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Review of Dam-break Research of Earth-rock Dam Combining with Dam Safety Management

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Abstract

Developmental characteristics of dam-break research on earth-rock dam were reviewed and nowadays researchers emphasized corporation and paid more attention to quantitative description, multiple processes coupling and system integration in research. Combining with most concerned problems in dam safety management (DSM), achievements were reviewed in three fields: causal factors of disasters, dam-break process and flood propagation. In order to perfect a DSM system, researches on variations of dam material properties and corresponding effect in dam-break process, scale effect, similarity criteria of dam-break process and uncertainty analysis of common used models should be enhanced.

Keywords: Dam safety management; Earth-rock dam; Dam failure; Dam-break mechanism; Flood; disaster

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1. Introduction

Dam failure disasters usually cause huge loss of lives and destructions of properties and environment. For example, the 1963 failure of Vajont dam in Italy caused 2600 deaths, the 1976 failure of Teton dam in America caused hundred deaths and economic loss about 1 billion dollars, and the 1993 failure of Gouhou dam in China caused 300 deaths. The statistical analysis of 534 dam failures from 43 countries before 1974 indicated that earth-rock dam failures accounted for the largest proportion of all failures and included 49% caused by overtopping, 28% seepage in dam body and 29% seepage in foundation [1]. There are about 3498 dam failures in China between 1954 and 2006, 90% of which are earth dam, especially homogeneous earth dam which accounts for 85% of all these failures [2].

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Reasons for dam failures can be divided into two types: natural causes and human attributes. The former includes: 1, external causes, such as heavy rains, hurricanes, earthquakes, etc.; 2, internal causes, aging of materials, dam body defects, foundation defects and so on. Human attributes include: 1, global climate warming, which enhanced atmospheric circulation and then extremely rain increased, caused glacier retreat and glacial lake were formed and the threats of dam break increased; 2, terrorist attacks or wars; 3, major construction projects increased the potential threats of dam break, for example, there were about 85 thousand reservoirs including 30 thousand in danger, as well as various embankments about 2500 thousand kilometers long in the flood control system of 7 biggest rivers in China by 2009.

Dam failure disasters and potential threats highlight the need for forecasting, prevention and reduction of dam-break disasters. Establishment and perfection of a modern DSM system is imperative. Modern DSM needs sound regulations and guidance, advanced safety management mode and related technologies (dam-break process modeling, flood propagation modeling, risk assessment technologies, etc.), all of which are established based on the achievements of dam-break research. In other words, the establishment and perfection of modern DSM system depends on the development of dam-break research. Dam-break studies of earth-rock dams as theoretical supports for DSM were reviewed and discussed in this paper.

2. History of dam-break research

Characteristics and contents of dam-break research have been changed with research background since studies of dam-break problems were started in 1850s in France. Based on different characteristics and contents of dam-break research at different times, three periods are divided: the first period (from 1850 to 1950), the second period (between 1950 and 1990) and the third period (from 1990 until now).

For there was no computer before 1948, dam-break studies in the first period were mainly focused on theoretical solutions for dam-break wave problems and related physical model tests. For example, Ritter neglected the bed shear friction and riverbed topography and obtained a simplified solution for the situation of rectangular instantaneous total collapse with dry riverbed in the downstream for the first time by using the characteristic form of Saint-Venant equations in 1892 [3]. Ignoring the riverbed topography and friction, Stocker divided the flow patterns of dam site into three types: continuous wave flow, critical flow and discontinuous wave flow and extend Ritter solution to the wet-bed situation [4]. Researches on analytical solutions for dam-break wave problem tended to be mature nowadays but only limited in some special cases [5-8].

Since large amount of dams were constructed in 1950s, causal factors of dam-break disasters and threats of dam-break flood on the downstream cities or towns had been paid much attention to during the second research period. For example, laboratory experimental tests and field tests of earth-rock dam were carried out by US and Austria to study the casual factors of dam-break disasters and timing scale for dam-break process [5]. For the design of different projects in China, dam-break process were modeled to investigate dam-break peak discharge, outflow hydrograph and flood inundation by several research institutions [5, 9-10]. As computer had been invented and used in dam-break research in this period, many modeling technologies had been developed and lots of dam-break mathematical models had been built, such as Cristofano model, HW (Harris-Wagner), DAMBRK, BREACH, BEED, SMPDBK, BRDAM, MIKE, DHI and so on.

In the third period, dam safety problems were highlighted by significant dam-break incidents in near several decades and the development of science, technology and society. Characteristics of dam-break research in this period were: 1, emphasizing cooperation between different countries and regions, such as NDSP (National Dam Safety Program hold by the Unite State), CADAM (Concert Action on Dam-break Modelling, hold by Europe Union, 1998.2-2000.1) and IMPACT (Investigation of Extreme Flood Processes and Uncertainty, hold by Europe Union); 2, putting more attention to quantitative description, multiple processes coupling and system integration in dam-break research. For example, inundation hazard assessment models were built, comprising hydrodynamic models for river channel, dam breach models and inundation models for the downstream areas of the failed dam [11-14].

3. Theoretical supports for Modern DSM

Modern DSM system includes regulations and guidance system, risk analysis system, safety monitor system, danger control and reinforcement system, early warning system, emergency plan system. Regulations and guidance system provide guidance for other systems. Just like aerial photography, remote sensing and GIS technology providing strong technological supports for DSM system, dam-break researches offer theoretical supports for it. For example, results of researches on causal factors of dam-break disasters make safety monitor system more targeted and probability calculation of dam-break disaster in risk analysis more rationality; emergency treatment depends on the understanding of dam-break process and the results from flood propagation modeling. As following, achievements in dam-break researches are reviewed and discussed as theoretical supports for DSM in three fields: causal factors of dam-break disaster and catastrophe conditions, dam break process, and flood propagation.

3.1. Causal factors of disaster and catastrophe conditions

The question, in which situation a dam would be destroyed, is cared much about by people and the answer for it is the key for risk assessment and early warning. For different dams, the causal factors and catastrophe conditions are different. As a moraine dam, the most important causal factor and catastrophic condition is the repeat overtopping wave at the almost-filled reservoir, while a single wave is generally unable to break a dam [15]. As a landslide dam, upstream reservoir level, and dam materials, and geometrical dam configuration, and seepage, and internal sedimentary have a great influence on catastrophic condition. Downstream-face slope angle greatly influences the types of failures and the minimum reservoir level that causes failure is determined by different sediment size, channel bed slope angles and geometrical dam configurations [16]. The time to failure for rock avalanche dams is about twice that observed for homogeneous dams due to the coarsening properties of the carapace [17]. For earthen dams, dam protection, and erodibility of dam materials, and water salinity, and compaction are important influencing factors for catastrophic conditions [18-19]. Hewlett found that dam protection would increase the dam-break water head, dam-break time and the maximum dam-break discharge [20]; Briaud, et al. [21] examined the erodibility of different samples collected from the New Orleans levees and the factors that influenced erodibility, such as compaction, water salinity, and fine materials content.

Catastrophe conditions are influenced by geometrical dam configuration, hydraulic conditions (reservoir level, inflow discharge, seepage, etc.) and dam materials properties (grading, cohesion, compaction, water salinity, etc.). It is hard to build mathematical expressions for catastrophe conditions with material properties and almost all the existing achievements are qualitative descriptions [22]. Quantitative study of catastrophe conditions should be enhanced because quantitative relations for critical catastrophe conditions are essential to DSM. For example, initial time for breach formation is critical reference factor for mathematical modeling of dam-break process and flood propagation and emergency treatment [22-23], while dam-break time by gradually failure ranges from several minuets (failure of Glashutte dam in Germany in 2002), several hours (failure of South-Fork dam in USA in 1889) to years (failure of a landslide dam in New Zealand) [24-25]. In order to make risk assessment more accurate, safety monitoring and reinforcement more targeted, and emergency plan more detailed, it is necessary to strengthen quantitative research on critical break conditions of all kinds of dams with different forms, and dam materials. Quantitative relations for critical break conditions must include all kinds of factors that represent geometrical dam configuration, hydraulic conditions and dam materials properties. At present, Chinese Academy of Sciences is carrying out related research based on a Natural Science Fund Project named “Research on destruction of soil structure and disaster control mechanism under water dynamic situation (2010.1 - 2013.12)”.

3.2. Dam-break process

Researches on dam-break process, which can dramatically influence the outflow hydrograph which directly impacts the hazard to life and property in the downstream areas, provide theoretical supports for emergency treatment and timely evacuation. Two main methods for studies of dam-break process are dam-break experiments and mathematical modeling.

Overtopping flow over a dam progresses through three zones: zone of subcritical flow from calm reservoir to portion of the embankment crest, zone of critical flow on the crest and zone of supercritical flow on the downstream slope [26]. Initial erosion often begins within the supercritical zone, especially at a point of slope discontinuity [18] and then a headcut or multiple headcuts form on the downstream slope, and after that these headcuts tend to be deepened and finally combine into a single upstream-migrating headcut [27]. Vegetal cover or other protections impact on catastrophe conditions and also dam-break process. Temple and Hanson divided the failure process of earth dam into three sub-processes: vegetal cover failure, headcut formation and migration upstream [28]. Dam erosion rate, similarity criteria of dam-break process, breach parameters and outflow hydrograph have been paid much attention to. Erosion rate in dam-break process is influenced by hydraulic head, thickness of cutoff wall and cohesive portion in dam materials [29-32]. Pugh [33] concluded that a cohesive core had a little impact on lateral erosion process and the nature of the noncohesive shoulder material was the determining factor for erosion rate. Flow in the breach is trans-critical and total head remains constant in the former part of the breach and decreases in the latter part because of the expansion and separation of flow in the breach [34-35]. Scale effect should not be neglected in the study of dam-break process by laboratory and field tests. Yang obtained a formula of formation time of dam breach, erosion rate and model scale based on about 30 dam failure tests of self bursting dams [36-37]. Li, et al. [38] derived similarity scale λ_R of headcut migration rate and similarity time scale λ_t in dam-break process of homogeneous embankment due to overtopping flow based on “headcut” mechanism and results from model tests. Although soil material properties such as compaction and water content strongly correlated with the observed erosion processes, they are difficult to be used in the development of a physical prediction model. On the other hand, soil properties such as erodibility and soil strength do have a physical basis [39], it is the common way to use erodibility and soil strength to represent the effect of dam materials on dam-break process. Researches on correlations between erodibility, soil strength and other soil materials properties such as compaction water content, energy, and density, as well as texture should be enhanced.

Based on the understanding of dam-break process, a lot of dam-break models, including parametric models, statistical models and physically based models, have been built to simulate the breach development and to predict outflow hydrograph. However, breach erosion is a multivariable and multidisciplinary problem and existing technologies for predicting of breach parameter and modeling of dam-break process contain great uncertainties [40-41]. Besides, most of these studies were based on small scale laboratory tests and large part of the data for validation of numerical models and establishment of regression expressions were obtained from small scale laboratory tests, therefore scale effect should be considered and more large scale field tests are necessary.

3.3. Flood propagation

Researches on flood propagation support the establishment of emergency evacuation plan and the calculation of loss of lives and properties in risk assessment. For example, China Institute of Water Resources and Hydropower Research carried out distorted model tests of the Three Gorges Dam to study dam-break flood path, submerged area, disaster losses and corresponding protective measures under different break modes and reservoir water levels between 1958 and 1959 [9]; Sun and Fu[42] provided a method of increasing (or reducing) roughness according to different water depths for flood tests with narrow reservoir front and wide dam-break front and described the fundamental characteristics of the evolution of dam-break flood at a wide dam-break front. Mathematical modeling is the main method for flood propagation modeling. Lots of mathematical models have been built and most of them are hydrodynamic models, except for some empirical statistical and simplified models. Though natural valleys with complex geometry, urban areas with dense buildings and sediment movement make the numerical modeling of flood propagation more complex, great improvements have been obtained. Aureli, et al. [43] used a 2D MUSCL-Hancock finite volume numerical model to simulate rapidly varying flows spreading out on horizontal plane with obstacle. Cao, et al. [44-45] built 1D and 2D shallow water hydrodynamic models to study the dam-break flood propagation over an erodible sediment bed. Other than modeling technologies, predictive accuracy of inundation models depends much on the rationality of outflow hydrograph at dam site calculated by models of dam-process.

3.4. Further research for DSM

Probabilities for dam failures and losses in disasters are the two factors of dam-break risk. There are two corresponding ways to reduce dam-break risk: reducing failure probabilities and mitigating disasters. In DSM system, dam safety monitor and repair decreases causal factors and diminishes probabilities of failures caused by different factors, and early warning and appropriate emergency plan reduces losses caused by dam failures. Based on the review of existing achievements of dam-break research, several key referential factors for DSM and researches needed to be implemented or enhanced are showed in Tab. 1.

Table 1. Discussion on further research for DSM

Components for DSM	Key reference factors	Researches needed to be implemented or enhanced
Dam safety monitor and repair	Causal factors and critical conditions of dam failure	Quantitative relations for critical conditions of dam failure; variations of geotechnical properties in dam break process
Early warning	Initial time for breach formation	Breach development under different hydraulic and dam material conditions
Emergency plan	Flooding area and submerged depth, propagation time.	Uncertainty analysis of common used models for dam-break process and flood propagation

Quantitative studies on critical conditions of dam failure and initial time of breach formation strongly correlate with soil material (geotechnical) properties, most of which do not have a physical basis. The widely accepted solution in the development of a physical predictive model is to build correlations among erodibility, soil strength (that do have a physical basis) and other soil materials properties (that do not have a physical basis, such as compaction, water content, texture, etc.). However, little work has been done to study the variations of geotechnical properties and corresponding effect in dam break process. Soil material properties have a great influence on dam-break process and the changes of them should be considered in the study on dam-break mechanism. For example, Zhang et al. [46] presented three new breach mechanisms, source-tracing erosion with the form of multilevel headcut, two-helix flow erosion of dam crest and collapse of breach sidewalls, then further researches should be carried out to study the influence of the variations of soil material properties caused by flow in the dam breach on these three processes. Scale effect in dam-break process in laboratory and field tests, which are the best way to study dam-break mechanism, should not be neglected, and studies on similarity criteria of dam-break process should be enhanced. Besides, lots of mathematical models used in DSM contain great uncertainties, which should be analyzed and assessed.

4. Conclusion

Nowadays in dam-break research, cooperation among different countries and regions is enhanced. Quantitative description, multiple processes coupling and system integration attract more attentions.

Quantitative studies on critical conditions of dam failure and initial time of breach formation and uncertainty analysis of common used models for dam-break problems are very important for DSM. Since soil material properties, most of which do not have a physical basis, have a great influence on dam-break process, more work should be done to identify the variations of dam material properties and corresponding effect in dam-break process. Besides, scale effect in dam-break experiments should be considered and researches on similarity criteria of dam-break process should be enhanced.

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