**American Journal of Civil Engineering**
2023; 11(3): 36-39
http://www.sciencepublishinggroup.com/j/ajce
doi: 10.11648/j.ajce.20231103.12
ISSN: 2330-8729 (Print); ISSN: 2330-8737 (Online)

# Enhancing Safety Monitoring and Management for Concrete Dams: A Comprehensive Lifecycle Approach in China

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## To cite this article:

Shuai Zhang, Guang Yang, Libing Zhang, Zhiyong Zhao. Enhancing Safety Monitoring and Management for Concrete Dams: A Comprehensive Lifecycle Approach in China. *American Journal of Civil Engineering*. Vol. 11, No. 3, 2023, pp. 36-39.
doi: 10.11648/j.ajce.20231103.12

**Received**: June 20, 2023; **Accepted**: September 6, 2023; **Published**: September 14, 2023

**Abstract:** Dams' safety affects their expected benefits and puts human life and property, in addition to local public security, at risk, as dams are important pillar infrastructures supporting the sustainable socioeconomic development of a number of countries. As an important means for safe dam operations and management, safety monitoring efforts should permeate all phases of the full lifecycle of dams, including design, construction, and operation, with objectives to be achieved at each phase. Equal emphasis should be placed on the construction and operations of monitoring systems, inspections and instrument observations, evaluation and acquisition of results, and risk warning and analysis feedback. This is to address the pressing issues encountered in routine monitoring work, such as increased effort in construction and decreased effort in management, superficial inspections, inadequate maintenance of monitoring facilities, and an absence of satisfactory analysis of monitoring results. Based on China's *Technical Standard for Concrete Dam Safety Monitoring* (GB/T 51416-2020), the systemic nature of the full lifecycle of concrete dam safety monitoring efforts and the "four equal emphases" were elaborated in this paper, revealing a shift from putting more effort on design and construction to focusing on the full lifecycle of monitoring work in a bid to comprehensively improve the safety monitoring and management of dams towards higher standards.

**Keywords:** Dam Safety, Concrete Dam, Monitoring, Standard, Four Equal Emphases

## 1. Introduction

Over the years, China has garnered international recognition for its achievements in the field of hydropower. The country has now constructed an accumulative total of over 100,000 dams, ranking it first in the world. Due to the complexity of factors such as geological conditions and natural environments, it is impossible for people, with their limited perception, to anticipate all engineering safety issues. As a result, safety monitoring as an important means of ensuring the safety of dams has emerged. China's administrative authorities have enacted laws and issued a series of industry standards to regulate dam safety monitoring to timely obtain accurate and complete monitoring data that can be used to guide the construction and operations of dams, provide feedback on their design, expand supervisory control over the safety of dams, and understand the nature of their operations, thereby ensuring the safety of dams during construction and operations.

The construction and management of dams in China have boomed over the past two decades, with an ever-increasing scale of construction and a growing difficulty of management, which has placed even higher demands on dam safety monitoring. The industry's previous technical specifications for monitoring [1, 2] focused on the design and construction phases and were revised with respect to monitored items such as deformation, seepage, and stress-strain, but failed to reflect the actual requirements for dam safety monitoring efforts under the new conditions.

In response, the China Electricity Council has called on

relevant organizations to complete the formulation of a new national standard, the *Technical Standard for Concrete Dam Safety Monitoring* [3], based on opinions solicited from China's water works and electric power industries and extensive research that summarizes the practical experience of the two industries in concrete dam safety monitoring. The Standard emphasizes the need to attach particular importance to monitoring as it is a systemic work that plays a significant role during all phases of a dam's life cycle. For an in-depth understanding, this paper provides a brief introduction to this concept of the Standard with necessary interpretations of its relevant contents and references to the actualities of concrete dam safety monitoring efforts.

## 2. Actualities of Monitoring Efforts

Concrete dam safety monitoring is to gain a comprehensive understanding of the apparent working conditions of hydraulic structures through instrument monitoring and on-site inspections to analyze and evaluate their safety properties and development trends. In general, the structures monitored for safety include the dam body, dam foundation, abutments, reservoir banks near the dam, and slopes at node junctions, as well as other structures and facilities directly related to concrete dam safety.

The research and application of concrete dam safety monitoring in China began in the 1950s; in the early stages, monitoring technologies were introduced from overseas and were improved through practice [4]. Later, China invested large amounts of funds in the construction of hydropower projects, which spurred the rapid development and application of safety monitoring technologies. China's dam safety monitoring capacities have been extensively enhanced from all respects, including monitoring design, monitoring equipment construction, automation system construction, operations and maintenance, and analysis of monitoring data, with gradually shifting toward normalization, standardization, and institutionalization.

As viewed from the design, construction, and operation and management conditions of safety monitoring systems for typical concrete dams built or under construction in China [5-13], taking into account the requirements of the competent administrative authorities of China, there are insufficiently maintained monitoring devices or facilities in some of the projects due to the huge maintenance workload caused by the harsh operating environment of monitoring instruments in hydropower projects, resulting in unreliable phenomena such as drifts or fluctuations in the readings of monitoring instruments. In addition, because safety monitoring is an interdisciplinary topic spanning multiple fields of research [14], the results of safety monitoring must be comprehensively analyzed and evaluated in conjunction with structural characteristics, geotechnical properties, and construction methods. However, the low entry threshold for service providers prevents comprehensive analyses from producing the expected results, which are insufficient for risk warnings.

## 3. Concept of Full-Lifecycle of Monitoring Efforts

The new national standard points out that safety monitoring efforts should permeate all phases of the full lifecycle of concrete dams, including design, construction, and operation, with objectives to be achieved at each phase, and equal emphasis placed on the construction and operations of monitoring systems, inspections and instrument observations, evaluation and acquisition of results, and risk warning and analysis feedback. The Standard regulates the design, construction, and operations of concrete dam safety monitoring by establishing a framework of standards for all phases, consolidating in the Standard the successful experiences from the monitoring efforts of recent years, and proposing technical regulations to avoid existing problems.

The new full-lifecycle concept proposed to emphasize continuous, unified, coordinated, and shared management throughout the full lifecycle of monitoring efforts from monitoring design to operations and maintenance or upgrades and retrofits, thereby raising awareness of the continuity and importance of the monitoring efforts of different personnel involved in different phases of the project and improving the seamless connection and integration of the different phases.

Monitoring efforts should permeate the full lifecycle of concrete dams. The design of the overall plan in the initial phase should focus on technical issues such as key difficult engineering problems to be solved, the relevance of selected monitored items, the suitability of the monitoring points arranged, and the effectiveness of the monitored items with different purposes in relation to the corresponding phases.

## 4. Characteristics of Full-Lifecycle Monitoring Efforts

The "four equal emphases" is a key feature of full-lifecycle monitoring efforts and an important strategy for addressing problems with work related to dam safety:

1) Equal emphasis on the construction and operations of monitoring systems, with increased investment in financial and human resources, ensures the reliability of monitoring instruments and the credibility of the readings;
2) Equal emphasis on the inspections and instrument observations enables inspections to be a routine component of the monitoring efforts;
3) Equal emphasis on the evaluation and acquisition of results changes the phenomenon in which more importance is attached to data collection and less importance to data analysis into a stricter control of the criteria for quality performance and market access for products;
4) Equal emphasis on the risk warning and analysis feedback enables monitoring efforts to serve as the basis for safe dam operations.

### *4.1. Equal Emphasis on Construction and Operations of Monitoring Systems*

At present, hydropower in China is gradually overcoming its technical and financial constraints and developing into one that is constrained by ecology and resources. With the gradual transition from the construction boom to the post-hydropower era, safe operations of dams that have already been put into operation are becoming the new focus of public attention. Since safety monitoring is an important management measure for dam safety, organizations operating dams should strictly follow relevant standards in the formulation of management systems and directives for monitoring efforts, invest in financial and human resources, engage in work related to dam safety monitoring, and conduct routine management and maintenance of the monitoring system to provide reliable data for evaluating the operations and safety status of dams.

### *4.2. Equal Emphasis on Inspections and Instrument Observations*

Inspections should pervade the full lifecycle of concrete dams; equal emphasis should be placed on inspections and instrument observations, which form a dynamic and complementary ensemble, in all phases of monitoring efforts, including design, construction, and operations. The scope, frequency, method, and path of the inspections should be clearly defined according to the characteristics of the dams, and records and reports of the inspections should be compiled.

In recent years, smart inspection technologies based on lightweight multi-rotor UAVs, QR codes, smart handheld terminals, GNSS technology, and GIS technology have been gradually applied to inspections of dams [15-19]. Real-time recording of inspection operators' work progress, positioning during inspections, recording of navigation paths, and automatic data storage using mobile terminals of the inspection system, coupled with features such as real-time transmission and voice prompt, could resolve issues including reporting, handling, and result tracking of engineering safety hazards.

### *4.3. Equal Emphasis on Evaluation and Acquisition of Results*

The work related to the collection and measurement taking of monitoring data needs to be standardized. The data collected must not be shelved; on the contrary, when conducting safety monitoring and inspection on dams, monitoring data should be classified and analyzed in a timely manner according to applicable technical standards to stay abreast of the operation conditions of dams. Upon detection of anomalies and unsafe factors, the competent authorities for the dams should be notified immediately so that they can take prompt corrective measures.

The work related to the analysis of monitoring data may seem simple, but it places high demands on analysts, who must be well-rounded professionals possessing practical experience in dam engineering and a comprehensive knowledge of the characteristics of monitoring instruments and equipment as well as the analytical method for monitoring data to qualify for the job. As some monitoring personnel do not meet these requirements, it is recommended to innovate the working procedures of monitoring data analysis and evaluation, and consider introducing a professional third-party monitoring technical service provider to effectively guide the construction and operations of dams and provide feedback on their design.

### *4.4. Equal Emphasis on Risk Warning and Analysis Feedback*

Safety monitoring efforts are work related to the monitoring of structures and the use of monitoring data to evaluate the safety of their structural operations to issue warnings of structural safety risks from the perspective of understanding their working conditions. Risk evaluation technologies and risk management methods are gradually being developed and applied to dam safety and management, and are new expressions when compared with previous industry standards, meaning that the idea of dam safety management is expanding from mere dam structural safety management to dam safety risk management. This approach that is present through all phases of the full lifecycle of dams and oriented towards reducing dam safety risks to an acceptable level, is scientific, objective, and economically viable, thereby raising the monitoring and management of reservoir dam safety towards a higher standard [20-22].

With the rapid advancements in technologies such as automated monitoring, digitalized engineering, and information technology, as well as the IT-based social progress and people-oriented working environment, this national standard highlights the proposal to establish online monitoring and control systems for the safety of dams. The monitoring and control indicators for key monitoring items should be proposed according to theoretical calculations, model experiments, or results of comprehensive analysis of monitoring data, and taking into consideration the experience from similar projects, which are dynamically adjusted based on actual conditions. Upon identifying anomalies, timely analysis, feedback, and warning should be carried out to make in-depth use of safety monitoring data and effectively guide routine safety monitoring efforts.

## 5. Conclusion

Despite a late start, China is now among the world leaders in dam safety monitoring technology after years of development. The *Technical Specification for Concrete Dam Safety Monitoring* summarizes theories and experiences validated in practice; over the years, dam safety monitoring has been practiced in countless projects, leading to multiple revisions of the Specification, which has played an indelible role in ensuring the safe operations of China's concrete dams. The newly compiled *Technical Standard for Concrete Dam Safety Monitoring* exceeded the Specification by proposing

two new concepts, that is, the full lifecycle and four equal emphases, and offering strong guidance to address the pressing issues encountered in current concrete dam safety monitoring efforts, such as increased effort in construction and decreased effort in management, superficial inspections, inadequate maintenance of monitoring facilities, and an absence of satisfactory analysis of monitoring results. The Standard will undoubtedly raise the monitoring and management of dam safety to a higher standard.

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