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Technical and scientific aspects of dams in Brazil: a theoretical approach

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ABSTRACT

The safety of a dam is the result of a series of factors, including structural, geotechnical, hydraulic, operational and environmental aspects. In Brazil, Law No. 12.334 of September 2010 establishes the National Dam Safety Policy, which requires safety reports and monitoring inspections for existing dams. The inspection comprises a set of devices installed on the dam, which are used to assess the structural behavior based on performance parameters of the structure, such as displacements, flows, stresses, slopes and others. Dam auscultation procedures, historically, have been performed since the 1950s. Since then, there have been significant advances in instrumentation and dam auscultation methods. This work presents a theoretical approach on technical and scientific aspects of dams in Brazil, based on a state-of-the-art literature review, involving auscultation of dams in the context of design codes, concepts, instrumentation, safety, procedures and monitoring methods.

Keywords: Auscultation, dams, instrumentation, safety.

Aspectos técnico-científicos de barragens no Brasil: uma abordagem teórica

RESUMO

A segurança de uma barragem é resultante de uma série de fatores, dentre os quais podem ser citados aspectos estruturais, geotécnicos, hidráulicos, operacionais e ambientais. No Brasil, a Lei nº 12.334 de setembro de 2010 estabelece a Política Nacional de Segurança de Barragens. A instrumentação compõe um conjunto de dispositivos instalados nas barragens, que são utilizados para avaliar o seu comportamento estrutural a partir de parâmetros de desempenho da estrutura, tais como deslocamentos, vazões, tensões, inclinações e outros. Procedimentos de auscultação de barragens, historicamente, tem sido realizado desde a década de 50, conforme a literatura. Desde então, houve avanços significativos na instrumentação e nos métodos de auscultação de barragens. Este trabalho tem como objetivo apresentar uma abordagem teórica sobre aspectos técnico-científicos de barragens no Brasil, fundamentada numa revisão de literatura no estado da arte, envolvendo auscultação de barragens no contexto de normas, conceitos, instrumentação, segurança, procedimentos e métodos de monitoramento.

Palavras-chave: auscultação, barragens, instrumentação, segurança.

1. INTRODUCTION

According to MSIB (Brasil, 2002), dams are built to raise the water level, holding back water and forming an upstream reservoir. These structures are built with earth, rock, concrete, or mixed structures, that aim to contain and control water flow to meet the diverse uses of humankind, such as irrigation, human consumption, electricity generation, among others.

Dam instrumentation is based on a set of devices installed on the monolith and adjacent structures, which are used to assess its behavior based on performance parameters, such as displacements, flows, stresses, inclinations and others.

MSIB (Brasil, 2002) comments that dams are undertakings with a high potential for risk and have significant consequences for the environment and that auscultation procedures are mandatory and essential to the dam, as they aim to correct and / or adapt processes involved in the construction, operation or maintenance of the dam. FERC (US, 2003) emphasizes that the auscultation processes of a dam are based on the observation, detection and characterization of eventual deteriorations that constitute a potential risk to the conditions of its global security.

Dam auscultation procedures, historically, have been performed since the 1950s. Since then, there have been significant advances in instrumentation and in dam auscultation methods. The literature presents important descriptions of several dam breaks in the world. These are accidents of different levels of severity, which were important to promote the scientific and technological development of current dam monitoring methods.

In Brazil, it is important to highlight Law No. 12.334 of September 2010, which establishes the National Dam Safety Policy (PNSB) for the accumulation of water for any use, in addition to creating the National Dam Safety Information System (Brasil, 2010).

The scientific community has carried out several studies and research in recent years in general, with the aim of improving the capacity and quality of dam monitoring. This is due to the availability of new technologies capable of integrating with traditional methods applied in monitoring, which involve different processes based on measurements obtained by geotechnical and geodetic sensors.

The technological advancement of sensor systems and the availability of online communication systems has currently allowed the generation of scientific research to improve the monitoring of dams, in real time, whether from the automation of geotechnical instrumentation supported by new sensors, or modern geodesic and geophysical monitoring systems.

In these circumstances, this work presents a theoretical approach on technical-scientific aspects of dam monitoring and safety in Brazil. The paper is based on a state-of-the-art literature review, involving auscultation of dams in the context of design codes, concepts, devices, security, monitoring procedures and methods.

2. DAMS

2.1. General Aspects

Article 2, Paragraph I of Brasilian Federal Law 12334/10 defines a dam as being "any structure in a permanent or temporary course of water for the purpose of containing or accumulating liquid substances or mixtures of liquids and solids, comprising the dam and associated structures" (Brasil, 2010).

The main types of dams are those built with concrete, called gravity dams, in arc or buttresses and embankment dams that are built from earth or a combination of earth and rocks (rockfill) (ICOLD; CIGB, 2007)

Dams, since the beginning of human evolution, have been fundamental to the development of humanity. According to CBDB (2011), dams were built using experimental procedures aimed at storing water.

According to Kutzner (1997), the oldest dams were built since the third millennium (BC) from soils and rocks, and were subsequently called "earth and rockfill dams". As Fahlbusch (2009) points out, the oldest known dams of humanity are those of Jawa (Jordan) and Sadd el Kafara, (Egypt), approximately 3000 BC and 2650 BC, respectively.

The book, "The History of Dams in Brazil - XIX, XX and XXI Centuries" (CBDB, 2011), discusses the history of the implementation of dams in Brazil and the International Commission for Large Dams (CIGB), which has been operating since the 1920s and its representation in Brazil. The emergence of the Brazilian Committee on Dams, founded in 1961, is highlighted. The book describes the history of the main electric energy concessionaires from the end of the 19th century to the present day, the evolution of environmental and dam safety legislation beyond progress in implementing dams to contain mining waste (CBDB, 2011).

For Costa (2012), conventional dams are classified into: Earth Dams (homogeneous and zoned); Rockfill Dams (with impermeable core and with impermeable face); Concrete Dams (gravity, relieved gravity, buttress; rolled or compacted concrete and arc) and Mixed Dams (concrete and earth).

According to the Bureau of Reclamation (US, 1987), earth dams tend to remain the most prevalent type. The number of favorable locations for concrete structures is gradually decreasing. This is the result of the great development of water storage facilities.

2.2. Dam Instrumentation and Safety

According to Law 12.334, Article 4, Item I: "The Safety of a Dam" must be considered in its planning, design, construction, first filling, first pouring, operation, deactivation and future-use phases" (Brasil, 2010). Law No. 12,334, in Art. 7, classifies dams by risk category, related damage and by their reservoir volume.

The safety of a dam is related to the event of a rupture, which can be caused by joint or separate events such as earthquakes, overtopping and internal erosion (piping).

USACE (1995) reports that inspections are mandatory operations on dams and should be carried out based on a preliminary analysis of the instrumentation conditions and the verification of local problems in the monitored area. Instrumentation can achieve these objectives by providing quantitative data to access useful information such as piezometric pressure, strain, total stress and water levels (USACE, 1995).

MISB (Brasil, 2002) comments on the need for preventive and corrective maintenance, directly associating them with structural safety, links predictive maintenance to monitoring and emphasizes emergency plans in order to reduce the remaining risks. Thus, it is essential to check the auscultation instrumentation based on visual and periodic inspections, combined with more detailed data analysis. These inspections must check piezometers, flow recorders, accelerometers, seismometers, joint gauges and pressure gauge points, strain gauges, clinometers, plumb lines, topographic landmarks, and level recorders (Brasil, 2002).

Risk is directly associated with danger and vulnerability. According to Metzger *et al.* (2006), the vulnerability can be considered as a response to risk.

MSIB (Brasil, 2002) presents a methodology based on mathematical and statistical models for the assessment of risk potential. In this study, dams are classified according to the safety aspects of their structures and risks to the downstream community. According to MSIB (Brasil, 2002), the most accepted classification is based on the potential for loss of life and the damage (economic, social and environmental) associated with the rupture of the dam. As a result of rupture (very high, high and low), loss of life (significant, to some extent, and none) and economic, social and environmental damage (excessive, substantial, moderate or minimal) (Brasil, 2002).

Several accidents related to dam ruptures in the world have been documented by Brown *et al.* (2012), involving past situations, such as the dams of St. Francis and Teton, and current ones such as British dams, European tailings dams, Chinese dams and American dams (Rico *et al.*, 2008).

Alves (2015) presents an important report of important dam accidents in the world and in Brazil, presenting damages and primary causes. Mariana in 2015, and Brumadinho in 2019, are examples of major recent dam accidents in Brazil, both in the state of Minas Gerais.

In Brazil, the number of dam ruptures is considerable, mainly in the State of Minas Gerais, where 7 mineral tailings dams have broken in the last 18 years: Information from Alves (2015) is give in Table 1.

Table 1. Recent dam ruptures in the state of Minas Gerais, Brazil.

Year	Dam	Location	Details
2001	Macacos	Nova Lima	5 deaths
2003	Cataguases	Cataguases	Contamination of the Paraíba do Sul River, death of animals and fish and interruption of water supply to 600,000 people
2007	Rio Pomba	Miraí	More than 4000 homeless or displaced people
2014	Herculano	Itabirito	3 deaths
2015	Fundão, Santarém	Mariana	19 deaths, 8 missing 600 homeless or displaced, interruption of water supply to thousands of people and pollution of the São Francisco River and the sea in Espírito Santo
2019	Brumadinho	Brumadinho	300 victims (identified and missing), immeasurable impacts on historical and cultural heritage, the environment and the local economy

Source: based on data from Alves (2015) and Almeida *et al.* (2019).

3. AUSCULTATION OF DAMS

The auscultation of a dam involves a set of monitoring procedures based on geotechnical, geodetic methods and instrumentation, aiming at the inspection, monitoring and verification of corrective measures of its safety conditions.

The dam literature presents the state of the art of dam auscultation, from the 1950's until the 21st century, characterizing the technological evolution of instrumentation and monitoring procedures (USACE, 1995; 2004). It is important to highlight the modernization of instrumentation and auscultation methods, together with computing and automation of data acquisition, transmission, processing and analysis systems.

According to the Department of the Army (USACE, 1994), measurement and instrumentation techniques for the geometric monitoring of structural deformations are classified into two groups, described in Table 2.

Table 2. Measure and instrumentation techniques.

Measure and instrumentation techniques	Description of equipment and sensors
Geotechnical and structural measures of local deformations and displacements	Pendulums, elongameter bases, triortogonal gauges, extensometers, inclinometers and other complementary instruments.
Geodetic surveys	Land surveys, satellite positioning, photogrammetric and some special techniques (interferometry, hydrostatic leveling and others).

Source: Department of the Army (USACE, 1994).

3.1. Geotechnical Measurements

Dunnicliff (1988) reports several aspects related to geotechnical auscultation, involving guidelines related to the safety of dams in the construction and operation phases, in order to provide alternatives aimed at improving the costs and effectiveness of geotechnical instrumentation programs. The use of instrumentation involves not just the selection of instruments, but a comprehensive engineering process that begins with the definition of the objective and ends with the implementation of the data (Dunnicliff, 1988).

Srivastava (2011) presents a general discussion of methods of geotechnical instrumentation for earth dams according to the USACE guidelines. Fell *et al.* (2014), in an important book for the area of dams, comprehensively addresses different categories of dams involving aspects of instrumentation and methods of Geotechnical Engineering for Dams.

Cruz (1996) describes general and specific aspects related to geotechnical instrumentation from the 1950s to the 1990s, where visual inspections predominated. More recent studies show the trend of automation of visual inspection in dams. Valença and Júlio (2018), for example, presented the MCrack-Dam method, which is based on image processing and is designed to automatically monitor cracks in dams. The method was tested under controlled laboratory conditions, later validated on site and applied in a pilot area of the Itaipu / Brazil dam. The results show the ability of the MCrack-Dam method to perform a comprehensive crack characterization in dams, not comparable to the traditional methods currently used (Valença and Júlio, 2017).

According to Nadia and Bouchrit (2017), many difficulties are registered to estimate the deformation modulus of landfills necessary for modeling. In this work, the authors carried out a parameterized analysis to estimate the settlement of an earth dam. This study led to the verification of the compatibility, for different values of deformation modulus, between the settlement of the dam by modelling and by monitoring in order to validate the mechanical behavior of the dam. Jia and Chi (2015) is another important reference in this theme.

Pires *et al.* (2019) carried out a study of structural reliability analysis in a concrete gravity dam. The work showed the importance of quantifying uncertainty, both in the design phase and in the constructed dam. The authors observed that structural reliability provides an objective assessment of the safety of the structure or its reliability, in addition to the probability of failure. The study corroborated previous results, illustrating the lack of proportionality between the safety factors, generally adopted in the project, and the assessed probabilities of failure (Pires *et al.*, 2019). Hu and Ma (2018) is another important reference in this theme.

In recent years, several researchers have focused attention on the development of statistical models applied to dam monitoring (Li *et al.*, 2013; Cheng and Zheng, 2013; Li *et al.*, 2013; Stojanovic *et al.*, 2016).

According to USACE (2004), automated data acquisition systems (ADAS - Automated Data Acquisition System) started at the end of the 20th century, providing the modernization of data transmission and processing. At the beginning of the 21st century, the technological evolution of the geotechnical auscultation process was focused on the development of fiber optic instrumentation. Fiber-based technology has been used since the 1970s in several areas of data transmission. In the auscultation of dams, they began to be used in the monitoring of structures as an alternative to replace the traditional electronic sensors, helping to monitor parameters such as displacements, strains, temperatures, pressures, among others.

In the 1980s, a fully distributed detection technology called Brillouin Optical Time Domain Analysis (BOTDA) was proposed and developed to measure voltage and temperature (Pei *et al.*, 2014). Pei *et al.* (2014) carried out an important review on the development and application of fiber optic sensors in geotechnical structures. Zeni *et al.* (2015) presented some experimental results of the BOTDA technology applied in geotechnical monitoring. The authors highlight the potential of these sensors applied in detecting early movements of soil slopes.

Distributed optical fiber (DOFS) sensors are important in structural and geotechnical engineering. Cheng-Yu *et al.* (2017) presented a comprehensive review of DOFS to monitor the performance of various geotechnical structures, including retaining walls, tunnels and landslides. The authors presented a comparative analysis of the typical advantages and limitations of different technologies for geotechnical monitoring.

Rittgers *et al.* (2014) presented the applicability of active and passive geophysical methods in order to monitor dams (Ijkdijk Experiment - Netherlands). The authors found that the integration of the spontaneous potential method with that of passive seismic enables identification and monitoring of hydromechanical disturbances in a dam. Planès *et al.* (2014), used passive seismic interferometry in the same dam, to detect temporal changes in the speed of seismic waves caused by internal erosion processes. Olivier *et al.* (2017), using similar seismic interferometry procedures, performed an experiment at the tailings dam in Tasmania (Australia). The results indicated that the passive seismic interferometry method can be used to monitor and locate small changes inside the tailings dam, making it a valuable tool for remotely monitoring the dam’s structural stability over time (Olivier *et al.,* 2017).

The study of the dynamic response of dams subjected to seismic actions appears expressively with the works of Chopra (1970), Chopra and Chakrabarti (1973), and Chopra (1978). These are motivated by the seismic event that took place in 1967 at the Koyna Dam (Satara, India), where the structure was damaged, despite having been designed under current seismic requirements. Until then, dams were evaluated using the Seismic Coefficient Method, which is based on the hypothesis of a rigid-mobile dam accelerated uniformly (by a fraction of the acceleration of the soil, or seismic coefficient) towards the reservoir, with a supposed incompressible fluid. In this case, the hydrodynamic pressures of the fluid-structure interaction are obtained according to the formulation proposed by Westergaard (1933), as recommended by USBR (1976).

Chopra (1978) effectively includes the elasticity of the structure and the interaction with the compressible fluid in the reservoir, defining the Pseudo-Dynamic Method, which is an extension of the Pseudo-Static Method. Additional contributions obtained by Chopra and his collaborators appear in the following years, such as Fenves and Chopra (1985), who investigated the effects of the foundation's flexibility and the absorption of waves at the bottom of the reservoir.

Studies related to local seismicity and the possible impact of these effects on structural analysis of dams are relatively recent in Brazil and became relevant with the publication of the first Brazilian code dedicated to the earthquake-resistant project in 2006 (NBR 15421, ABNT, 2006). The Seismic Coefficient Method (or Pseudo-Static Method) remains a frequent hypothesis in several dams designed in Brazil. In 2006, the national standard code NBR 15421 stimulated the interest of the Brazilian technical community (including dam engineers) by presenting prescriptions for the seismic design of structures, including analysis using the seismic response spectrum. This is the first and only Brazilian technical standard dedicated to this purpose.

In the following years, many publications were dedicated to the analysis of dams by more advanced methods than the Pseudo-Static Method, and possible repercussions on the structure of the dam. These appear in a majority form from the 2000s. The publications below indicate contributions in this sense, with emphasis on the last five years.

Nóbrega and Nóbrega (2016) address the importance of considering seismic actions in the analysis of civil structures, making an assessment of the seismic hazard map brought by NBR 15421, indicating procedures that must be taken for the proper design.

Duarte (2016) carried out seismic analyzes with several calculation methods in landfill dams (homogeneous and with material distributed by zones), without considering hydrodynamic effects. The author concludes that the stability of the dam is compromised in different scenarios, in different positions, being more critical for zoned dams.

Miranda (2017) presents discussions and applications of existing methods for seismic analysis of gravity dams, such as seismic coefficient, equivalent lateral force, and analysis by response spectrum. Routines were developed with MATLAB software and demonstrate results in line with those obtained in finite element models.

Silva Junior *et al.* (2017) carried out a case study for tensions produced by earthquakes in the “E” section of the Itaipu Dam. Applications of the Pseudo-Dynamic Method proposed by Chopra (1978) were conducted, and the evaluation of the quality of this approach concerning analyses with the response spectrum method in the ANSYS finite element program. The authors concluded that the Pseudo-Static Method produces satisfactory and conservative results.

Da Silveira (2018) carried out a two-dimensional study on finite elements of the dam-reservoir interaction applied to the Koyna Dam, according to the dimensions proposed by Chopra and Chakrabarti (1973). Finite element simulations reproduce the results of this pioneering study.

LØkke and Chopra (2018) present a direct approach to the non-linear analysis of the dam-reservoir-foundation system under earthquakes, with the consideration of semi-infinite domains. The authors discuss the benefits of this implementation over existing options with the use of commercial software.

The work of De Falco *et al.* (2018) indicates a recent example of how numerical strategies can be employed in the solution of multi-domain interaction with soil-structure aspects and the dissipation of waves in infinite media. According to Mendes (2018), several numerical models have been developed for the three-dimensional analysis of the dam-reservoir-foundation interaction, such as the developments by LØkke and Chopra (2018).

Additional investigations emerge in the work of Mendes (2018), which discusses the state of the art of seismic analysis of arch dams, involving several works by national and international researchers in the area, in addition to publications by researchers associated with research centers such as LNEC Portugal and Spain's CIMNE, and from US government agencies such as USACE and USBR. This author carried out detailed investigations with the Finite Element Method at progressive levels of analysis for the Morrow Point Dam (Colorado, USA).

These analyses advance to refined models with the inclusion of effects such as (i) the flexibility of the rock and elements of absorption of mechanical waves in the foundation and (ii) fluid-structure interaction with appropriate boundary conditions for radiation in infinite domains.

It is noticed that the problem is still relevant and of interest in the scientific community, mainly in the search for solutions capable of high computational efficiency and accuracy in three-dimensional numerical models. More recent work indicates some strategies developed by researchers in this direction.

Silva and Pedroso (2019) investigated the dissipative and conservative effects in the analysis of the dam-reservoir interaction with the hypothesis of an incompressible fluid. It is a theoretical study that allows detailed analysis of aspects such as the additional mass produced by the fluid and the influence of surface waves on the analytical solution of hydrodynamic pressures. Gao *et al.* (2019) performed the transient analysis of dam-reservoir interaction problems using asymptotic contours for simulating semi-infinite media with the finite element method. In this case, with immediate repercussions on the use of efficient boundary conditions for computer simulations, being able to reduce the size of the reservoir's discretization domain.

3.2. Geodetic Measurements

Geodetic methods enable monitoring of absolute displacements in structures using geospatial methods, with the use of instruments such as: Total Station, Digital Levels, Inclinometers, LASER System (overhead or terrestrial), GPS Receivers (Global Positioning System), Remote Sensors in UAVs (Unmanned Aerial Vehicles) and Aerial or Ground Laser Systems. According to Kahmen and Faig (1994), the determination of spatial coordinates of a point can be obtained by classical topographic methods such as polygonation, trilateration, triangulation and irradiation, geometric and trigonometric leveling or through positioning by artificial GNSS satellites (Global Navigation Satellite System).

The evolution of the automatic recognition of targets with robotic total stations, made the auscultation of structures more effective and widespread due to the automatic search of the monitored points. It is possible to use these sensors in continuous geodetic monitoring, mainly when listening to large structures.

According to Scaioni (2018), robotic total stations and GNSS (Global Satellite Navigation System) techniques, generally in an integrated manner, can provide efficient solutions for measuring 3D displacements in precise locations on the external surfaces of dams.

Global Navigation Satellite Systems (GNSS) receivers are nowadays commonly used in monitoring applications, e.g., in estimating crustal and infrastructure displacements. This is basically due to the recent improvements in GNSS instruments and methodologies that allow high-precision positioning, 24 h availability and semiautomatic data processing (Barzaghi *et al.*, 2018).

Positioning by GNSS allows the obtaining of coordinates in a punctual manner on or near the Earth's surface, in relation to a pre-established geocentric geodetic framework (Hofmann-Wellenhof *et al.*, 2008). The term GNSS currently includes the American NAVSTAR-GPS (Navigation Satellite with Time and Ranging-Global Positioning System), the Russian GLONASS (Global Orbiting Navigation Satellite System), the European Galileo (European Satellite Navigation System), the Chinese BeiDou/ BDS / Compass (Compass Navigation Satellite System), the Indian IRNSS (Indian Regional Navigational Satellite System). GPS and GLONASS are the systems currently operational and the use of GALILEO is scheduled for mid 2020. GNSS technology is in constant process of modernization, such as the availability of the new NAVSTAR-GPS carrier, transmitting signals in three frequencies (L1 / L2 / L5).

Xiao *et al.* (2019) stated that the performance of the BeiDou space positioning system is comparable to GPS. Improvements in estimating high-precision geodetic networks, such as, for example, ITRF14 (International Land Reference Framework 2014), available from January 2017, provide improvements in accurate products such as orbits and satellites (Altamimi *et al.*, 2016). The linking of these products associated with scientific "software" allows the estimation of spatial position with precision of millimeters. Monico (2008) and Hofmann-Wellenhof *et al.* (2008) approach in great detail the aspects of spatial positioning from GNSS data, involving description, fundamentals and applications.

Radhakrishnan (2014) evaluated the application of the GPS technique in monitoring the structural deformation of the Koyna Dam (India). The analysis of the results indicated a significant correlation between the pattern of deformation of the dam and the change in the water level in the reservoir (Radhakrishnan, 2014).

According to Liu *et al.* (2015), the accuracy of displacement monitoring for deformable objects with GPS is severely affected in highly occluded spaces, such as urban canyons and surface mines. These authors proposed an integrated GPS /Pseudolite positioning technique as an effective solution for accurate monitoring of deformation in obstructed areas. The Experimental Results showed that the proposed model can effectively eliminate the effect of multipath errors of the pseudolite in the parameter estimation, thus improving the positioning accuracy (Liu *et al.*, 2015).

Caldera *et al.* (2016) analyzed the impact of low-cost hardware and software in the analysis of positioning data with GPS and GNSS receivers. According to these authors, using a low-cost GPS receiver and analyzing its data with free and open source software, movements of the order of a few millimeters can be detected. According to Xi *et al.* (2018), GPS technology has been widely applied to monitor displacements using direct measurements. In conventional forms of direct measurement, the displacement can achieve precision at the millimeter level: better than 1 mm horizontally and 2 mm in the vertical component (Xi *et al.*, 2018).

Scaioni *et al.* (2018) performed a review of geodetic and remote sensing techniques applied in studies of dam deformation monitoring. The authors pointed out that geodetic measurements can provide horizontal / vertical displacements of the surface of control points located in key positions, while remote sensing techniques can generate a broader image of displacements over the entire structure and surroundings. Geotechnical / structural sensors can provide important information about those processes within the dam structure and foundations. This data / sensor integration can create added value and increase the data redundancy to be used for cross-observations (Scaioni *et al.*, 2018).

Barzaghi *et al.* (2018) performed a comparative analysis of GNSS data time series and geotechnical observations of pendulums in a dam in Sardinia. The models were able to properly adjust the pendulum and GNSS data with a standard deviation of residues less than one millimeter. The authors found that the GNSS technique allowed a more dense description of spatial and temporal displacements of the dam, when compared with pendular observations. The monitoring configuration involving GNSS and pendulum measurements can be further improved if complementary terrestrial data from synthetic aperture radar (SAR) and observations from the total topographic station are used (Barzaghi *et al.*, 2018). Yu *et al.* (2019) did an important job of revising GNSS technology applied to structural monitoring. In this context, below are listed other recent and important references: Kaloop *et al.* (2017); Pipitone *et al.* (2018); Konakoğlu and Gökalp (2018).

In Brazil, some dissertations and theses related to the application of GNSS in the monitoring of dams have been developed; however, the number of publications in journals with a high impact factor is not yet representative. Fazan (2010) and Muguio (2012) are important researches on this theme.

The use of digital mapping technologies based on aerial laser scanning technology (ALS) and terrestrial laser scanning (TLS) stand out as efficient alternatives in comparison with conventional three-dimensional methods of data acquisition for topography and cartography. Laser technology has been applied in several areas related to dams, such as flood risk assessment, structures, geomorphology, mining, seismology and land use and occupation.

Some important studies were carried out from ALS surveys to estimate the topography of dam rupture studies In general, there is a greater predominance of dam monitoring with a terrestrial laser scanner than with an aerial laser scanner. Alba *et al.* (2006), for example, used data from TLS, three-dimensional geometric models and finite elements in order to assess the structural behavior of a dam in Italy. The results of the study clearly showed that the use of the TLS technique can make an important contribution to the analysis of deformation of large dams, being useful for periodic monitoring, and not continuous, where current sensors are sufficient to control a small set of critical points (Alba *et al.*, 2006).

The use of laser data in dam monitoring studies has been used as an integration tool with other technologies. Hu and Ma (2016), for example, used TLS in combination with GNSS to monitor three-dimensional changes in the surface between 2014 and 2015 on the permafrost slope at QTEC, which experienced two thawing periods and a freezing period.

Several later studies involving the TLS technology were carried out with the objective of evaluating deformations in structures, which can be observed in the international literature, such as in the works Lague *et al.* (2013), Hu and Ma (2016) and Benito-Calvo *et al.* (2018).

In Brazil, studies involving ALS and / or TLS technologies applied to dam monitoring are currently related to dissertations, theses, congresses and some publications in scientific journals.

Remote sensing techniques, such as terrestrial laser scanning, terrestrial SAR (synthetic aperture radar) and differential satellite interferometric SAR, offer the chance to extend the observed region to a large part of a structure and adjacent areas, integrate the information that is usually provided at a limited number of on-site control points (Scaioni *et al.*, 2018).

The first generation of InSAR (Synthetic Aperture Interferometry Radar) technology applied in deformation measurements was known as DInSAR (Differential Interferometric Synthetic Aperture Radar). The DInSAR and PSI (Persistent Dispersion Interferometry) technologies allow detecting vertical displacements at the subcentimeter level (Fárová *et al.*, 2019).

According to Zhou *et al.* (2016), the results of the InSAR technique allow the continuous investigation of dam deformation over a wide area, which includes the entire dam surface and the surrounding area, offering a clear image of the dam deformation continuously. Riccardi *et al.* (2017) performed an analysis of recent deformations in a dam, considering the SAR data from the C Sentinel-1 band. They found that this 20 m ground resolution data can provide millimeter accuracy of displacements.

Di Pasquale *et al.* (2018), for example, showed that radar interferometry can provide measurements of displacements of the surfaces of earth dams and vibration frequencies of their main concrete infrastructures.

Gama *et al.* (2019) carried out Remote Sensing studies in the Mariana / Brazil region after the rupture of the "Fundão" mining tailings dam in 2015. The authors used Advanced Differential Interferometry (A-DInSAR), SBAS (Small Baseline Subset) and PSI (Interferometry Persistent Scatterer) from TerraSAR-X and Pleiades images. The research demonstrated the potential of the SBAS and PSI techniques to monitor linear and non-linear deformations of the mining structures of the dam, presenting A-DInSAR results compatible with geodetic measurements in situ. A-DInSAR analysis, using satellite SAR coverage with short revision times, can be used to check for possible signs of stability in an area impacted by a major dam rupture, aiming at risk mitigation strategies (Gama *et al.*, 2019).

Rotta *et al.* (2020) used satellite-driven soil moisture index, high spatial resolution multispectral images and InSAR products to assess pre-disaster scenarios and the direct causes of the tailings dam collapse in Brumadinho / MG / Brazil. The rapid rate of subsidence measured by the InSAR analysis (even after the lagoon drought) and the large-scale fall of the rupture collectively indicated that there was a liquid action process underway internally (Rotta *et al.*, 2020). Reyes-Carmona *et al.* (2020) used the DInSAR technique to recognize and monitor landslides in the Rules Reservoir (Spain). The integration of the DInSAR results with a comprehensive geomorphological study made it possible to understand the typology, evolution and triggering factors of three active landslides (Reyes-Carmona *et al.*, 2020).

Latrubesse *et al.* (2020) used a series of images from the Sentinel-1 Satellite (SAR), data from the SRTM Mission (Shuttle Radar Topography Mission) and daily rain measurements to assess the sudden violation of a saddle dike on July 23, 2018, at the perimeter the Xe Nammoy hydroelectric power reservoir (Mekong Basin, southern Laos). Among the various previous conclusions, the authors found that the failure of the dam does not appear to have been triggered by overlapping dams due to exceptionally heavy rains. Instead, the dam failed because the construction involved the improper use of permeable materials (Latrubesse *et al*., 2020).

The following are some recent works that complement the approach to technology (radar), applied in monitoring deformations in dams: Barra (2016); Gama *et al.* (2017); Ullo *et al.* (2019); and Solari *et al.* (2018).

According to Barbosa *et al.* (2019), it is possible to make inferences about the composition of water from the interaction between electromagnetic radiation and the optically active constituents (OACs) of water, such as suspended solids, photosynthetic pigments (chlorophyll) and colored dissolved organic matter. Several studies have been carried out in recent decades to monitor water quality by remote sensing. The Works of Khandelwal *et al.* (2017), Binding *et al.* (2018), and Fassoni-Andrade and De Paiva (2019) are recent representative references. In Brazil, there are several important studies carried out by the remote water sensing research group of the National Institute for Space Research (INPE), which are reported in the book by Barbosa *et al.* (2019).

4. CONCLUSIONS

The approach presented in this work gives technical and scientific context to the dam safety segment involving the state of the art of instrumentation, safety and monitoring methods.

Some companies focused on the dam security area, after the Mariana tragedy, and started using military technology to monitor dams. Remote Sensing Systems involving Orbital Satellites, Airborne Laser Systems, UAVs, Radar and Spatial Positioning through GNSS Receivers integrated with software for recording and analyzing data in real time are current examples of technologies employed in the current dam safety practice in Brazil. This characterizes efforts to ensure that extreme events can be identified in a timely manner and alert procedures can be initiated to ensure the safety of dams.

The technological advancement of sensors and software, combined with online communication, has allowed the generation of scientific research aimed at monitoring dams in real time, whether from the automation of geotechnical instrumentation or geodetic and geophysical monitoring systems. The integration and automation of these processes is the current modern trend of dam monitoring.

The new technologies and methods discussed in this study help in a more modern way the detection of structural damage and disasters with the rupture of dams, increasing operational and environmental safety. The environmental consequences resulting from structural damage and disasters with the rupture of dams generate immeasurable socioenvironmental impacts on the biotic and abiotic environment. The non-destructive technologies presented in this work for auscultation of dams, by electromagnetic radiation at a distance, allow less environmental interference.

The knowledge presented in this work, with theoretical information based on scientific and technological basis in current dam engineering practice, aims to enrich the studies of dam monitoring. It is hoped that the approach presented can add knowledge and motivate the generation of new technical-scientific publications in the area of dam safety in Brazil.

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