DAM MONITORING AND SAFETY: THE IMPORTANCE OF INTEGRATED MONITORING

AUSCULTAÇÃO E SEGURANÇA DE BARRAGENS: A IMPORTÂNCIA DO MONITORAMENTO INTEGRADO

MONITOREO Y SEGURIDAD DE PRESAS: LA IMPORTANCIA DEL MONITOREO INTEGRADO

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Hosana Emilia Sarmento Costa Leite[1], Lícia Mouta da Costa[2], Leonardo José Nascimento Guimarães[3], Silvio Romero de Melo Ferreira[4], Olavo Francisco dos Santos Júnior[5]

ABSTRACT
Dam instrumentation and visual inspections are the main means of evaluating the operational and physical continuity of a dam and should be considered as mutually complementary. The objective of this article is to present the state of the art on aspects of this association, as well as on the dam monitoring plan, focusing on Brazilian legislation and technical literature. The main emphasis in terms of monitoring is dam safety, observing the plan in the various phases from planning, decharacterization and future uses, in order to maximize dam safety. It is also related to the relevance of failure mode studies to determine the best monitoring method to perform and risk analyses. Among the main considerations, it is observed that a good sounding of the dam enables preventive and corrective interventions, minimizing the risk of accidents, preserving the safety of the structure, the environment and third parties in its area of influence. It also allows the mitigation of project unknowns and uncertainties, resulting in progressive refinements and improvements in risk analysis techniques and future projects.

Keywords: Auscultation. Monitoring. Dams.

RESUMO
A instrumentação de barragens e as inspeções visuais são os principais meios para avaliar a continuidade operacional e física de uma barragem, devendo ser consideradas como mutuamente complementares. O objetivo deste artigo é apresentar o estado da arte sobre aspectos dessa associação, bem como, sobre o plano de monitoramento de barragens, com

[1] Professor Dr. Instituto Federal de Pernambuco (IFPE). Pernambuco, Brazil.
E-mail: hosanasarmento@recife.ifpe.edu.br Orcid: https://orcid.org/0009-0008-4127-2789
Lattes: http://lattes.cnpq.br/2576546532401998
[2] Professor Dr. Universidade Federal de Pernambuco (UFPE). Pernambuco, Brazil.
E-mail: licia.costa@ufpe.br Orcid: https://orcid.org/0000-0002-5432-8779
Lattes: http://lattes.cnpq.br/5361457935042088
[3] Professor Dr. Universidade Federal de Pernambuco (UFPE). Pernambuco, Brazil.
E-mail: leonardo.guimaraes@ufpe.br Orcid: https://orcid.org/0000-0001-6803-6024
Lattes: http://lattes.cnpq.br/3821425977868488
[4] Professor Dr. Universidade Federal de Pernambuco (UFPE). Pernambuco, Brazil.
E-mail: silvio.mferreira@ufpe.br Orcid: https://orcid.org/0000-0002-5760-1494
Lattes: http://lattes.cnpq.br/8035357058902261
[5] Professor Dr. Universidade Federal do Rio Grande do Norte (UFRN). Rio Grande do Norte, Brazil.
E-mail: olavo.santos@ufrn.br Orcid: https://orcid.org/0000-0001-7552-6646
Lattes: http://lattes.cnpq.br/1573496204231636

foco na legislação brasileira e literatura técnica. A ênfase principal quanto ao monitoramento aborda a segurança de barragens, observando o plano nas diversas fases desde o projeto, a descaracterização e usos futuros, de forma a maximizar a segurança de barramentos. Relaciona-se também a pertinência de estudos de modos de falhas para determinar o melhor método de monitoramento a se executar e as análises de risco. Entre as principais considerações, observa-se que uma boa auscultação do barramento possibilita intervenções preventivas e corretivas, minimizando o risco de acidentes, preservando a segurança da estrutura, do meio ambiente e de terceiros em sua área de influência. Permite, também, mitigar incógnitas e incertezas de projeto, tendo por consequência refinamentos progressivos e melhorias nas técnicas de análise de risco e projetos futuros.

Palavras-chave: Auscultação. Monitoramento. Barragens.

RESUMEN

La instrumentación y las inspecciones visuales de presas son los principales medios para evaluar la continuidad operativa y física de una presa y deben considerarse mutuamente complementarias. El objetivo de este artículo es presentar el estado del arte en aspectos de esta relación, así como en los planes de monitoreo de presas, centrándose en la legislación brasileña y la literatura técnica. El énfasis principal del monitoreo está en la seguridad de la presa, examinando el plan en varias etapas, desde el diseño hasta el desmantelamiento y el uso futuro, para maximizar la seguridad de la presa. También se discute la relevancia de los estudios de modos de falla para determinar el mejor método de monitoreo y análisis de riesgos. Entre las principales consideraciones, un buen monitoreo de presas permite intervenciones preventivas y correctivas, minimizando el riesgo de accidentes y preservando la seguridad de la estructura, el medio ambiente y terceros dentro de su área de influencia. También permite mitigar las incógnitas e incertidumbres del diseño, lo que resulta en mejoras progresivas en las técnicas de análisis de riesgos y proyectos futuros.

Palabras clave: Escuchando. Monitoreando. Represas.

1 INTRODUCTION

The construction of a dam requires a laborious construction process and multidisciplinary engineering, and is often subject to large loads and special foundation conditions. Added to the fact that during their useful life dams deteriorate and their reliability indicators change. In addition, no structure is immune to the risk of failure. "Risk of failure" is related to some anomalous behavior, "inadmissible movements" that can cause accidents (Silva *et al*., 2015 *apud* Guimarães Filho, 2021).

Dam Instrumentation and Visual Inspections are the main means available to assess the operational and physical continuity of a dam, and should always be seen as mutually complementary. Zuculin (2020) states that Dam Safety is the area of engineering that takes care of the "health" of the dam. In this sense, the risk of accidents is minimized through monitoring in the quality of diagnosis of the dam's health, as it enables preventive and corrective interventions, resulting in a reduction in the risk of accidents and, consequently, preserving the safety of the structure and area of influence. The monitoring stage is also known as predictive maintenance, in which possible problems with the structure are "predicted" (Piasentin, 2020).

In this context, inspections associated with a careful analysis of the data provided by the dam's auscultation instrumentation, when properly designed, correctly installed and systematically interpreted, form the most important and efficient tool in the evaluation of the behavior of these structures, in the same way that potential risks have a greater possibility of being detected, based on this association (Oliveira, 2008). It also allows for the mitigation of project unknowns and uncertainties, resulting in progressive refinements and improvements in risk analysis techniques and future projects (Andrade, 2021).

The article aims to discuss aspects of this association, such as the dam monitoring plan with a focus on the Brazilian legislation on dam safety and technical literature, in the phases of planning, design, construction, first filling and first pouring, operation, deactivation, decharacterization and future uses, in order to maximize dam safety. In short, it is a literature review on the subject.

The study also related the relevance of studies of failure modes to determine the best monitoring method to be performed, and complementing the theme, a concept that has been considered as the most complete for the control of these structures is committed to the Integrated Safety System.

2 AUSCULTATION INSTRUMENTATION DESIGN

According to Law No. 14,066 of 2020, Article 4, item I, the foundations of the National Dam Safety Policy (PNSB) "the safety of the dam, considering the phases of planning, design, construction, first filling and first pouring, operation, deactivation, decharacterization and future uses" (Brasil, 2020). Thus, the Monitoring and Instrumentation Plan must be prepared in the planning and design phase, being detailed and complemented, as new information about the work and its behavior is obtained.

In the planning and design phase, according to Zuculin (2020), the type and arrangement of the dam is defined and, based on these, the main quantities that should be monitored by the instrumentation are established. This plan is implemented in the construction phase, so as to be able to effectively control the behavior during the first filling of the reservoir and throughout the life of the dam, until its deactivation, decharacterization and future uses. In addition, dam instrumentation takes on different characteristics and purposes depending on the stage of the work.

The type of instrument is chosen according to the quantity to be measured, taking into account the scale, from the first measurement to the end of the structure's useful life. The compatibility between the magnitude of the measured parameter and the accuracy of the instrument is a fundamental aspect, as well as its reading field. Failure to do so may damage the device. In this phase, the decision on the automation of the instrumentation is also considered. The quantities to be monitored in embankment and concrete dams, along with the most common instruments for their measurement, can be found in the ANA's Entrepreneur's Manual on Dam Safety (National Water and Basic Sanitation Agency), *Volume V - Guidelines for the Preparation of Dam Projects* (ANA, 2016a, p. 144-145).

Throughout the construction It's time to verify that the design hypotheses are evolving positively, that the relationship between the loads and the stresses generated is as specified, that the deformations are within the expected limits, in the massifs, foundation and attached structures, etc. (Zuculin, 2020).

The first filling of the reservoir, the stage where the dam enters full load for the first time, is one of the most relevant stages from the point of view of safety, it also reflects the initial test of the performance of the dam and its foundations, and therefore safety control should deserve special care in this phase (ANA, 2016a). At this stage, the readings of the instruments can not only report the occurrence of anomalies that may threaten the safety of the bus structure, but also serve as parameters of retroanalysis in mathematical models, providing efficiency and simplifications for new projects (Smiderle, 2014).

"The operation phase encompasses the entire useful life of the dam. At this stage, the dam will "work", that is, deform, repress, displace, heat, cool. It will go through floods and droughts and, some even, earthquakes." (Zuculin, 2020, p. 18). The instrumentation in this phase aims to provide data for continuous verification of the design hypotheses, in general, to monitor the performance of the dam and associated structures, in addition to the foundation and critical areas, to indicate if the structure is working as planned, to alert to any events that may cause risks to its safety (possible risk zones), and to obtain information for the improvement of future dam projects (Oliveira, 2008).

In addition to the instrumentation of the dam structures, it may be relevant to monitor the reservoir area, as well as the meteorological, hydrological, and limnological conditions that may influence the performance of some instruments (Zuculin, 2020).

In short, the Monitoring Manual can be considered the main link between the design, construction, and operation phases of a dam. In the complete instrumentation auscultation plan, all the aforementioned steps must be foreseen, including those set out below (ANA, 2016a and 2016b; Piasentin, 2020). The structuring of these steps is fundamental for the success of the process.

- Design of the instrumentation to be installed: arrangement, details, material specifications, installation and assembly. After installation, it is essential that the dam has the technical documentation of the project, instrumentation and drawings as built. When choosing the type of instrument, attention should be paid to the following precautions: simplicity of operation and installation; reliability; sensitivity, measuring range; durability; resistance; stability; costs, operation and maintenance; previous experience with its use; manufacturer's technical assistance; automation of data collection, among others (Fonseca, 2003; ANA, 2016a).
- Definition of the predicted values and acceptable behavior limits for all instruments (in all phases), established in the project and based on the expected behavior of the structure in relation to the parameter read by the instrument. This definition is important to translate the designer's expectations in comparison to a certain parameter to be monitored and to allow the collected readings to gain meaning and usefulness in the safety assessment, namely in the filling and start-up phases, when the monitoring teams are not yet fully familiar with the work (Fusaro *et al.*, 2017).

- Instrumentation operation plan: a reading methodology, responsibilities, applicable procedures, reading frequencies throughout the useful life of the work and during possible exceptional cases must be established. It is also recommended that readings should be scheduled with a fixed sequence and itinerary; that the readers are the same, and also act as visual inspectors, at least once a week, especially during the operational period, covering the various stretches and galleries of the dam. Minimum frequencies recommended for reading auscultation instruments in embankment and concrete dams for the different stages of the dam's life can be found in the ANA Manual (2016b).
- Plan of visual observations and on-site inspections with their frequencies. Observations analogous to the instrumentation operation plan.
- Plan for analysis and interpretation of the dam's behavior based on the results of instrumentation and visual inspections. The analysis of this information must be done by a qualified professional (geologist and/or geotechnical engineer), so that any anomalous situations indicative of the need for corrective interventions or more detailed investigations, such as slope stability analysis, can be identified.
- Plan for storing historical information, such as reports and the instrumentation database. It refers to the processing of data and records to be adopted. Taking into account that over time, these documents will form a data history, which is essential to clarify any unexpected behaviors and assist in the interpretation of the results obtained.
- Maintenance procedures: These are the maintenance rules, procedures, records, and responsibilities that must be developed and implemented to ensure that instruments are kept in fully operational and safe condition.

Fusaro *et al.* (2017) present suggestions for structuring a Monitoring Manual as a tool for dam safety. The article divides the monitoring activities into three elements: visual inspection, instrumentation and tests on electromechanical equipment and comments on each of these items, in the case of instrumentation it is discussed from the general description of the instrumentation and objectives, description of the instrumentation by section, program for collecting the instrumentation readings, procedures for calibration and maintenance of the instruments to data analysis procedures.

In this way, with an efficient monitoring plan, it becomes possible to anticipate all the necessary action scenarios to minimize the damage resulting from a possible rupture. However, when the stages of predictive (monitoring) and preventive (repair works) maintenance are not enough to avoid an accident, it is necessary to have defined rules to be adopted, and in this case, the Emergency Action Plan (PAE) is inserted, whose main objective is to minimize the damage and fatalities of catastrophic events (Piasentin, 2020).

It is important to consider that the interpretation of the data provided by the instrumentation is as relevant as the existence of the instrumentation itself and the best instrument is not a guarantee of safety if the data obtained are not analyzed correctly, in addition, the geotechnical instruments alone do not guarantee structural safety, as these are only components for observing the behavior of the dam (Silveira, 2006). Smiderle (2014, p. 29) mentions that "the installation of instrumentation without adequate analysis and interpretation is the same as having no instrumentation at all".

A good field instrumentation system must be able to examine the design hypotheses, the adequacy of construction methods and the safety conditions in the various phases of the work (Danese, 1998).

3 INTEGRATED SECURITY SYSTEM (SIS)

A concept that has been considered the most complete for the control of these structures is the so-called Integrated Security System (SIS), which discerns the issue on three pillars: Technical-Operational (T-O); Monitoring-Surveillance (M-V); and Risk/Emergency Management (G-E). Where each pillar must be analyzed as a necessary condition and complement the others, which in sum, keeps the dam safe in all its phases of life (Perini, 2009; Leite 2019).

Dam safety has been controlled by a traditional engineering approach based on current technical criteria and standards. In the SIS, this approach refers to the first two components mentioned above, with the T-O being responsible for the control of structural, hydraulic and operational safety, applied in the design, construction, operation and decommissioning phases, and the M-V for monitoring, inspection, auscultation of the dam, detection and analysis of the work (ICOLD, 2005; Melo, 2014; Leite 2019).

Authors such as Pimenta (2009) emphasize the need for the traditional perspective to evolve towards risk-oriented approaches, dealing with performance actions and consequences in an integrated way. Menescal (2004) also reports the importance of recognizing threats to enterprises through the risk analysis methodology.

It is in this context that the third pillar of support for the safety of a dam is inserted: Risk / Emergency Management. comprising "the implementation and preparation of all the measures and procedures necessary to control risks and to respond to any accidents that may occur in a dam", with the objective of anticipating the detection of crises and failures (Perini, 2009, p. 6). This insertion should be seen as a complement to traditional practice, and not as a sense of substitution.

Conceptually, dam safety risk management corresponds to a series of integrated activities, such as risk assessment (identification, analysis and assessment of risks) and risk control (mitigation, prevention, detection, emergency planning, review and communication). Once the context in which the controls and reference standards are framed has been defined, the next step is the risk assessment, which should: integrate the risk analysis and assessment process and also provide recommendations on the need to reduce these risks (ICOLD, 2005; Melo, 2014; Perini, 2009).

It is possible to carry out a risk assessment qualitatively, quantitatively or with variations of these approaches. The qualitative methods are based on descriptive forms of probabilities and consequences, in the semi-quantitative method, numerical values are associated with these descriptions, while the quantitative methods explain the uncertainties, thus based on numerical values of probability and consequence. The decision on which approach to adopt depends on the desired level of detail, the types of risks analyzed, the objective of the analysis and, above all, the information, data and resources available (Perini, 2009).

There are several methods proposed in the literature: Failure Risk, Cause and Indicator Indices (LCI), Failure Modes and Effects Analysis (FMEA) which are considered essentially qualitative, and Failure Tree Analysis (FTA) and Event Tree Analysis (ETA) which can be used both qualitatively and quantitatively (Melo, 2014).

Quantitative methods should not be considered more precise or adequate. Qualitative analysis is sufficient, and often the only possibility, for certain types of decisions, either due to lack of numerical information on specific failure modes or due to insufficient resources and time. On the other hand, the quality of quantitative analysis depends on the precision and quality of the numerical values and the analytical model chosen (Fusaro, 2011).

According to Yokozawa (2019) it is possible to accurately analyze the risk of dams, but this analysis requires the calculation of the probability of failure, which is the result of a probabilistic approach. The authors say that this type of analysis has been criticized because the evaluation method is considered subjective, which makes it difficult to establish criteria for the elaboration of a project, ending up making the deterministic analysis more accurate and safer. However, this second category of analysis does not take into account uncertainties, which makes the assessment less reliable.

Rebêlo (2021) states that probabilistic methods can be interpreted as complementary deterministic analyses. From them, knowing the probability distribution of the independent variables (such as the parameters of the material), it is possible to evaluate the probabilistic distribution of the dependent variables (such as the safety factor). The author points out that international bodies and standards, such as ISO (*International Organization for Standardization*) already adopt the theory of reliability. However, the current criteria for analyzing Brazil's stability are restricted to the development of projects with an inherently deterministic philosophy. And even recognizing the existence of geotechnical uncertainties, the concepts of reliability for project development work in a very limited way.

In the case of dams, in view of the need to classify and quantify risks, CNRH Resolution No. 143 of 2012 (Brasil, 2012) presents qualitative criteria for the classification of dams by risk category, associated potential damage and reservoir volume, in compliance with article 7 of Law No. 12,334 of 2010 (Brazil, 2010). The aforementioned Resolution considers risk as the possibility of an accident occurring. Its formulation, however, diverges from what is formally defined and found in the literature, being restricted to the technical and conservation characteristics of the dam and its associated structures (Leite, 2019).

Melo (2014) points out, however, that although it fails in terms of the technical nomenclature of risk, the methodology of Law No. 14,066, of 2020 (updated Law No. 12,334 of 2010), fits into one of the "good practices" of dam safety management adopted internationally. The cited author adds that, in addition to the rapid classification of dams, this method allows a primary consideration of possible dam failure modes, and can establish monitoring values. The Law also contemplates construction methods, age of the project, and precedents for regulators to establish standards according to their needs (Brasil, 2020).

Another change, in the scope of risk management, is the first objective of Law No. 12,334, of 2010, in Article 3, Item I, previously written as: "to ensure compliance with dam safety standards in order to reduce the possibility of accidents and their consequences;" (Brasil, 2010), being modified by Law No. 14,066, of 2020, where the concept of "prevention" regarding the possibility of accidents or disasters is inserted in the wording of the text. The last objective (Item 8) also included the need to define emergency procedures in the event of an incident, accident, or disaster (Brasil, 2020; Pereira, 2021).

In the Brazilian PNSB, the document that consolidates the procedures for risk management and responses to emergency situations is the Emergency Action Plan (PAE), serving as a supplementary tool to support decision-making for each alert level established. This document is now mandatory for all dams intended for the accumulation or disposal of mining tailings regardless of their classification in terms of associated potential damage and risk (Brasil, 2020).

Ladeira (2007) points out that qualitative probability analysis for risk assessment applied to dam safety management is developing rapidly, particularly in the United States, Australia, Canada, Norway and the United Kingdom. The author used in his dissertation the ETA safety analysis method with a probabilistic focus in order to evaluate the possibility of dam rupture by piping and the method called UNSW (*University of New South Wales*), which was developed at the aforementioned University, in Sydney, Australia.

The dam of the HPP – São Simão was used by the aforementioned author as a case study and the database in the quantification of ruptures and historical accidents contained 1,462 dams (approximately 13% of the world population of dams existing until 1982). The result was an estimated annual failure probability per piping in large dams of 4.5×10^{-4} per dam, which proved to be consistent with the historical data collected in the study. The results also identified key points that require attention and preventive actions to avoid environmental impacts resulting from dam failures (Ladeira, 2007).

Other works that deserve to be highlighted in Risk Management with a focus on risk assessment and its application in dam engineering through case studies are: Perini (2009), Melo (2014), Vianna (2015), Yokozawa (2019) and Leite (2019). In general, studies assess the impasses in the application of the risk-based approach and the advantages arising from its results.

Yokozawa (2019) in his dissertation applied the probabilistic methods FOSM (*First Order Second Moment*), EMP (*Point Estimated Method*), HPEM (*Hibrid Point Estimated Method*) and Monte Carlo, based on statistical data of the input parameters, ascertaining the main differences between them, as well as their limitations and advantages. The case study was the object of two hypothetical types of dams, one of the mixed type (rockfill with clay core) for hydroelectric use, and one of tailings, with three elevations. Among the methods analyzed, the author cited Monte Carlo as the most reliable and accurate, despite some limitations.

Another recent work, which has a good literature review on the subject, is the work of Leite (2019). His research is characterized as an exploratory case study, seeking to improve and increase the experience around risk analysis within the theme of dam safety, the author proposed to develop a structured model to support the Process of Monitoring and Risk Assessment in Dam Safety of the National Electric Energy Agency – ANEEL. A major difficulty in carrying out the survey by Leite (2019) was the lack of official statistics on accidents in Brazilian dams. The lack of a historical database with information on the nature of the possible rupture, its probable causes and consequences prevents the creation of credible scenarios capable of understanding the realities of national engineering.

It should always be considered that risk analysis is only one step in a management process that does not end in itself. Further development of research based on this analysis would be meaningless without a focus on maintaining safety (Fusaro, 2011).

4 FINAL CONSIDERATIONS

The essentiality of dams for the functioning and development of society is unquestionable, since they guarantee the supply of water, generation of electricity and the accumulation of tailings from mining and industrial production, among other functionalities. However, in addition to their attributes, there is the potential risk of these works. The structural safety of these works ranges from the conception of the dam (design), construction quality, proper maintenance and monitoring, efficient emergency management of its useful life, etc.

To contribute to the reduction of dam risk, many aspects are included. With the research, it is observed that a good auscultation of the bus enables preventive and corrective interventions, minimizing the risk of accidents, preserving the safety of the structure, the environment and third parties in its area of influence. It also allows to mitigate project unknowns and uncertainties, resulting in progressive refinements and improvements in risk analysis techniques and future projects. It is important to consider that the interpretation of the data provided by the instrumentation is as important as the existence of the instrumentation itself and the best instrument is not a guarantee of safety if the data obtained are not analyzed correctly, moreover, the geotechnical instruments alone do not guarantee structural safety, as these are only components for observing the behavior of the dam.

Regarding failure modes, it is observed that designing with a focus on specific failure modes of a structure allows monitoring activities to be directed to the most critical sensitive points, thus contributing to a more accurate diagnosis of behavior. In this aspect, it is concluded that the Monitoring and Instrumentation Plan should be prepared in the planning and design phase, being detailed and complemented, as new information is obtained about the work and its behavior in its other phases, thus enhancing the safety of the dam.

It should be noted that it is not possible to establish a rule to define the number of instruments. The determination is based on an evaluation by the designer. Two dams of the same size, for example, can have different amounts of instruments, depending on their type of foundation. However, it is recommended, in defining the number of instruments, to provide some reserve instruments.

As for the SIS, it is believed that the combination of deterministic and probabilistic analyses allows an optimization in the analyses, representing a significant advance in the evaluation of dam safety, especially taking into account the variability of material properties and providing results related to reliability levels.

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