DAM SAFETY TECHNICAL AUDIT BASED ON FAILURE MODE IDENTIFICATION AND ANALYSIS

A. MORALES-TORRES AND J. CASTILLO-RODRÍGUEZ
iPresas Risk Analysis, Avenida del Puerto, Valencia, Spain

I. ESCUDER-BUENO
Universitat Politècnica de València, Camino de Vera SN, Valencia, Spain

ABSTRACT

Dams are essential infrastructures whose failure may cause losses not only to the hydropower or water supply system itself but also to downstream communities, infrastructures, services and the environment. In such demanding context of operation and maintenance of our infrastructures, periodic safety reviews should evolve from merely diagnosis or simple technical audits to more comprehensive processes through failure mode identification and analysis. This qualitative risk analysis process is performed through group working sessions, as a cooperative effort between dam owners, operators, technical stuff, external experts and key actors involved in dam operation and maintenance. In this work, the experience of the authors applying this methodology to evaluate safety management of critical hydropower dams worldwide is explained. Finally, the main advantages of making dam technical audits through failure mode identification are providing a more integral approach for dam safety management, relating the recommendations to potential failures, and involving the dam safety managers and key actors in the audit through collaborative sessions.

1. INTRODUCTION

Any technical audit should aim to review the different aspects related to dam safety in a comprehensive approach. For this reason, identifying potential failure modes that may occur and making recommendations for improving safety management of the dam-reservoir system, such as actions aimed at reducing risk and increasing knowledge about the system, constitute actions of great added value.

Initially, qualitative risk analysis methodologies that include this type of failure mode analysis began were first implemented in the United States, starting with the Bureau of Reclamation (USBR) in the second half of the 1990s and, since 2005, the United States Corps of Engineers (USACE) (USBR and USACE 2015) as well as the hydroelectric power regulator in that country (FERC) (FERC 2016).

On the other hand, in Spain, the Spanish National Committee on Large Dams (SPANCOLD 2012) has published a technical guide to support its implementation. There is also a wide implementation of risk analysis techniques for dam safety management in countries such as Canada, Australia or South Africa. These techniques have also been implemented in other countries by iPresas team such as Argentina, Albania, Colombia or India.

These practices and legislations worldwide recognize and explicitly call for carrying out risk analysis as a management tool in modern countries, so that risk management processes are reinforced from the improvement in the prediction of natural phenomena, through the proper operation and maintenance of infrastructures, to the need for good practices to minimize the impacts on citizens and the environment. In the context of dam safety, which is complex and interdisciplinary, risk analysis techniques emerged to perform a more comprehensive, transparent, and effective dam safety management.

In this sense, qualitative risk analysis and the identification of failure modes allow a comprehensive review of the dam, which goes beyond the traditional technical audit actions and allows completing these actions, including the participation of experts in the process, covering the different safety aspects (structural behavior, geotechnical aspects, hydraulic performance, etc.), from a collaborative point of view and a more detailed analysis of the safety conditions of the system.

A failure mode is defined as the particular sequence of events that can lead to an inadequate dam-reservoir system performance or a part of it. This series of events is associated with a specific loading scenario and has a logical sequence, which consists of an initial triggering event, a series of development or propagation events and culminates with dam failure or mission disruption, as shown in Figure 1.

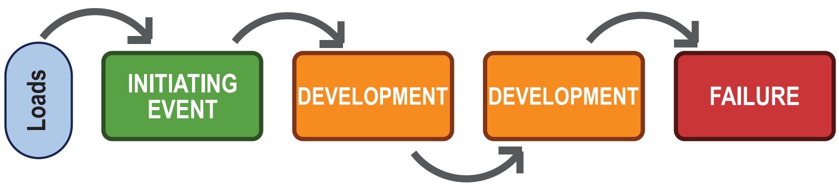

Figure 1 : Structure of a risk-informed dam safety program.

2. PROPOSED FAILURE MODE IDENTIFICATION PROCESS

The failure mode identification methodology to carry out this technical audit is summarized in Figure 2. This methodology is based on a participatory approach through joint working sessions, including international experts in different disciplines and people responsible for dam safety, as explained in (CWC 2019; iPresas 2014; SPANCOLD 2012).

Figure 2 : Steps for technical audit though failure mode identification (left) and pictures of failure mode identification sessions (right).

These steps are:

Step 1. Review of available information.

The review and analysis of the existing information is the first step of the qualitative analysis and should cover all the key aspects in terms of safety management, as shown in Figure 3.

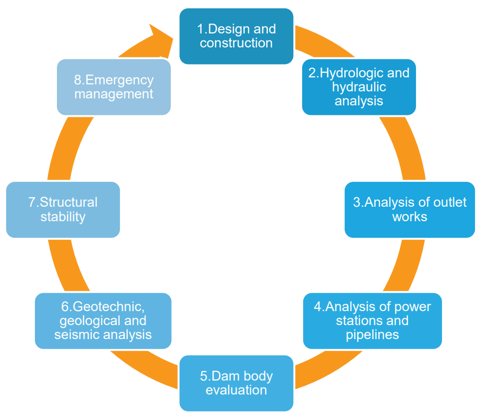

Figure 3 : Key issues to be discussed during information review.

The review process starts from the aspects related to the design and construction phases of the dam, to the evaluation of the hydrological and hydraulic capacity of the system, the performance and conditions of the outlet works and other components of the system.

Subsequently, the current situation of the dam body is evaluated, as well as geotechnical, geological and seismic aspects, to proceed with the analysis of the structural stability of the dam. Finally, the current emergency management system should be analyzed.

To carry out this review of information, all existing dam documentation is analyzed and summarized to be discussed in detail during the workshops for the identification of potential failure modes.

Step 2. Technical visit.

Conducting a technical visit to the dam allows gathering additional information, as well as verifying the information reviewed during the previous phase. The conclusions of the visit are of great value for the subsequent stages, aimed at discussing the current situation of the dam.

Step 3. Discussion on current dam situation.

The discussion about the current state of the system allows to evaluate different aspects and it is analyzed in which international safety standards in dam engineering are met, making a diagnosis for different aspects reviewed in previous stages. The results of this phase represent a starting point to discuss the current status of the dam. They constitute a summary of the opinion of the working group on the situation of the dam and allows to focus the identification of failure modes.

Step 4. Failure mode identification. Individual phase.

After the previous stages, a first individual phase for failure mode identification (FMI) is considered. Participants provide an individual proposal regarding failure modes that could potentially develop in the system with the support of FM handbooks which allow a complete review of all related aspects and factors that may contribute to potential failures.

The failure mode must be clearly and completely described, including all the events necessary for its development, so that it can be understood by people not involved in the identification process, as shown in the following example:

Example of internal erosion failure mode for an earth dam: "In normal operation scenario, there is a seepage network collected by the drain at dam toe with a sufficient hydraulic gradient to cause material migration, not avoided by the filter system. The phenomenon progresses, and then an erosion process starts towards the upstream area, causing wash-out of the finest material, and finally, there is either a material collapse of the dam body, which causes the failure due to loss of freeboard and dam overtopping, or, a failure due to instability of the dam from internal erosion".

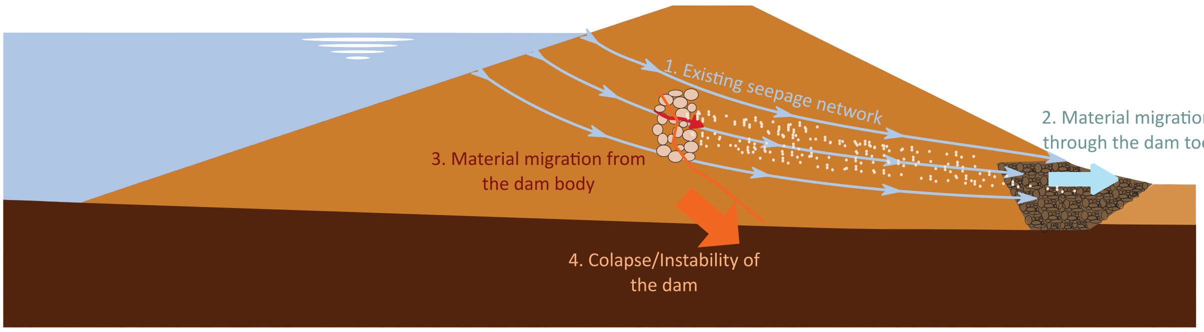

Figure 4 : Example of internal erosion failure mode.

Step 5. Failure mode identification. Group phase.

In this phase, the participants expose the failure modes identified to combine them and reach a consensus regarding the failure modes identified by the group. This sharing is coordinated by a facilitator in one or more working sessions, with enough time to analyze each of the possible failure modes in detail. The process of identifying failure modes also includes the identification and discussion of the existing factors that make the failure modes more or less probable, in order to later classify them.

Step 6. Failure mode classification.

The identified failure modes by the working group are classified into four categories, taking into account the possibility of occurrence and the potential consequences, based on the (FERC 2005) recommendations:

- *Level I* : Failure modes which are clearly considered to be feasible, with probability of occurrence and it cannot even be discarded that they are already under progress. In addition, they involve high potential consequences. Very short term risk reduction actions are recommended to avoid them.

- *Level II* : Failure modes that are considered also feasible, although with less occurrence probability and potential consequences. It is recommended to implement risk reduction actions in the medium term (months or years).
- *Level III* : Failure modes for which the available information is insufficient although they are considered feasible and with important potential consequences. Actions are recommended to reduce their uncertainty, such as new studies or new instrumentation measures.
- *Level IV* : Failure modes that are discarded as their occurrence is not considered feasible or present very low probability and/or consequences. In any case, documentation is recommended and should be considered during monitoring works, as well as in future FM identification updates.

This classification is the basis for the proposal of actions and research needs.

Step 7. Proposal for risk reduction measures, and improvement of surveillance and research.

The final stage of the qualitative analysis includes the proposal of measures to reduce risk associated with the identified failure modes, as well as the definition of actions to improve auscultation systems or new studies that reduce existing uncertainty and improve the knowledge of the system.

The risk reduction measures can be both structural (mainly referring to civil works), aimed at improving the response of the system, as well as non-structural.

Some measures include improving the condition of the dam body, modifying the capacity of outlet works, carrying out new studies, or improving operation and maintenance, among other actions.

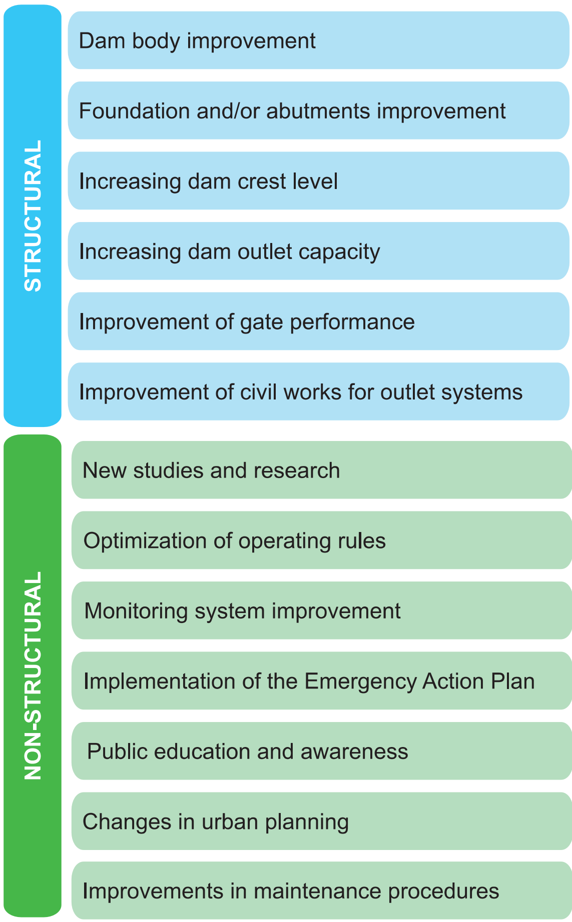

Figure 5 : List of potential options for risk reduction measures.

3. ADVANTAGES OF TECHNICAL AUDIT BASED ON FAILURE MODE IDENTIFICATION

Based on the experience of the iPresas team applying this methodology in more than 60 dams worldwide, the following benefits have been identified:

- Recommendations to improve dam safety defined in a joint approach with the participation of those responsible for dam operation, enhancing consensus on the recommendations made in contract with general technical audits.
- It is useful to propose improvements in the design phase, reinforcing the adopted solution, identifying future problems during the construction and operation phase.

- Participation of experts from different disciplines for a more comprehensive vision of safety, understanding the interrelations between the different involved aspects and providing space and time for discussion.
- Improvement of the knowledge of the physics of the system, helping to better understand the structural behavior and interactions with its components.
- Detection of research and study needs, identifying possible gaps in available information and in the auscultation system.
- Smarter inspection and monitoring of the system, helping to focus efforts with the identified failure modes and building capacity within the organizations.
- Proposal for maintenance improvements of civil and outlet works.

4. DEVELOPING A RISK-INFORMED DAM SAFETY PROGRAM

Figure 6 shows a conceptual framework of a dam safety program informed by risk analysis, which includes all the aspects involved in a modern vision for dam safety management, and which involves aspects that had already been considered for more than 40 years (summarized in three pillars: maintenance and operation, instrumentation, surveillance and inspections, and Emergency Action Plans) until the development and use of risk quantification models to support decision making in an adapted legislative and regulatory environment.

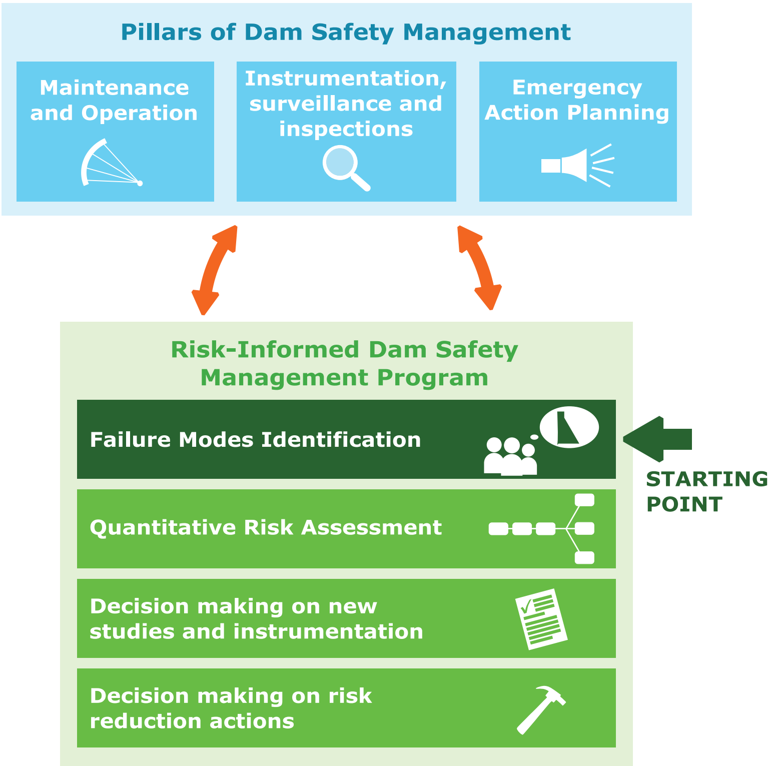

Figure 6 : Structure of a risk-informed dam safety program.

As can be observed in this figure, the identification of failure modes is an ignition point towards a modern and transparent dam safety program, since as detailed in the previous sections, it allows to reinforce and improve the periodic tasks of dam safety, including the documents and procedures in which safety is based, the evaluation of instrumentation needs and improvement of monitoring and, ultimately, of what they imply in terms of acceleration in learning curves of personnel involved, and of inspiration for the development of new processes and policies.

When the risk governance framework is applied to the operation and safety of dams and reservoirs, the main challenge is to align people, processes and policies to support decision making (Escuder-Bueno and Halpin 2016): develop policies, implement tools and train qualified personnel to achieve the necessary skills.

As described by ICOLD in its Bulletin 130 (ICOLD 2005), the path from the implementation of (traditional) systems of dam safety to its full incorporation into a (modern) risk management framework is a journey and requires a roadmap that is not independent of the starting situation or the context in which it is applied. Consequently, establishing a vision and a roadmap towards a smart governance in dam safety management is not and has not been an easy task for any country, public agency or private corporation, and requires the alignment of policies, tools (processes) and capacities, especially in terms of qualified personnel, to carry out a practical and successful implementation.

REFERENCES

CWC. 2019. "Guidelines for Assessing and Managing Risks Associated with Dams." Central Water Commission. Ministry of Water Resources India.

Escuder-Bueno, Ignacio, and Eric Halpin. 2016. "Overcoming Failure in Infrastructure Risk Governance Implementation: Large Dams Journey." Journal of Risk Research 9877 (August):1–18. https://doi.org/10.1080/13669877.2016.121535.

FERC. 2005. "Dam Safety Performance Monitoring Program." In Engineering Guidelines for the Evaluation of Hydropower Projects. Federal Energy Regulatory Commission.

FERC. 2016. "Risk Guidelines for Dam Safety - Interim Guide." Federal Energy Regulatory Commission.

ICOLD. 2005. Risk Assessment in Dam Safety Management. A Reconnaissance of Benefits, Methods and Current Applications. International Commission on Large Dams. Committee on Dam Safety. Bulletin 130. Paris: International Commission on Large Dams. Committee on dam safety. Bulletin 130.

iPresas. 2014. Procedure for the Identification and Analysis of Failure Modes in Dam-Reservoir Systems. iPresas Risk Analysis. Universitat Politècnica de València. http://ipresas.com/en/publicaciones.php.

SPANCOLD. 2012. Risk Analysis as Applied to Dam Safety. Technical Guide on Operation of Dams and Reservoirs. Vol. 1. Madrid: Professional Association of Civil Engineers. Spanish National Committee on Large Dams.

USBR, and USACE. 2015. "Best Practices in Dam And Levee Safety Risk Analysis. United States Bureau of Reclamation and United States Army Corps of Engineers." Denver: United States Bureau of Reclamation and United States Army Corps of Engineers.