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A quantitative model for danger degree evaluation of staged operation of earth dam reservoir in flood season and its application

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Abstract

Based on the natural disaster risk evaluation mode, a quantitative danger degree evaluation model was developed to evaluate the danger degree of earth dam reservoir staged operation in the flood season. A formula for the overtopping risk rate of the earth dam reservoir staged operation was established, with consideration of the joint effect of flood and wind waves in the flood sub-seasons with the Monte Carlo method, and the integrated overtopping risk rate for the whole flood season was obtained via the total probability approach. A composite normalized function was used to transform the dam overtopping risk rate into the danger degree, on a scale of 0−1. Danger degree gradating criteria were divided by four significant characteristic values of the dam overtopping rate, and corresponding guidelines for danger evaluation are explained in detail in this paper. Examples indicated that the dam overtopping danger degree of the Chengbihe Reservoir in China was 0.33−0.57, within the range of moderate danger level, and the flood-limiting water level (FLWL) can be adjusted to 185.00 m for the early and main flood seasons, and 185.00 m−187.50 m for the late flood season. The proposed quantitative model offers a theoretical basis for determination of the value of the danger degree of an earth dam reservoir under normal operation as well as the optimal scheduling scheme for the reservoir in each stage of the flood season.

Keywords: Reservoir staged operation in flood season; Earth dam; Danger degree; Quantitative evaluation; Overtopping risk rate

1. Introduction

According to statistics from the National Bureau of Statistics of the People's Republic of China (MWR and NBS, 2013), there are currently more than 98000 reservoirs in China, with a total capacity of over 900 billion cubic meters. Of these reservoirs dams, up to 90% are embankment dams. However, due to historical reasons (e.g., inadequate survey and design, poor construction quality, and improper management), more than 36% of these dams and reservoirs are in dangerous conditions, with various degrees of risk, which not only limit the use of the reservoirs and maximization of economic benefits, but may also cause potentially catastrophic consequences like life loss and property damage if they are wrecked. For these reasons, dam safety and danger condition evaluation are of the utmost importance (Hartford and Baecher, 2004; Jiang and Fan, 2008). Moreover, according to the International Commission on Large

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Dams (ICOLD, 1973), nearly 50% of earth dam disasters in China and one-third in the world are caused by flood overtopping, seepage, and piping, and other causes make up the rest (Hege, 1997; Jin, 2008). In principle, an earth dam is considered to be destroyed after suffering flood overtopping, which might lead to unexpected consequences. Therefore, it is important and urgent to improve danger degree analysis and assessment, thus offering a scientific basis and reference for risk management and security decision-making. In the case of modification of dangerous dams, including repairs and reconstruction, economic feasibility and social safety goals need to be addressed. When evaluating the priority of earth dam rehabilitation, it is necessary to estimate the danger degree of these dams and reservoirs and sort them, in order to determine the urgency of reinforcement, which will contribute to reasonable allocation of limited resources. Thus, danger degree evaluation is a potentially useful approach. On the other hand, a flood-water resources utilization strategy with higher standards has been put forward to meet the requirements of rapid industrial and agricultural development. Fortunately, reservoirs are one of the most efficient types of infrastructure for integrated water resources development and management, and flood-limiting water level (FLWL) during the flood season is an important parameter in reservoir operation and the key to coordinating the contradiction between flood risk and reservoir benefit (Eum and Simonovic, 2010; Yun and Singh, 2008). In addition, an annual fixed FLWL for the whole flood season may reduce electricity generation, because of the lower water level. In this case, water shortage may occur when the flood season is delayed or ends prematurely, which prevents the reservoir from refilling to the normal water level by the end of the flood season. Sub-season flooding and the corresponding FLWL for flood control have been proposed to coordinate flood control and water resources utilization. When the highest water level in front of the dam exceeds the elevation of the dam crest, it will lead to earth dam overtopping and cause earth dam failure. Higher standards for flood water resources utilization seek a more suitable scheduling solution for reservoir optimal operation. The scheduling solution with optimal utilization of water resources, including flood resources that could otherwise lead to disasters in some rainy regions, cannot excess a dam's flood control risk. Therefore, research on the danger degree for flood control risk of earth dam reservoir staged operation is a key step for solidification or reconstruction for dangerous reservoirs, as well as an effective way to flood water resources utilization.

At present, risk-based analysis and management of hydropower projects are developing rapidly, especially in the U.S., Australia, and Canada. In the 1970s, risk-based analysis conducted by Hagen of U.S. Army Corps of Engineers (USACE), who employed several risk indices to define dam risk, was used to analyze the failure of the Teton Dam in the U.S. for the first time (Seed and Duncan, 1987). Then, guidelines for risk assessment were issued by Australian National Committee on Large Dams in 1994 (ANCOLD, 1994), mainly with regard to some key steps for risk classification, risk assessment, and risk handling, and then the guidelines were revised in 2003 (ANCOLD, 2003), Furthermore, Canada BC Hydro conducted risk analysis to assess dam safety, and argued that dam risk analysis should include the recognition of dam accident patterns, the estimation of failure probability, and risk valuation, etc. (Lou, 2000). China lags behind other countries in risk management in hydropower projects, but has still generated some relevant research findings (e.g., Li et al., 1999; Feng et al., 1995; Zhu, 2001; Ru and Niu, 2001; Ma, 2004; Li, 2006; Mo et al., 2008).

The aforementioned studies have improved and perfected the operation system for reservoir flood control risk analysis. However, these methods established risk models mostly in the form of frame diagrams, which can only evaluate risk qualitatively according to risk standards; they did not include quantitative calculation and analysis concerning the risk of earth dam overtopping failure. At the same time, it is difficult to obtain unified risk assessment results because of the diversity of risk standards, leading to the disadvantage of risk ranking of dangerous dams and the utilization of reservoir flood water resources (NRC, 1983). A natural disaster risk evaluation mode was proposed by the Office of the United Nations Disaster Relief Co-ordinator (UNDRO, 1991): $R = H \times V$, where R, H, and V are the dam overtopping risk degree, danger degree, and vulnerability, respectively, and they all have a value ranging from 0 to 1. However, most researchers have not judged the applicability of this mode or improved the risk model, especially the danger degree model. Therefore, this study focused on setting up a quantitative danger degree evaluation model to evaluate the danger degree of earth dam reservoir staged operation in the flood season. The model was based on the calculation formula of the natural disaster risk evaluation mode. In the model, the uncertainties of flood and wind waves were comprehensively considered in the sub-season flood overtopping risk rate formula, which can transform the dam overtopping risk rate into the danger degree. In addition, the quantitative expression divided the interval of dam overtopping danger on a scale of 0−1 using a four-tier system. Each had its accordant dam overtopping danger attributes, providing a foundation for reservoir danger degree assessment. The proposed model and the solution method were applied to the analysis of the danger degree of an earth dam of the Chengbihe Reservoir, in China. Reasonable FLWLs for reservoir flood season management are proposed below.

2. Solution method of danger degree evaluation model

2.1. Total probability approach

The total probability formula can transform the probability of complex events into the conditional probability of the events in some cases and the probability of occurrence of these events (Tang et al., 2011). It was used to calculate the integrated dam overtopping risk rate for the whole flood season in this study. The definition and expression of the total probability formula can be described as follows: (1) Variables S and A are the sample space and the possible event in the text event