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
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).

Scaiioni 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 (Scaiioni 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 Nammo...
In a hydroelectric power reservoir (Mekong Basin, southern Laos), among the 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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6. REFERENCES

ABNT. NBR 15421: Projeto de Estruturas Resistentes a Sismos – Procedimento. Rio de Janeiro, 2006.

ALBA, M. et al. Structural monitoring of a large dam by terrestrial laser scanning. International Archives of Photogrammetry. Remote Sensing and Spatial Information Science, v. 36, p. 1-6. 2006.

ALMEIDA I. M.; JACKSON FILHO, J. M.; VILELA R. A. G.; SILVA, A. J. N. Razões para investigar a dimensão organizacional nas origens da catástrofe industrial da Vale em Brumadinho, MG. Cadernos de Saúde Pública, v. 35, n. 4, p. 1-5, 2019. https://doi.org/10.1590/0102-311X00027319

ALTAMIMI, Z.; REBISCHUNG, P.; MÉTIVIER, L.; XAVIER, C. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. Journal of Geophysical Research: Solid Earth, v. 121, p. 6100-6131, 2016.

ALVES H. R. O rompimento de barragens no Brasil e no mundo: desastres mistos ou tecnológicos? Belo Horizonte: Faculdade Dom Helder Câmara, 2015.

BARBOSA, C. C. F.; NOVO, E. M. L. M.; MARTINS, V. S. Introdução ao Sensoriamento Remoto de Sistemas Aquáticos: princípios e aplicações. 1. ed. São José dos Campos: LabISA/INPE, 2019. 160 p.

BARRA, A. et al. First insights on the potential of Sentinel-1 for landslides detection. Geomatics, Natural Hazards and Risk, v. 7, n. 6, p. 1874-1883, 2016. https://doi.org/10.1080/19475705.2016.1171258

BARZAGHI, R. et al. Estimating and Comparing Dam Deformation Using Classical and GNSS Techniques. Sensors, v. 18, p. 1-11. 2018. https://doi.org/10.3390/s18030756

BENITO-CALVO, A. et al. 4D Monitoring of Active Sinkholes with a Terrestrial Laser Scanner (TLS): A Case Study in the Evaporite Karst of the Ebro Valley, NE Spain. Remote Sensing, v. 10, p.1 -19, 2018. https://doi.org/10.3390/rs10040571

BINDING, C. E.; GREENBERG, T. A.; MCCULLOUGH, G.; WATSON, S. B.; PAGE, E. An analysis of satellite-derived chlorophyll and algal bloom indices on Lake Winnipeg. Journal of Great Lakes Research, v. 44, n. 3, p. 436-446, 2018. https://doi.org/10.1016/j.jglr.2018.04.001

BRASIL. Ministério da Integração Nacional. Secretaria de Infra-Estrutura Hídrica. Manual de segurança e inspeção de barragens. Brasília, 2002. 148p.

BRASIL. Presidência da República. Lei nº 12.334, de 20 de setembro de 2010. Estabelece a Política Nacional de Segurança de Barragens destinadas à acumulação de água para quaisquer usos, à disposição final ou temporária de rejeitos e à acumulação de resíduos industriais, cria o Sistema Nacional de Informações sobre Segurança de Barragens e altera a redação do art. 35 da Lei no 9.433, de 8 de janeiro de 1997, e do art. 40 da Lei no 9.984, de 17 de julho de 2000. Diário Oficial [da] União: seção 1, Brasília, DF, 21 set. 2010.

BROWN, D. et al. Desastres mais devastadores de todos os tempos. 1. ed. São Paulo: Lafonte, 2012. 501p.
CALDERA, S.; REALINI, E.; BARZAGHI, R.; REGUZZONI, M.; SANSO, F. Experimental study on low-cost satellite-based geodetic monitoring over short baselines. Journal of Surveying Engineering, v. 142, 2016. https://doi.org/10.1061/(ASCE)SU.1943-5428.0000168

COMITÊ BRASILEIRO DE BARRAGENS. A História das Barragens no Brasil nos Séculos XIX, XX e XXI: 50 Anos do Comitê Brasileiro de Barragens. Rio de Janeiro: Sindicato nacional dos editores de livros, 2011. 533p.

CHENG, L.; ZHENG, D. Two online dam safety monitoring models based on the process of extracting environmental effect. Advances in Engineering Software, v. 57, p. 48–56. 2013. https://doi.org/10.1016/j.advengsoft.2012.11.015

CHENG-YU, H. et al. Recent progress of using Brillouin distributed fiber optic sensors for geotechnical health monitoring. Sensors and Actuators A: Physical, v. 258, p. 131-145, 2017. https://doi.org/10.1016/j.sna.2017.03.017

CHOPRA, A. K. Earthquake resistant design of concrete gravity dams. Journal of the Structural Division, v. 104, n. 6, p. 953-971, 1978.

CHOPRA, A. K. Earthquake Response of Concrete Gravity Dams. Berkeley: Earthquake Engineering Research Center, University of California, 1970.

CHOPRA A. K.; CHAKRABARTI, P. The Koyna earthquake and damage to Koyna Dam. Bulletin of the Seismological Society of America, v. 63, n. 2, p. 381-3977, 1973.

COSTA, W. D. Geologia de Barragens. São Paulo: Oficina de Textos, 2012. 352p.

CRUZ, P. T. da. 100 Barragens Brasileiras: Casos Históricos, Materiais de Construção, Projeto. São Paulo: Oficina de Textos, 1996. 648p.

DA SILVEIRA, I. V. Estudo da influência da crosta local no comportamento sísmico do sistema barragem gravidade-reservatório-fundação. 2018. 148f. Dissertação (Mestrado em Estruturas e Construção Civil) - Faculdade de Tecnologia, Universidade de Brasília, Brasília, 2018.

DE FALCO, A.; MORI, M.; SEVIERI, G. Simplified soil-structure interaction models for concrete gravity dams. In: EUROPEAN CONFERENCE ON COMPUTATIONAL FLUID DYNAMICS, 7., 11a 15 June 2018, Glasgow, UK. Proceedings[...] Barcelona: ECCOMAS, 2018.

DI PASQUALE, A. et al. Monitoring Strategies of Earth Dams by Ground-Based Radar Interferometry: How to Extract Useful Information for Seismic Risk Assessment. Sensors, v. 18, p. 1-25, 2018. https://doi.org/10.3390/s18010244

DUARTE, S. C. H. Estudo comparativo de diferentes abordagens na análise sísmica de barragens de aterro. 2016. 60f. Dissertação (Mestrado em Engenharia Civil) - Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Lisboa, 2016.

DUNNICLIFF, J. Geotechnical Instrumentation for Monitoring Field Performance. Wiley, 1988. 577p.

FAHLBUSCH, H. Early dams. Proceedings of the Institution of Civil Engineers - Engineering History and Heritage, v. 162, n. 1, p. 13-18, 2009.
FÁROVÁ, K.; JELÉNEK, J; KOPACKOVÁ-STRNADOVÁ, V.; KYCL, P. Comparing DInSAR and PSI Techniques Employed to Sentinel-1 Data to Monitor Highway Stability: A Case Study of a Massive Dobkovicky Landslide, Czech Republic. Remote Sensing, v. 11, p. 1-23, 2019. https://doi.org/10.3390/rs11222670

FAZAN, J. A. Aplicação do teste de congruência global e análise geométrica para detecção de deslocamentos em redes geodésicas: Estudo de caso na UHE de Itaipu. 2010. 248f. Dissertação (Mestrado) - Escola Politécnica, Universidade de São Paulo), São Paulo, 2010.

FASSONI-ANDRADE, A. C.; DE PAIVA, R. C. D. Mapping spatial-temporal sediment dynamics of river-floodplains in the Amazon. Remote sensing of environment, v. 221, 94-107, 2019. https://doi.org/10.1016/j.rse.2018.10.038

FELL, R.; STAPLEDON, D.; BELL, G; FOSTER, M. Geotechnical Engineering of Dams. 2. ed. Boca Raton: CRC Press, 2014. 1348p.

FENVES, G. F.; CHOPRA, A. K. Effects of Reservoir Bottom Absorption and Dam-Water-Foundation Rock Interaction on Frequency Response Functions for Concrete Gravity Dams. Earthquake Engineering and Structural Dynamics, v. 13, p. 13-31, 1985. https://doi.org/10.1002/eqe.4290130104

GAO, Y.; JIN, F.; XI, Y. Transient Analysis of Dam–Reservoir Interaction Using a High-Order Doubly Asymptotic Open Boundary. Journal of Engineering Mechanics, v. 145, n. 1, 2019. https://doi.org/10.1061/(ASCE)EM.1943-7889.0001553

GAMA, F. F.; CANTONE, A.; MURA, J. C.; PASQUALI, P.; PARADELLA, W. R.; DOS SANTOS, A. R.; SILVA, G. G. Monitoring subsidence of open pit iron mines at Carajás Province based on SBAS interferometric technique using TerraSAR-X data. Remote Sensing Applications: Society and Environment, v. 8, p. 199-211, 2017. https://doi.org/10.1016/j.rsase.2017.09.001

GAMA, F. F.; PARADELLA, W. R.; MURA, J. C.; OLIVEIRA, C. G. Advanced DINSAR analysis on dam stability monitoring: A case study in the Germano mining complex (Mariana, Brazil) with SBAS and PSI techniques. Remote Sensing Applications: Society and Environment, v. 16, p. 1-13, 2019. https://doi.org/10.1016/j.rsase.2019.100267

HOFMANN-WELLENHOF, B.; LICHTENEGGER, H.; WASLE, E. GNSS - Global Navigation Satellite Systems: Gps, Glonass, Galileo & more. New York: Springer-Verlag, 2008. 516 p.

HU, J.; MA, F. Comprehensive Investigation Method for Sudden Increases of Uplift Pressures beneath Gravity Dams: Case Study. Journal of Performance of Constructed Facilities, v. 30, n. 5, 2016. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000874

ICOLD; CIGB. Dams & The World's Water - An educational book that explains how dams help to manage the world's water. Paris, 2007. 64p.

JIA, Y.; CHI, S. Back-analysis of soil parameters of the Malutang II concrete face rockfill dam using parallel mutation particle swarm optimization. Computers and Geotechnics, v. 65, p. 87-96, 2015. https://doi.org/10.1016/j.compgeo.2014.11.013

KAHMEN, H.; FAIG, W. Surveying. Berlin: Walter de Gruyter, 1994. 578 p.
KALOOP, M. R.; ELBELTAGI, E.; Hu, J. W.; ELREFAI, A. Recent advances of structures monitoring and evaluation using GPS-time series monitoring systems: a review. ISPRS International Journal of Geo-Information, v. 6, n. 12, 2017. https://doi.org/10.3390/ijgi6120382

KHANDELWAL, A. et al. An approach for global monitoring of surface water extent variations in reservoirs using MODIS data. Remote sensing of Environment, v. 202, p. 113-128, 2017. https://doi.org/10.1016/j.rse.2017.05.039

KONAKOĞLU, B.; GÖKALP, E. Deformation Measurements and Analysis with Robust Methods A Case Study Deriner Dam. Turkish Journal of Science & Technology, v. 13, n. 1, p. 99-103, 2018.

KUTZNER, C. Earth and rockfill dams: principles of design and construction. Rotterdam: A. A. Balkema, 1997. 333 p.

LAGUE, D.; BRODU, N.; LEROUX, J. Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). ISPRS Journal of Photogrammetry and Remote Sensing, v. 82, p. 10–26, 2013. https://doi.org/10.1016/j.isprsjprs.2013.04.009

LATRUBESSE, E. M. et al. Dam failure and a catastrophic flood in the Mekong basin (Bolaven Plateau), southern Laos. Geomorphology, v. 362, p. 1-16, 2020. https://doi.org/10.1016/j.geomorph.2020.107221

LI, F. et al. Towards an Error Correction Model for dam monitoring data analysis based on Cointegration Theory. Structural Safety, v. 43, p.12-20, 2013. https://doi.org/10.1016/j.strusafe.2013.02.005

LIU, C.; GAO, J.; ZHAO, X.; ZHANG, A.; YU, X. Simulation and experiment analysis of dynamic deformation monitoring with the integrated GPS/pseudolite system. Journal of Geophysics and Engineering, v. 12, p. 45-56, 2015. https://doi.org/10.1088/1742-2132/12/1/45

LØKKE, A.; CHOPRA, A. K. Direct finite element method for nonlinear analysis of semi-unbounded dam-water-foundation rock systems. Earthquake Engineering & Structural Dynamics, v. 46, n. 8, p. 1267–1285, 2017. https://dx.doi.org/10.1002/eqe.2855

MENDES, N. B. Um estudo de propagação de ondas e aplicação do sismo na análise dinâmica acoplada a barragem em arco - reservatório - fundação. 2018. 289 f. Tese (Doutorado em Estruturas e Construção Civil) - Universidade de Brasília, Brasília, 2018.

METZGER, M. J.; ROUNSEVELL, M. D. A; ACOSTA-MICHLIK, L.; LEEMANS, R.; SCHOTER. D. The vulnerability of ecosystem services to land use change. Agriculture, Ecosystems & Environment, v. 114, n. 1, p. 69-85, 2006. https://doi.org/10.1016/j.agee.2005.11.025

MIRANDA, R. J. G. Análise do comportamento sísmico de uma barragem gravidade tipo. 2017. 98f. Dissertação de Mestrado (Engenharia Civil) - Instituto Superior de Engenharia de Lisboa, Lisboa, 2017.

MONICO, J. F. G. Posicionamento pelo GNSS: descrição, fundamentos e aplicações. São Paulo: Editora Unesp, 2008. 477 p.
MUGUIO, M. R. Implantação e análise da estação GNSS para o monitoramento contínuo da barragem da Usina Hidrelétrica de Mauá. 2012. 155f. (Dissertação de Mestrado em Ciências Geodésicas) - Universidade Federal do Paraná, Curitiba, 2012.

NADIA, S.; BOUCHRIT, R. Influence of deformation moduli on the settlement of earth dams. International Journal of Geomate, v. 13, n. 38, p.16-22, 2017. http://dx.doi.org/10.21660/2017.38.64964

NÓBREGA, P. G. B.; NÓBREGA, S. H. S. Perigo Sísmico no Brasil e a Responsabilidade da Engenharia de Estruturas. Holos, v. 4, p. 162-175, 2016. https://doi.org/10.15628/holos.2016.4703

OLIVIER, G.; BRENGUIER, F.; WIT, T.; LYNCH, R. Monitoring the stability of tailings dams with ambient seismic noise. Society of Exploration Geophysicist. The Leading Edge, v. 36, n. 4, p. 72-77, 2017. https://doi.org/10.1190/tle36040350a1.1

PEI, H.-F.; TENG, J.; YIN, J. H.; CHEN, R. A review of previous studies on the applications of optical fiber sensors in geotechnical health monitoring. Measurement, v. 58, p. 207-214, 2014. https://doi.org/10.1016/j.measuremen.2014.08.013

PIPITONE, C. et al. Monitoring water surface and level of a reservoir using different remote sensing approaches and comparison with dam displacements evaluated via GNSS. Remote Sensing, v. 10, n. 1, p. 71, 2018. https://doi.org/10.3390/rs10010071

PIRES, K. O.; FUTAI, M. M.; BITTENCOURT, T. N.; BECK, A. T. Reliability analysis of built concrete dam. IBRACON Structures and Materials Journal, v. 12, n. 3, p. 551 – 579, 2019. https://doi.org/10.1590/s1983-41952019000300007

PLANÈS, T.; MOONEY, M. A.; RITTGERS, J. B. R.; PAREKH, M. L.; BEHM, M.; SNIEDER, R. Time-lapse monitoring of internal erosion in earthen dams and levees using ambient seismic noise. Géotechnique, v. 66, n. 4, p. 301-312, 2014. https://doi.org/10.1680/jgeot.14.P.268

RADHAKRISHNAN, N. Application of GPS in structural deformation monitoring: A case study on Koyna dam. Journal of Geomatics, v. 8, n. 1, p. 48–54. 2014.

REYES-CARMONA, C. et al. Sentinel-1 DInSAR for Monitoring Active Landslides in Critical Infrastructures: The Case of the Rules Reservoir (Southern Spain). Remote Sensing, v. 12, n. 5, p. 1-13, 2020. https://doi.org/10.3390/rs12050809

RICCARDI, P.; TESSARI, G.; LECCI, D.; FLORIS, M.; PASQUALI, P. Use of Sentinel-1 SAR data to monitor Mosul dam vulnerability. 19th EGU General Assembly. In: EGU GENERAL ASSEMBLY, 19., 23-28 April, 2017, Vienna. Proceedings […] Munich, 2017.

RICO, M.; BENITO, G.; SALGUEIRO, A. R.; DÍEZ-HERRERO, A.; PEREIRA, H. G. Reported tailings dam failures: a review of the European incidents in the worldwide context. Journal of Hazardous Materials, v. 152, p. 846-852, 2008. https://doi.org/10.1016/j.jhazmat.2007.07.050

RITTGERS, J. B.; REVIL, A.; PLANES, T.; MOONEY, M. A.; KOELEWIJN, A. R. 4-D imaging of seepage in earthen embankments with time-lapse inversion of self-potential data constrained by acoustic emissions localization. Geophysical Journal International, v. 200, n. 2, p. 758-772, 2014. https://doi.org/10.1093/gji/ggu432
ROTTA, L. H. S. et al. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. **International Journal of Applied Earth Observation and Geoinformation**, v. 90, n. 100267, p 1-12, 2020. https://doi.org/10.1016/j.jag.2020.102119

SCAIONI et al. Geodetic and Remote-Sensing Sensors for Dam Deformation Monitoring. **Sensors**, v. 18, p. 1-25, 2018. https://doi.org/10.3390/s18113682

SILVA JUNIOR, E. J.; ARACAYO, L. A. S.; COELHO, D. P. Comparação entre o método pseudo-dinâmico e o método espectro de resposta aplicado como análise sísmica em uma barragem tipo: estudo de caso Itaipu. *In: IBERIAN LATIN-AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING*, 38., 2017, Florianópolis. *Proceedings [...]* Belo Horizonte: ABMEC, 2017.

SILVA, S. F.; PEDROSO, L. J. Interaction dam-reservoir: study of conservative and dissipative effects. **Ibracon Structures and Materials Journal**, v. 12, n. 4, p. 858-873, 2019. https://doi.org/10.1590/s1983-41952019000400008

SOLARI, L. et al. Satellite radar data for back-analyzing a landslide event: the Ponzano (Central Italy) case study. **Landslides**, v. 15, p. 773–782, 2018. https://doi.org/10.1007/s10346-018-0952-x

STOJANOVIC, B. et al. A self-tuning system for dam behavior modeling based on evolving artificial neural networks. **Advances in Engineering Software**, v. 97, p. 85-95, 2016. https://doi.org/10.1016/j.advengsoft.2016.02.010

ULLO, S. L. et al. Application of DInSAR Technique to High Coherence Sentinel-1 Images for Dam Monitoring and Result Validation Through In Situ Measurements. **IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing**, v. 12, n. 3, p. 875–890, 2019. https://doi.org/10.1109/JSTARS.2019.2896989

UNITED STATES. Bureau of Reclamation. **Design of Gravity Dams**. Denver, 1976.

UNITED STATES. Bureau of Reclamation. **Design of Small Dams**. 3. ed. Denver, 1987. 860p.

UNITED STATES. Army. Corps of Engineers. **General Design and Construction for Earth and Rock-Fill Dams**: in 1110-2-2300. Washington, D.C., 2004.

UNITED STATES. Army. Corps of Engineers. **Instrumentation of Embankment Dams and Levees**: Manual No. 1110-2-1908. Washington, DC., 1995. 75 p.

UNITED STATES. Army. Corps of Engineers. **Manual 1110-1-1004 Deformation Monitoring and Control Surveying**. Washington, DC., 1994.

UNITED STATES. Federal Energy Regulatory Commission. **Engineering Guidelines for the Evaluation of Hydropower Projects**. Chapter IX – Instrumentation and Monitoring. Washington, DC., 2003.

VALENÇA, J.; JÚLIO, E. MCrack-Dam: the scale-up of a method to assess cracks on concrete dams by image processing. The case study of Itaipu Dam, at the Brazil–Paraguay border. **Journal of Civil Structural Health Monitoring**, v. 8, n. 3, p. 857-866, 2018. https://doi.org/10.1007/s13349-018-0309-0
WESTERGAARD, H. M. Water pressures on dams during earthquakes. Transactions of the American Society of Civil Engineers, v. 98, p. 418-433, 1993.

XIAO, R. et al. Deformation Monitoring of Reservoir Dams Using GNSS: Application to SNWD Project, China. IEEE ACCESS, v. 7, p. 54981-54992, 2019. https://doi.org/10.1109/ACCESS.2019.2912143

Xi, R. et al. Simultaneous estimation of dam displacements and reservoir level variation from GPS measurements. Measurement, v. 122, p. 247–256, 2018. https://doi.org/10.1016/j.measurement.2018.03.036

YU, J. et al. Global Navigation Satellite System-based positioning technology for structural health monitoring: a review. Structural Control and Health Monitoring, v. 27, n. 1, p. 3-27. 2019. https://doi.org/10.1002/stc.2467

ZENI, L. et al. Brillouin optical time-domain analysis for geotechnical monitoring. Journal of Rock Mechanics and Geotechnical Engineering, v. 7, n. 4, p. 458-462, 2015. https://doi.org/10.1016/j.jrmge.2015.01.008

ZHOU, W.; LI, S.; ZHOU, Z.; CHANG, X. Remote Sensing of Deformation of a High Concrete-Faced Rockfill Dam Using InSAR: A Study of the Shuibuya Dam, China. Remote Sensing, v. 8, n. 255, p. 1-15, 2016. https://doi.org/10.3390/rs8030255