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INTEGRATION OF SEISMIC DATA INTO DAM SAFETY MANAGEMENT SYSTEMS: STATE CRITERIA AND MONITORING

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Abstract:

The safety of hydraulic structures (HS), particularly dams, in seismically active regions, represents a critical task in engineering practice. This article considers an integrated approach to incorporating seismic data at all stages of a dam's lifecycle—from site selection to operation. Special attention is given to the system of safety criteria indicators (K1 and K2), which define the transition of a structure from normal operation to potentially hazardous and pre-failure conditions. The role of automated monitoring systems, including seism metric instrumentation, in operational decision-making is analyzed. Based on the analysis of regulatory requirements and historical precedents (for example, the Sardoba reservoir accident), the necessity of continuous monitoring of foundation deformation and filtration parameters under seismic loading is substantiated [1].

Keywords: Dam Safety, Seismic Micro Zonation, Safety Criteria K1 And K2, Hydraulic Structure Monitoring, Seismic Resistance, Filtration Strength

Introduction

Hydraulic structures (HS) of responsibility classes I and II represent potential sources of technogenic disasters. In seismically active regions, earthquakes constitute the primary risk factor, capable of initiating destructive processes in the dam body and its foundation [2]. Accident statistics, including catastrophic dam failures, demonstrate that neglecting foundation rock deformation and underestimating natural forces can lead to tragic consequences [3].

Modern approaches to dam design and operation require the integration of seismic data not only into structural strength calculations but also into operational monitoring systems. The purpose of this study is to systematize methods for utilizing seismic information in managing hydraulic structure safety, including the development of criteria for diagnosing structural conditions and action protocols when threshold values are exceeded [4].

Methodology

Consideration of the Seismic Factor in Dam Design and Monitoring

Consideration of the seismic factor is a fundamental aspect of ensuring the safety of hydraulic structures and begins at the pre-design stage. According to modern regulatory requirements, seismic microzonation is mandatory for regions with normative seismicity of six points or higher. This procedure makes it possible to refine the initial seismic parameters of a specific site by taking into account local soil conditions, which can significantly amplify seismic effects.

Seismic micro zonation The problems that are solved within the engineering-geological survey and risk assessment in seismic micro zonation are of great importance. Firstly, dangerous terrestrial processes are determined: the probability of seismogenic displacements in the active faults; risks (values) of a landside breaker, snow slip and soil liquefaction in foundation. And, the seismic exploration technology even allows to investigate in detail the physical and mechanical properties of rocks such as, for example, to ascertain the elasticity of rock masses and information about deep geological structures. The received data has direct effect on the calculations accuracy in system of “dam-foundation” interaction.

During the design, seismic effects are identified as an equivalent special load combination. Compared to the basic load combination applicable in routine operating conditions, calculation of special combinations is more complicated. This may involve checking the strength of a section using elastic theory procedures or an experimental model test.

In addition, calculating maximum filtration discharge is mandatory to eliminate the risk of filtration regime disruption and ensure the hydrodynamic stability of the structure during earthquakes.

Result

Safety Criteria Indicators of Hydraulic Structures

The fundamental basis of the diagnostic system for assessing the technical condition of hydraulic structures is a two-level scale of diagnostic indicator criteria. These criteria are initially established at the design stage and are subsequently refined based on field monitoring data [5].

Criterion K1 (warning level) reflects the normal-working structure for example, under conditions of operation at NRL. Structures may be judged as potentially unsafe if K1 values are surpassed, but do not exceed K2. The characteristic signs of this phenomenon are deviations of crown motion from design indicators non-attenuating subsidence as well as equal to initial values of turbidity of filtering and sludge reservoir waters. This situation necessitates the close investigation of the causes for and remedies of these defects in order to establish their relationship without stopping the operation of facilities [6].

Criterion K2 (Critical level) This second level corresponds to special load combinations, such as forced reservoir, level (FRL) and seismic effects. Beyond this limit the structure is placed into a pre-failure state of damage to such extent that operations in design regimes cannot longer be acceptable. Critical condition is indicated by an increase in settlement rate with time, the development of filtration discharge at recorded filtrations giving FRL, and occurrence of mechanical suffusion (filtration turbidity greater than reservoir water turbidity) [7]. In these conditions an emergency action becomes necessary, that is the drawdown of the reservoir in order to lower hydrostatic pressure acting on the structure. The assignment of the criteria for some parameters is collected in Table 1.

Table 1. Examples of Criteria Values for Hydraulic Structure Diagnostics.

Parameter	Criterion K1 (Normal Load Combination)	Criterion K2 (Special Load Combination)
Displacements	Design values at Normal Reservoir Level (NRL) and temperature effects	Design values at Forced Reservoir Level (FRL) and extreme temperatures
Concrete stresses	According to elasticity theory (normal load combination)	Ultimate strength limit (special load combination)
Filtration discharge	Discharge at NRL	Discharge at FRL
Filtrate turbidity	Equal to reservoir turbidity ($M_{(res)}$)	> $M_{(res)}$ (indicates suffusion)
Settlement (soil)	Upper limit of confidence interval	Increasing settlement rate (non-attenuating process)

1.1 Monitoring System and Automation of Safety Control

The design of large dams necessarily includes the implementation of an Automated Monitoring System (AMS), intended to ensure continuous control of diagnostic indicators of the structure. One of the crucial parts of AMS is a seismic station, which is located right on the dam body or within its construction field. The functional purpose of this station is the recording in automatic (wait) mode of kinematic parameters -accelerations, amplitudes, vibration frequencies- of a structure and its foundation.

Comparisons of the measured instrumental data with the accepted safety criteria values; K1 and K2. In addition, the system performs the function of generating control signals for initiating emergency protocols; in particular, regulatory documentation prescribes extraordinary underwater technical inspection of hydraulic structures after seismic events exceeding intensity level 6 on the MSK-64 scale (Fig.1).

Figure 1. Integrated Dam Safety Management Framework

To ensure operational reliability, geodetic observations of displacements and settlements must be comprehensively analyzed in relation to seismological factors. This is due to the fact that seismic events, along with hydrostatic pressure and temperature effects, represent dominant causes of deformation processes. The application of Global Navigation Satellite System (GNSS) technologies, combined with traditional geodetic methods, enables the establishment of high-precision geodetic networks that ensure accurate spatial control of key reference points of the dam [11-12].

Emergency Response Procedures

Seismic data incorporated into the design determine threshold values for initiating risk management procedures.

Exceedance of K1:

An enhanced monitoring mode is activated. The operating service conducts analysis of process dynamics, for example, monitoring mechanical suffusion processes.

Exceedance of K2:

An emergency mode is declared. For earthfill dams, a critical measure is the rapid lowering of the reservoir water level [13]. Ignoring these warning signals may lead to the development of destructive processes, such as non-attenuating or accelerating settlement.

Discussion

The analysis shows that the effectiveness of hydraulic structure safety depends not only on structural strength but also on the quality of feedback provided by the monitoring system. The experience of the *Malpasset* dam failure confirms that unaccounted foundation deformation represents a critical risk factor [14]. A two-tier criteria system (K1/K2) enables distinction between operational responses – from scheduled anomaly removal to emergency reservoir depletion [15].

However, there is another big problem from the working point of view in terms of criterion value and criteria modify [16]. Guidelines suggest adjusting K1 and K2 after the first two operating years, using the real controlling data, but sometimes it is not completely carried out (Fig.2).

Figure 2. Aftermath of the Malpasset Dam failure (1959)

Conclusion

The integration of seismic data into dam design and operation is a fundamental condition for ensuring structural safety. The key elements of a comprehensive safety assurance system include mandatory seismic micro zonation during site investigation, application of a two-level diagnostic criteria system (K1 and K2), and equipping structures with automated monitoring systems integrating seismmetric instrumentation.

An essential component of this system is the existence of clearly defined emergency response procedures when critical thresholds are exceeded, including measures such as forced reservoir drawdown to reduce hydrostatic load. Future research perspectives in this field are associated with improving automatic emergency prediction algorithms through the application of machine learning methods to large monitoring datasets.

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