam overtopping risk is calculated as 5.00 * 10^{-6} and 6.63 * 10^{-6} using the improved MCS method and MFOSM method, respectively. The overtopping risk computed by the improved MCS method is slightly lower than that computed by the MFOSM method. However, there are some limitations in this research. Only dam overtopping risk induced by concurrent flood and wind is studied in this paper.

5. MAHABAD DAM OVERTOPPING RISK ANALYSIS

Mahabad dam is the oldest rockfill dams in Iran that is located Orumieh lake basin. Since the dam after construction and impoundment have been much vertical settlement and horizontal displacements of the dam body and So far, two stages of rehabilitation has been done on the dam. Given that in most previous studies on the overtopping risk of earth dams vertical settlement and horizontal displacement of the dam is discussed less. We will discuss to evaluate the overtopping risk analysis of Mahabad dam based on the displacement which the impact of particle breakage and the results will be presented in the future.

6. CONCLUSION

Dam overtopping risk assessment and uncertainty analysis by mathematical and statistical methods provide useful information for managers. The paper demonstrates the procedure of evaluating overtopping probability considering the joint occurrence of wind and flood events subjected to uncertainties. The uncertainties of dam height, initial water surface level, precipitation, and wind velocity are considered in analyzing the overtopping risk.

We will discuss to evaluate the overtopping risk analysis of Mahabad dam based on the displacement which the impact of particle breakage and the results will be presented in the future.

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