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A Review of Safety Inspection Methods for Reservoir Dams

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Abstract

Reservoir dams, as critical hydraulic structures, are also key components of flood control engineering, playing a significant role in China's economic construction and social development. Therefore, the safety of dams is of utmost importance. It is essential to conduct long-term safety inspections of dams during their operational period to detect potential safety issues in advance. This paper discusses various methods for dam leakage detection and dam displacement monitoring, which contribute to the overall safety inspection of reservoir dams.

Keywords

Reservoir Dams; Dam Leakage Detection; Dam Displacement Monitoring.

1. Introduction

A dam achieves temporal and spatial regulation of water resources by intercepting rivers for water storage, and it also serves as a vital component of flood control engineering. According to statistics, by 2014, China had constructed approximately 90,000 reservoir dams, making it a world leader in dam engineering. These dams play a significant role in China's economic construction and social development[1-3]. The safety of reservoir dams is closely related to the lives of the people; thus, ensuring dam safety is of paramount importance for safeguarding lives and property. Detecting dam leakage and monitoring dam deformation are crucial aspects of dam safety. This paper introduces the commonly used methods for dam leakage detection and dam deformation monitoring.

2. Forms of Leakage in Reservoir Dams

Leakage in reservoir dams can be categorized into several forms: porous leakage, fissure leakage, and piping leakage.

Porous Leakage: This type of leakage occurs when water flows through the pores and gaps in the soil and rock materials. The amount of seepage mainly depends on the particle size distribution and permeability coefficient of the soil and rock materials.

Fissure Leakage: This occurs when water flows through joints, fissures in rock formations, or cracks in concrete. The extent of leakage depends on the development of the joints and fissures or the size and connectivity of the concrete cracks.

Piping Leakage: This type involves water flowing through cavities, karst, or dissolution structures. The amount of leakage is determined by the size and connectivity of the cavities, karst features, or dissolution structures.

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3. Methods for Detecting Leakage in Reservoir Dams

3.1. Drilling Method

Drilling is conducted at suspected leakage areas or geophysical anomaly locations. By observing and analyzing the extracted core samples, it is possible to determine whether leakage issues exist. Drilling television cameras can be used to assist in this process. Various detection methods can be employed through drilling, such as the water pressure method, tracer method, charging method, seepage field method, and CT method, to further investigate the leakage situation[4].

3.2. Seepage Field Method

By measuring the flow velocity and flow field of groundwater in boreholes at different locations, inverse fitting analysis is conducted to establish the seepage flow field in the area. The distribution characteristics of the seepage field are then used to determine the leakage locations and leakage channels.

3.3. Seepage Field Method

According to the source of tracers, the tracer method is divided into natural tracer methods and artificial tracer methods[5]. Natural tracer methods include temperature tracing, conductivity tracing, and dissolved oxygen tracing. Artificial tracer methods are classified into dye tracing, salt tracing, and isotope tracing. Natural tracer methods analyze the source of leakage water and determine the leakage entry point based on the similarity between the temperature, conductivity, or dissolved oxygen concentration of downstream leakage water and the reservoir water upstream of the dam. Artificial tracer methods involve introducing tracers such as dyes, salt, or isotopes at specific locations in the reservoir or boreholes, then detecting the presence and concentration of these tracers at various leakage points downstream or other locations. This helps analyze the relationship between the upstream reservoir water and the leakage water, determine the leakage entry point, and calculate the seepage velocity[4]. These methods are generally used as supplementary verification techniques for leakage detection and cannot determine the internal distribution of leakage channels within the dam.

3.4. Computed Tomography Method (CT Method)

Computed Tomography (CT) technology, inspired by medical CT, is based on the principle of wave projection. It uses ray scanning and inverse calculation of the obtained information to reconstruct images of the elastic and electrical distribution patterns within the measured rock mass. This geophysical method allows for the inference of the structure and shape of the target geological body. CT imaging is further divided into elastic wave tomography, electromagnetic wave tomography, and resistivity tomography[6].

The CT method generally includes acoustic CT, seismic CT, and electromagnetic CT. By observing the travel time or amplitude of acoustic waves, seismic waves, or electromagnetic waves penetrating the strata, it reconstructs the structure, wave velocity, or attenuation coefficients of the strata or concrete medium. This helps detect underground karst, fracture structures, or concrete defects and analyze leakage channels. The CT method typically requires the use of boreholes[4].

For instance, Li Xiulin et al.[7] used the travel time of elastic waves on various rays of the detection section within the measured structure to invert the distribution of elastic P-wave velocity on the section. By continuously improving the processing software for the relationship between borehole electromagnetics and CT, data is obtained from the inversion of the imaging process[8].

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4. Applicability Analysis of Seepage Detection Methods

Based on the principles of commonly used leakage detection methods and considering the structural characteristics of earthfill, rockfill, and concrete dams, the current methods for detecting leakage in reservoir dams focus on identifying leakage entry points and leakage channels. The main methods for detecting leakage entry points include the pseudo-random flow field method, tracer method, and (inverse) water injection method. The commonly used methods for detecting leakage channels include high-density electrical method, natural electric field method, and ground-penetrating radar (GPR) method. Among these:

(1) **Pseudo-Random Flow Field Method**: Suitable for concentrated leakage and downstream concentrated water outflow situations. For instance, if the reservoir's dead water level is high, the leakage volume is large, and there are surface holes, the reservoir water may penetrate the curtain under high hydraulic head, forming leakage channels[9]. It is not suitable for detecting surface leakage in soil and rock, small crack leakage, or leakage with no visible downstream outflow points.

(2) **Tracer Method**: Primarily uses ink tracing, chemical tracing, and radioactive tracing. For example, Li Zheng et al.[10] used the ink tracing method to detect leakage entry points in concrete dams. Chemical and radioactive tracers are rarely used due to testing methods and environmental concerns.

(3) **(Inverse) Water Injection Method**: Suitable for detecting single-channel leakage entry points in concrete or bedrock; it is not suitable for loose soil and rock bodies or complex leakage channels. Traditional methods of monitoring and controlling dam fill quality involve artificial pit water injection to detect dry density of fill material, with the number of roller passes counted on-site by personnel. This method has drawbacks such as high labor intensity, slow detection speed, discontinuous measurement points, low monitoring efficiency, susceptibility to human error, high costs, and destructiveness[11].

5. Prospects for Reservoir Dam Safety Inspection Technologies

In the future, the development and application of advanced technologies will significantly enhance the effectiveness and efficiency of reservoir dam safety inspections. Here are some prospects for the future of dam safety inspection technologies:

1) Integration of Multi-Technology Approaches: Combining various detection methods, such as integrating electrical resistivity tomography (ERT), ground-penetrating radar (GPR), and thermal imaging, can provide a comprehensive understanding of dam conditions. The integration of these technologies will help overcome the limitations of individual methods and improve overall detection accuracy.

2) Artificial Intelligence and Machine Learning: AI and machine learning algorithms can analyze large volumes of data collected from various sensors and monitoring systems to identify patterns and predict potential issues. These technologies can enhance the accuracy and speed of data interpretation, enabling proactive maintenance and early warning of potential dam failures.

3) Remote Sensing and UAVs: The use of remote sensing technologies, including satellite imagery and unmanned aerial vehicles (UAVs), can provide real-time monitoring of dam conditions. These technologies offer a cost-effective and efficient way to inspect large and inaccessible areas, identify surface deformations, and monitor environmental changes around the dam.

4) Smart Sensors and IoT: The deployment of smart sensors and Internet of Things (IoT) devices can provide continuous and real-time monitoring of various dam parameters, such as

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water levels, pressure, temperature, and structural movements. These sensors can transmit data to central monitoring systems, enabling timely analysis and response to any abnormalities.

5) Advanced Data Analytics and Visualization: The development of advanced data analytics and visualization tools can help engineers and decision-makers better understand the condition of dams. These tools can process and visualize complex data sets, providing intuitive and actionable insights for dam safety management.

6) Non-Destructive Testing (NDT) Methods: The advancement of non-destructive testing methods, such as acoustic emission testing, ultrasonic testing, and infrared thermography, will enable the assessment of dam conditions without causing damage. These methods can detect internal defects, cracks, and other anomalies, ensuring the integrity and safety of the dam.

7) Environmental and Climate Monitoring: Considering the impact of climate change on dam safety, incorporating environmental and climate monitoring systems will be essential. These systems can provide data on weather patterns, precipitation levels, and other environmental factors that affect dam stability, enabling better risk management and adaptation strategies.

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