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Research on Dam Safety and Risk Management in Water Conservancy Engineering

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Abstract: As the country with the highest number of dams in the world, China's dam safety management and risk control are crucial to public safety and economic development. This paper systematically analyzes the current status of dam safety in China, explores the causes of accidents such as design and construction defects, poor operation management, the impact of natural disasters, and proposes comprehensive dam safety management measures based on these analyses.

Keywords: Dam safety; Risk management; Water conservancy engineering; Risk assessment; Emergency response

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1. Introduction

With the rapid development of society and economy, China has achieved remarkable success in water conservancy construction, with a continuous increase in the number of dams and diversification of types. However, some dams built in the early stages have potential safety hazards due to low design standards and limited construction technologies. Therefore, methods to effectively evaluate dam risks and take scientifically reasonable management measures has become an urgent issue. This article aims to systematically review the current status of dam safety, analyze the causes of accidents, and explore effective methods for risk assessment and management, providing reference for ensuring the safe and stable operation of dams.

2. Analysis of dam safety status

2.1. General status of dam safety in China

2.1.1. Number and types of dams

According to the latest statistics, China has more than 98,000 dams of various types, making it the country with the most dams in the world. These dams include traditional types such as concrete gravity dams, arch dams, and earth-rock dams, as well as new types developed in recent years to meet different geographical environments and functional needs, such as panel rockfill dams and asphalt concrete core wall dams. Each type of dam exhibits significant differences in safety performance due to its structural characteristics, construction materials, and construction methods.

2.1.2. Current status of dam safety

Dam safety management in China's water conservancy projects faces multiple challenges. On one hand, some older dams suffer from varying degrees of safety hazards due to low design standards, limited construction technologies, or structural aging caused by long-term operation. On the other hand, extreme weather events caused by climate change, such as heavy rainstorms and floods, pose new threats to dams. Although relevant government departments have formulated relatively complete dam safety regulations and technical standards and strengthened daily monitoring and maintenance work, a small number of dams still fail to meet current safety requirements.

2.2. Causes of dam accidents

2.2.1. Design and construction defects

In the design phase, factors such as insufficient geological surveys, inaccurate hydrological condition estimates, or inappropriate selection of structural calculation models may cause design parameters to deviate from actual conditions, thereby affecting the safety of dams. During construction, issues such as poor material quality control, non-compliance with construction standards, and neglecting quality due to tight schedules can all lead to potential defects. Additionally, if specific natural factors in special environments (such as earthquake-prone areas or cold regions) are not fully considered, potential safety hazards may arise.

2.2.2. Poor operation management

An effective operation management system should include sound rules and regulations, professional technical personnel, and advanced monitoring equipment. However, in practice, some dams may experience situations where management systems are not properly implemented or operating procedures are not strictly followed. Moreover, inadequate personnel training makes it difficult to identify and handle abnormal situations in a timely manner. Aging or malfunctioning monitoring systems or incorrect data interpretation can also render early warning mechanisms ineffective, preventing preemptive preventive measures. Long-term lack of necessary maintenance and repair work accelerates the aging and degradation of dam facilities, increasing the risk of accidents [1].

2.2.3. Impact of natural disasters

Natural disasters pose significant external threats to dam safety. Extreme weather events such as heavy rains causing floods or sudden precipitation after prolonged droughts may exceed the design capacity of dams, leading to overflow in spillways or damage to the dam body. Earthquakes generate strong vibrations and ground deformations that compromise the structural integrity of dams, especially in earthquake-prone areas where such risks are more prominent. The pressure changes caused by freezing and thawing processes can also affect the stability of the dam body and surrounding soil masses. These natural factors often have suddenness and unpredictability, increasing the difficulty of prevention and requiring scientific planning and engineering measures to mitigate their adverse effects on dam safety.

3. Methods for dam risk assessment

3.1. Risk identification

3.1.1. Risk source identification

Risk source identification is the foundation of dam risk management, aiming to determine all potential sources that may threaten dam safety. This includes internal and external aspects; internal risk sources mainly refer to factors related to the dam's own structure, material properties, and construction quality, such as concrete cracks and foundation settlement; external risk sources cover changes in the natural environment (such as floods and earthquakes) and human activities (such as illegal sand mining and nearby construction). By analyzing historical data, conducting field investigations, and utilizing remote sensing technology for monitoring, all types of risk sources can be comprehensively and systematically identified, providing a basis for subsequent risk factor analysis.

3.1.2. Risk factor analysis

Risk factor analysis focuses on deeply analyzing the specific influencing factors behind each identified risk source. For different types of internal risk sources, it is necessary to assess their occurrence probability and impact on the dam's structural integrity and functionality under specific conditions. For external risk sources, the mechanism, intensity, and frequency of their actions must be examined. Additionally, the interrelationships between various risk factors and the possibility of chain reactions must be considered.

3.2. Risk analysis

3.2.1. Qualitative analysis

Qualitative analysis is primarily used to preliminarily judge the nature and likelihood of risks without involving specific numerical calculations. This method relies on expert experience and engineering intuition, combined with relevant theories and technical standards, to categorically describe risk sources and factors. By constructing risk event trees or causal diagrams, the logical path from risk sources to potential accidents can be intuitively displayed. Furthermore, qualitative analysis helps identify risk factors that are difficult to quantify but are crucial to dam safety, such as public awareness and emergency response capabilities. Although qualitative analysis results have a certain degree of subjectivity, they provide necessary background information and support for more precise quantitative analysis.

3.2.2. Quantitative analysis

Quantitative analysis uses mathematical models and statistical tools to estimate the probability and consequences of risks numerically. This process typically relies on extensive historical data, monitoring records, and experimental test results, employing methods such as fault tree analysis (FTA), event tree analysis (ETA), and Monte Carlo simulation to quantify uncertainties and variabilities. By calculating expected loss values (ELV) and risk indices (RI), the harm levels of different types of risks can be accurately measured, providing scientific evidence for decision-makers. It is important to note that the effectiveness of quantitative analysis depends on the quality of data and the rationality of model assumptions, so careful handling of input parameter selection and uncertainty analysis is essential.

3.3. Risk evaluation

3.3.1. Risk level classification

Risk level classification involves categorizing and prioritizing identified risks according to their severity and urgency based on the results of risk analysis. Generally, both the likelihood of risk occurrence and the consequences once it occurs are comprehensively considered, using two-dimensional matrixes or three-dimensional cube models for evaluation. For example, high-probability and high-consequence risks are classified as Level 1 risks, requiring immediate action to control them. While, low-probability and low-consequence risks are categorized as Level 4 risks, serving as long-term monitoring targets. This grading approach not only facilitates the rational allocation of resources but also lays the foundation for formulating targeted risk management strategies.

3.3.2. Risk evaluation methods

Risk evaluation methods refer to systematic procedures and technical means for comprehensively assessing the risk levels faced by dams and guiding corresponding management actions. Common methods include Analytic Hierarchy Process (AHP), Fuzzy Comprehensive Evaluation (FCE), and Grey Relational Analysis[2]. These methods address different aspects of complexity and multidimensionality in risk evaluation. For instance, AHP is suitable for comparing the relative importance of risk elements with clear hierarchical structures, while FCE performs well in handling fuzzy information and uncertain conditions. Choosing appropriate risk evaluation methods is critical to ensuring the objectivity and reliability of evaluation results, while also considering the operability and cost-effectiveness in practical applications.

4. Dam safety management measures and emergency response plans

4.1. Dam safety management measures

4.1.1. Safety management during design and construction stages

In the design phase, national and industry standards must be strictly followed, fully considering the influence of geological and hydrological conditions, and adopting advanced computational models and technical means for structural optimization. During construction, a sound quality management system should be established to strengthen control over raw material quality, construction techniques, and procedures, implementing full-process supervision. Additionally, introducing third-party independent review mechanisms ensures the reasonableness of design schemes and compliance of construction quality with safety requirements. Conducting risk assessments to identify and address potential safety hazards in advance is also essential.

4.1.2. Safety management during operation stage

Safety management during the operation stage focuses on combining routine maintenance with emergency management. A comprehensive operation management system should be established, clearly defining operational procedures and responsibility divisions, ensuring strict adherence to norms in all operations. Regular comprehensive inspections of dams and their ancillary facilities should be conducted to promptly identify and repair defects or damages that could affect safety. Detailed emergency response plans should be formulated for different types of emergencies (such as floods and earthquakes), and drills should be carried out to enhance emergency response capabilities [3].

4.1.3. Monitoring and testing

Monitoring and testing are key components of dam safety management, aimed at continuously tracking changes in the dam's condition through scientific means. Modern sensor technologies and satellite remote sensing tools should be adopted to construct a comprehensive, multi-level monitoring network, enabling real-time monitoring of key parameters such as deformation, seepage, and stress. Specialized tests, including concrete strength testing and crack depth measurement, should be conducted regularly to obtain accurate data support. In data analysis, statistical principles and machine learning algorithms should be employed to uncover hidden patterns and predict future trends, providing scientific evidence for decision-making.

4.2. Emergency response plan compilation

4.2.1. Emergency response plan system

An emergency response plan system refers to a complete organizational structure and procedural arrangement for responding to dam emergencies. This system covers all levels of government and relevant functional departments from central to local levels, forming a responsibility chain that extends vertically and horizontally. Core content includes the establishment of command coordination institutions, division of responsibilities among departments, smooth communication channels for information reporting, and the improvement of public participation mechanisms. Cross-regional cooperation needs should also be considered to ensure rapid mobilization of resources and coordinated operations in emergencies. Regular updates to the plan content and joint drills should be organized to continuously improve the operability and adaptability of the plan [4].

4.2.2. Content of emergency response plans

Emergency response plans specify the steps and measures to be taken when specific types of emergencies occur. First, the event level should be determined based on the scale of the disaster and its impact range to define the response level. Second, evacuation plans should be established, clearly specifying evacuation routes, assembly points, and transportation arrangements to ensure the safety of affected populations. Third, detailed rescue plans should be listed, including inventories of emergency supplies, professional team assembly locations, and on-site handling methods. Finally, an information release mechanism should be included to promptly inform the public about the progress of the situation, avoiding panic caused by rumors. All this content should undergo expert review and be continuously optimized and adjusted based on actual circumstances.

4.2.3. Implementation and evaluation of emergency response plans

The implementation and evaluation of emergency response plans are critical steps in testing their effectiveness. Once the emergency response plan is activated, all relevant departments must act swiftly according to predetermined procedures, ensuring accurate instruction transmission and resource allocation. Afterward, a comprehensive review and summary of the entire emergency response process should be conducted to analyze existing problems and deficiencies, particularly focusing on weak links in communication coordination, resource allocation, technical support, and proposing improvement suggestions [5].

5. Conclusion

In summary, dam safety management is a complex and systematic project that requires strict control throughout the entire lifecycle from design and construction to operation and maintenance, as well as precise risk assessment and prevention measures for potential risk sources. By establishing a sound monitoring and early warning mechanism and optimizing the compilation and implementation process of emergency response plans, the ability to respond to emergencies can be significantly improved. In the future, continued investment in scientific research, promotion of technological innovation, improvement of legal frameworks, and promotion of multi-department collaboration will be necessary to achieve the modernization transformation of dam safety management, thereby better protecting people's lives and property and promoting sustainable social and economic development.

Disclosure statement

The authors declare no conflict of interest.

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