Dam safety management methodology in front of the national dam safety policy

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Abstract

Most of the dams registered on the National Information System on Dam Safety (SNISB of Brazil) do not have enough information to assess whether they fit into the National Dam Safety Policy (PNSB), or to assess their safety conditions. According to the National Agency of Waters (ANA, 2021b), there are currently 122 dams with some important structural problems indicated by their inspectors in 23 states. Therefore, this article proposes a methodology for identifying faults in dam safety activities. The method applies to all types of existing dams. The proposed methodology comprises ten stages that, according to the progress of the steps, are defined by three levels of completeness of the information. Tables were developed with the objective of being a verification guide for these ten stages. This research applied the proposed methodology to two dams in Paraná, Brazil. The first is the Iraí dam, located in the metropolitan region of Curitiba, and the second is the Jordan River Derivation dam, located in Reserva do Iguaçu. The example of the Iraí dam could complete all stages of the proposed methodology. For the Jordan River Derivation dam, stages 1 to 5 of the proposed methodology were carried out. The application of the proposed methodology intends to become a useful tool, especially for inspectors, aiming at a more effective registration process, accelerating the completion of the SNISB.

Keywords: dam safety, national dam safety policy, dam analysis.

1. Introduction

According to the Brazilian Committee on Dams (CBDB), dams are defined as artificial obstacles with the ability to retain water or any other liquid, tailings, debris for storage or control purposes. They can range in size from small clumps of land, often used on farms, to massive concrete or embankment structures commonly used for water supply, hydropower, flood control, irrigation, and many other purposes. Their construction is complex, with high potential risk, and require large public and private investments (CBDB, 2021).

According to the National Agency for Water and Basic Sanitation (ANA), (ANA, 2021a), a safe dam is a well-maintained dam in which efforts, energy, attention, resources, and trained professionals are directed towards a sound conception, a good design, and construction that follows good engineering practices, while for the post-construction stages: first filling, maintenance, operation, and decommissioning, if applicable.

However, recent dam accidents in Brazil, notably in the mining sector, in tailings dams, have significantly increased society's concern about the safety of these projects, as well as extending this feeling to hydraulic designs (Czap, 2022). As seen in the Dam Safety Report (RSB) published by ANA (2021b), many dams have problems, and solutions must be studied based on contemporary technology and concepts.

According to the RSB of 2020 (ANA, 2021b), during that year, 44 accidents and 95 incidents were reported in 16 states, mainly in the southeast and midwestern regions of the country. Most of these events occurred due to heavy rains from January to March, causing the dams to overtop (overflow), some of them "in cascade".

Most of the dams registered on the SNISB do not have enough information to assess whether they fit into the National Dam Safety Policy (PNSB) of Brazil or to assess their safety conditions. Of the multiple-use dams submitted to the PNSB, only 6.6% have the Dam Safety Plan (PSB), 6.4% have the Emergency Action Plan (PAE), and only 6.3% were subjected to regular inspections by their developers (ANA, 2021b).

As mentioned, there are currently 122 dams with some critical structural problems, indicated by their inspectors in 23 states. The main reasons for concern cited by the inspectors are related to the state of conservation, indicated in 52% of the cases (63 dams), as well as the classification regarding Associated Potential Damage (DPA) and Risk Criterion (CRI), indicated in 34% of the cases (42 dams). Other reasons cited are project characteristics, mainly for the overflow organs (8 dams), "orphan" dams - those that do not have identification of the entity responsible for their operation and maintenance (entrepreneur) - (5 dams), and lack of documents, such as the Declaration of Stability of the dam or bestowal (4 dams). The structures often have more than one of these concerns (ANA, 2021b).

However, when it comes to classifying dams according to their risks and potential damage, not only the dam structure itself is considered, but also the nature of the downstream floodplain; its topography and its extension (Adamo *et al*., 2020). Risk quantification is essential for project management and should ensure that uncertainties are properly balanced with competent technical judgment (Fusaro, 2012).

Laws 12334/10 and 14066/20, which address the PNSB, clearly indicate that the risk approach must be used to guarantee the safety of dams, even indicating that the process must be formal and auditable (Czap, 2022). Risk analysis needs reliable data in sufficient quantity, since the lack of data on sedimentation represents an increase in risk perception.

Knowing that risk is the product of the probability of a certain event by the consequences of the occurrence of this event, said event can be the failure of a dam and can be studied through the problem of fundamental reliability (Czap, 2022). The most widespread determination of risk acceptability is that defined by the "As Low As Reasonably Practicable" (ALARP) principle (ICOLD, 2005).

Therefore, given the importance of ensuring safety in existing dams in the country, the national legislative panorama regarding dam safety, and the need for standardization of processes in this field of activity, this article aims to propose a methodology for identifying faults in the safety of dams, whether procedural, technical, human or otherwise.

2. Material and method

This article presents a methodology for identifying faults in dam safety activities of existing dams, as Figure 1 illustrates. The methodology was developed based on international experience. Literature records from countries such as France, United Kingdom, Switzerland, Austria, Spain, Portugal, USA, Canada, Australia, India and China were consulted in order to base the development of the methodology proposed herein (Jansen, 1983; Melbinger, 1991; Government, 1998; McGrath, 2000; ancold, 2003a; Ancold, 2003b; Zuffo & Genovez, 2009; Cuiyun *et al*., 2010; Icold, 2011; Méan *et al*., 2012; Zenz *et al*., 2012; Castillo-Rodriguez *et al*., 2013; FEMA, 2014; Zhou *et al*., 2015; Government, 2016; Sayed, 2018; Adamo *et al*., 2020; ICPDR, 2020; Adamo *et al*., 2021; NIPFP, 2021).

The method applies to all types of existing dams. It is also recommended that the methodology be applied by two agents: a dam safety analyst and a dam engineer. The analyst must be a dam specialist, with experience in the project to be studied, and who can carry out the activities of the first stages (1 to 4). On the other hand, the later stages (5 to 10) require more in-depth technical-theoretical knowledge and must be carried out by a dam engineer. The author advises that, to be considered a dam engineer, one must have at least 10 years of working with dams.

The overview of the proposed methodology is demonstrated through the flowcharts presented in Figure 1. It consists of 10 stages, described below:

(1) Identification: in this stage, the entrepreneur, the inspector, and the primary data of the dam are identified, such as height, reserve volume, use(s), age, construction material(s), type(s) of foundation, and maintenance(s) record(s). This information can be obtained through a visual inspection, if not registered.

(2) Database: the database must be composed of all the existing technical documentation about the dam under study, that is: pre-design, basic design, executive design, work log(s), such as construction documentation, design documentation, and maintenance reports. The main objective of this stage is to verify if the amount of information is sufficient for a dam stability analysis. Field surveys and tests must be conducted to allow a technically reliable analysis if there needs to be adequate technical information. An "as is" design may be indicated in this case.

(3) Materials: with all the design documentation, memorials, and reports in hand, it is possible to survey the materials that make up the dam and the foundation. All materials must be described in terms of specific weight, cohesion, angle or coefficient of friction, and permeability coefficient. It may be necessary to conduct in situ tests to complement the characterization of the materials. Here, too, is determined whether there is any deterioration or change in behavior that should be simulated in the studies. Therefore, access to existing inspection and safety studies is required, or else complement them.

(4) Loading: as well as materials, loadings must also be described according to construction stages, reservoir water levels, hydrometeorological studies, etc. Therefore, it is necessary to point out that the loading cases must be wholly formulated. They are: end of construction, first filling, rapid drawdown, earthquakes, or permanent percolation with the minimum, normal, maximum, and maximum water levels. In addition, it is essential to indicate the presence of the cascade effect.

(5) Stability: once the technical information about the design, materials, and loads has been quantified, this stage aims to analyze the possibility of stability analysis. Henceforth, from this stage onwards, a dam safety engineer must be involved in the proposed methodology due to the need for a higher level of technical and theoretical expertise. Here, it is necessary to answer if the stability analysis can be performed for sliding, toppling, support capacity of foundations, internal stresses, and effectiveness of filters and drains. Subsequently, the stability analysis is performed based on the main cross-sections of the dam and in any necessary location. In this analysis, it is possible to perform more complex numerical simulations to assess stability. Here, the possibility of carrying out probabilistic analysis can also be evaluated, i.e., whether the parameters needed for the analysis can be described using mean and standard deviation. This phase is important to analyze the stability of the instrumentation data.

(6) Instrumentation: Once the dam's stability is assessed, it is necessary to quantify and evaluate the number of instruments the monitoring system contains. So, at this stage, all instruments calibrated and in the entire operation are listed and located in the design. The question "Is the existing instrumentation system in the dam sufficient?" must be answered. Maintenance actions and/or the addition of instrumentation can result from the analysis of this stage.

(7) Auxiliary structures: this step comprises the holistic analysis of the dam, now considering its entire body and auxiliary structures. In Step 5, the stability analysis is carried out based on the main cross-sections of the dam. However, here, the aim is for a global analysis. Based on finite element methods, three-dimensional computer simulation software can be an excellent ally for the dam engineer at this stage. If the dam is unstable, interventions or de-characterization should be studied (stage 10).

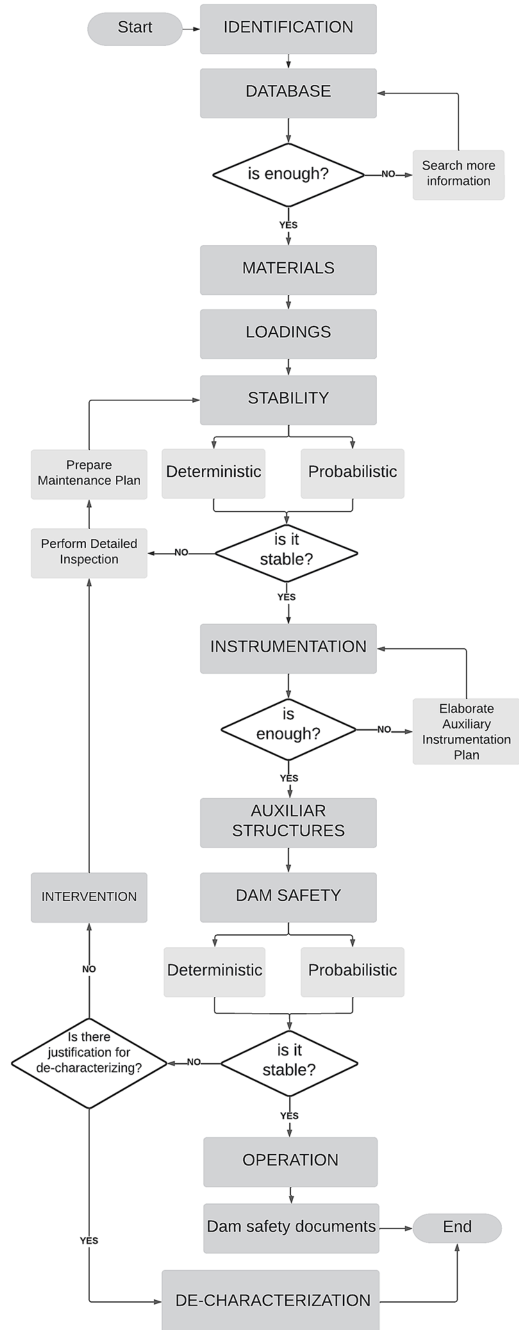

Figure 1 - Flowchart of the methodology for identifying faults in dam safety activities. Source: Own authorship.

(8) Dam safety: one of the biggest problems reported by the dam sector bodies is the need for more communication between the technical staff and society. Therefore, Step 8 aims to help the dam engineer list the documents that must be developed. Further details regarding the content of these documents must be consulted by their respective supervisory body. Currently, each inspector has its regulations to establish this essential documentation required by the PNSB.

(9) Operation: checks whether the main actions are covered in the Operation and Maintenance Manual, such as instrument reading routine, visual inspections, spillway operative rules, and preventive and corrective maintenance. In this phase, it is necessary to evaluate the reservoir control through spillways and other structures.

(10) Intervention or De-characterization: If it is impossible to intervene in the dam to guarantee its safety, its de-characterization is analyzed. Stage 10 was included in this methodology to raise awareness among entrepreneurs and inspectors about planning the de-characterization of dams. The author believes that awareness of the perpetual responsibility of an entrepreneur is necessary nowadays. There is a reality of neglect, especially in small dams, where not even the entrepreneur can be identified, let alone their level of responsibility with the valley in which the dam is inserted or the population that lives downstream. The minimum documentation for a possible de-characterization process must include at least an Environmental Management Plan, a risk acceptability limit, the definition of the design's useful life, and a Perpetual Monitoring Plan. Furthermore, the author recommends a period of 5 years for a new assessment of the structure using the presented methodology.

Tables 1 and 2 were developed with the objective of being a verification guide for the ten stages of the proposed methodology. Table 1 illustrates stages 1 to 5, and Table 2 illustrates stages 6 to 10.

In stage 1, the first two blank fields must be filled in with the names of the entrepreneur and the dam inspector. Then, the white fields referring to essential data, type of dam, and type of foundation must be marked according to the existence of the information. Moreover, the question "Was there any major structural maintenance?" and "Is there treatment on the foundations?" must be answered with "yes" or "no".

The white fields of stage 2 must be ticked with an "X", pointing out the existence of the cited documents and whether there is a need for new surveys through technical inspections.

Stages 3 to 5 must be marked indicating the existence of the required information. Then, at the end of stage 5, the complete stability analysis must be carried out. It must be noted that the indication of the type of analysis can already be made based on the volume of information collected so far.

In the event of any anomalous instrument reading, a stability analysis must be carried out specifically to verify the safety condition of the dam or the incorrect functioning of the instrument in question.

Table 1 - Fillable form of the proposed methodology - Stages 1 to 5.

STAGE 1	IDENTIFICATION									
	Of ENTREPRENEUR					Of INSPECTOR				
	Basic data:			What is the type of dam?			What type of foundation?			
	Height				Concrete			Soft ground		
	Reserve volume				Earth			Solid ground		
	Use(s)				Tailing			Fractured rock		
	Age				Mixed			Sane rock		
	Was there any major structural maintenance?			Other			Is there treatment on the foundations?			
STAGE 2	DATABASE									
		Pre-design		Basic design				Executive design		
		Work diary(s)		As-built				Maintenance reports		
	Is the volume of information sufficient to determine the parameters of the dam materials?									
	Yes					No				
	Proceed to the next step					Collect more information				
STAGE 3	MATERIALS									
	Which parameters of the dam materials have their complete definitions?									
	Soil(s)		Concrete(s)		Land(s)		Rock(s)		Other(s)	
	Specific weight		Specific weight		Specific weight		Specific weight		Specific weight	
	Cohesion		Cohesion		Cohesion		Cohesion		Cohesion	
	Angle of friction		Coefficient of friction		Angle of friction		Coefficient of friction		Coefficient of friction	
	Permeability coefficient		Permeability coefficient		Permeability coefficient		Permeability coefficient		Permeability coefficient	
STAGE 4	LOADINGS									
	Do the load cases below have their full definitions?									
	End of construction		First filling		Rapid drawdown		Earthquakes			
							Vertical acceleration		Horizontal acceleration	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	Permanent percolation								Cascade effect	
	Minimum water level		Normal water level		Maximum water level		Maximorum water level			
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
STAGE 5	STABILITY									
	Is there sufficient information to analyze the stability of the dam?									
	Sliding		Toppling		Support capacity of foundations		Internal stresses		Effectiveness of filters and drains	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	What is the nature of the stability analysis, based on the available data, that can be performed?									
	Deterministic					Probabilistic				

Source: Own authorship.

Table 2 - Fillable form of the proposed methodology - Stages 6 to 10.

STAGE 6	INSTRUMENTATION									
	Indicate the number of instruments, in full operation, installed in the dam.									
	Inclinometer		Piezometer		Flowmeter		Load cell		Surface frame	
	Inverted plumb		Pore pressure cell		Displacement plate		Seismograph		Accelerometer	
	Joint gauge		Deformimeter		Tensometer		Thermometer		Other	
	Is the existing instrumentation system in the dam sufficient for the correct monitoring of its safety?				The existing instrumentation system at the dam is:					
	Yes		No		Manual		Semi-automated		Automated	

STAGE 7	AUXILIARY STRUCTURES			
	What auxiliary structures are present in the dam?			
	Spillway		Bottom downloader	
	Powerhouse		Bypass tunnel	
	Water intake		Floodgates	
	Others		Others	
	Can auxiliary structures compromise the stability and/or safety of the dam?			
	Yes		No	
			If yes, new computational modeling must be performed.	

STAGE 8	DAM SAFETY		
	Does the dam developer have the following reports and documents?		
	Periodic inspection report	Yes	No
	Risk analysis	Yes	No
	Dam Safety Plan (PSB)	Yes	No
	Emergency Action Plan (PAE)	Yes	No
	Communication plans	Yes	No
	Others		

STAGE 9	OPERATION		
	Does the dam entrepreneur have an operations routine that includes the following actions?		
	Identification of pathological manifestations	Yes	No
	Maintenance planning	Yes	No
	Periodic reading of instructions	Yes	No
	Periodic analysis of the dam's behavior	Yes	No
	Others		

STAGE 10	INTERVENTION OR DE-CHARACTERIZATION		
	Does the dam entrepreneur have a dam de-characterization plan that contains the following information?		
	Environmental management plan	Yes	No
	Risk acceptability limit	Yes	No
	Perpetual monitoring plan	Yes	No
	Definition of the useful life of the enterprise	Yes	No
	Others		

Source: Own authorship.

The execution of the stability analysis required by stage 5 refers to a representative cross-section of the dam; only in stage 7 will the global stability of the structure be evaluated.

In Table 2, stage 6, the instrumentation present in the dam, with calibration up to date and in the entire operation, must be accounted for. Therefore, in the blank fields of stage 6, the number of instruments must be filled in.

The question "Is the existing instrumentation system in the dam sufficient for the correct monitoring of its safety?" must be answered with technical criteria by the dam safety engineer. Furthermore, the instrumentation system automation information must be marked.

Stage 7 should show the existence of auxiliary structures in the dam and assess their influence on the structure's overall stability. At this stage, three-dimensional simulation software can be essential.

In stages 8 to 10, the existence of listed documentation must be indicated. The non-existence of a specific document does not interfere with the dam's safety but rather with the completeness of the information accessible to inspection bodies and the general population.

Achieving the completeness of the information that represents the ten stages proposed in this methodology means that the dam is supervised, inspected, and its safety aspects are informed to society. In addition, this means that the information required by the SNISB is complete.

However, this does not mean the dam does not need periodic or occasional inspections. On the contrary, the safety of dams must be periodically reassessed. Moreover, the proposed methodology only aims to make the work developed by engineers responsible for assessing the safety of these designs more succinct and agile.

Each stage must be completed with all the information required to advance to the next step. The impossibility of completing a particular stage highlights a point of fault in the dam's safety under study. Also, according to the progress of the steps, three levels of completeness of information are defined. These levels will correlate with the safety level of the dam under study. They are:

Level 1: UNCERTAIN. Corresponds to studies of dams that do not have enough information to go beyond stage 4 of the proposed methodology and, therefore, it is concluded that there is not enough information to determine if the dam is stable;

Level 2: STABLE. Corresponds to studies of dams that have enough information to assess to their stability, and therefore, advance to stage 7 of the proposed methodology but that does not have all the necessary documentation, according to the PNSB and complementary regulations, registered with the inspection body;

Level 3: INFORMED. The dam is stable, and all documentation required by inspectors is duly registered.

3. Results

Example 1: Iraí dam

Measuring the volume of information is already an essential step in the safety of Brazilian dams, as the deficit of existing information is still huge, requiring urgency in its completeness, as pointed out by ANA (2021b).

A lack of information is common, especially in smaller dams. Loss of documentation, change of ownership, and others can be the reasons for the lack of essential data. However, using the proposed methodology is one way to continue testing the safety level of the dam under study, with the progress of stages.

To confirm the effectiveness of the suggested methodology, two dams located in the state of Paraná underwent the ten stages outlined in this study.

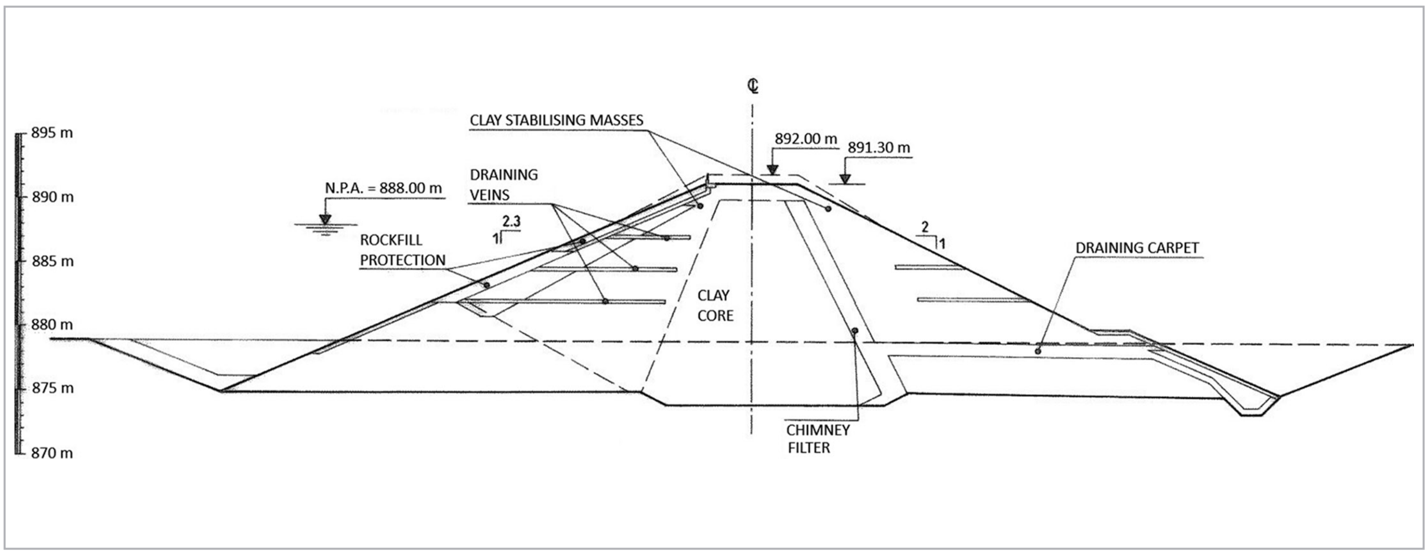

Figure 2 - typical Cross Section od Iraí Dam. Source: COBA, 1996.

The first is the Iraí dam (Figure 2), located in the metropolitan region of Curitiba. It is an earth dam, with 19 meters height, 1.220 meters of crest extension, and 58 hm³ of reserve volume, built-in 1999 to comprise the SANEPAR water supply network. The second is the Jordan River Derivation dam in Reserva do Iguaçu (Figure 3). It is a gravity concrete dam built in Roller Compacted Concrete (RCC), with 73 meters height, 550 meters of crest extension, and 109.9 hm³ of reserve volume. It began to operate in 1997 to generate electricity.

All methodology stages were successfully completed for the Iraí dam, as shown in Table 5 and 6, with extensive documentation on design, construction, and operation being consulted. A deterministic stability analysis was conducted on twenty-one cross-sections. All of them yielded Safety Factor (SF) higher than the stability requirements recommended by Eletrobras (2003) for dams, as shown in Table 3. The loading cases considered were: the end of construction, reservoir filling, variations in operational levels, and rapid drawdown.

The information collected on Iraí dam made it possible to conduct a stability analysis with a probabilistic approach using the simplified Bishop method and the Monte Carlo simulation. For probabilistic analysis, three cross sections were selected according to their geometric arrangement, representing three typical dam sections.

A convergence test was performed, and it found the ideal number of repetitions of 100 thousand Monte Carlo simulations. For all materials involved in the dam stability analysis, averages (μ) and standard deviations (σ) were calculated, as shown in Table 4. The specific weight was assigned to the normal probabilistic distribution, while the effective cohesion and friction angle was assigned to the log-normal distribution. Additionally, an inverse proportion correlation was considered between the effective cohesion and friction angle.

Table 3 - Results of deterministic stability analysis for Iraí dam.

Cross-section	Minimal SF	Cross-section	Minimal SF
P0	3.9	**P11**	1.1
P1	1.9	**P12**	1.1
P2	1.4	**P13**	1.2
P3	1.3	**P14**	1.1
P4	1.3	**P15**	1.1
P5	1.1	**P16**	1.3
P6	1.1	**P17**	1.3
P7	1.1	**P18**	1.3
P8	1.1	**P19**	1.3
P9	1.2	**P20**	1.3
P10	1.1	**P21**	2.0

Source: adapted from Czap (2022).

Table 4 - Averages and Standard Deviations of the materials for Iraí Dam.

Material	Specific Weight (kN/m³)		Effective Cohesion (kPa)		Friction Angle (°)	
	μ	σ	μ	σ	μ	σ
Silt clay	20	0.65	10	8.9	30	2.62
Filters	19	1.79	0	0.74	35	4.61
Sandstones	16	1.79	0	0.74	20	4.61
Drains	20	1.79	0	0.57	36	6.17
Rockfills	19	1.79	0	0.57	36	6.17

Source: adapted from Czap (2022).

The material's probabilistic behavior was determined based on all documented surveys conducted since the pre-project phase. According to the ANCOLD standard (ANCOLD, 2003), the probabilistic approach yielded acceptable rupture probabilities for the submitted sections. The rapid drawdown scenario was the worst-case loading condition, and cross-sections P5, P11, and P14 exhibited probabilities of rupture less than $1{,}0.10^{-7}$.

The analysis of stage 7 for the Iraí dam determined that the auxiliary structures have a negligible impact on the dam's stability. Hence, a three-dimensional analysis was deemed unnecessary to evaluate the overall stability of the dam.

In the proposed methodology's final stages (8 to 10), the study examined documents, such as the Periodic Inspection Report, Risk Analysis, PSB, and PAE. Additionally, the study identified various measures outlined in the documents provided by the entrepreneur of the Iraí dam, including the identification of pathological manifestations, maintenance planning, periodic monitoring of instrumentation, and systematic analysis of the dam's behavior.

Table 5 - Form of the proposed methodology to Iraí dam - Stages 1 to 5.

STAGE						
STAGE 1	IDENTIFICATION					
	Of ENTREPRENEUR			Of INSPECTOR		
	SANEPAR			ANA		
	Basic data:		What is the type of dam?		What type of foundation?	
	Height	19 m		Concrete		Soft ground
	Reserve volume	58 hm^3	X	Earth	X	Solid ground
	Use(s)	supply		Tailing		Fractured rock
	Age	24		Mixed	X	Sane rock
	Was there any major structural maintenance?		Other		Is there treatment on the foundations?	
	No				Yes	

STAGE						
STAGE 2	DATABASE					
	X	Pre-design	X	Basic design		Executive design
		Work diary(s)	X	As-built	X	Maintenance reports
	Is the volume of information sufficient to determine the parameters of the dam materials?					
	Yes			No		
	Proceed to the next step			Collect more information		

STAGE										
STAGE 3	MATERIALS									
	Which parameters of the dam materials have their complete definitions?									
	Soil(s)		Concrete(s)		Land(s)		Rock(s)		Other(s)	
	Specific weight	X	Specific weight		Specific weight	X	Specific weight	X	Specific weight	
	Cohesion	X	Cohesion		Cohesion	X	Cohesion	X	Cohesion	
	Angle of friction	X	Coefficient of friction		Angle of friction	X	Coefficient of friction	X	Coefficient of friction	
	Permeability coefficient	X	Permeability coefficient		Permeability coefficient	X	Permeability coefficient	X	Permeability coefficient	

STAGE										
STAGE 4	LOADINGS									
	Do the load cases below have their full definitions?									
	End of construction		First filling		Rapid drawdown		Earthquakes			
							Vertical acceleration		Horizontal acceleration	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	Permanent percolation								Cascade effect	
	Minimum water level		Normal water level		Maximum water level		Maximorum water level			
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No

STAGE										
STAGE 5	STABILITY									
	Is there sufficient information to analyze the stability of the dam?									
	Sliding		Toppling		Support capacity of foundations		Internal stresses		Effectiveness of filters and drains	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	What is the nature of the stability analysis, based on the available data, that can be performed?									
	Deterministic					Probabilistic				

Source: Own authorship.

Table 6 - Form of the proposed methodology to Iraí dam - Stages 6 to 10.

STAGE 6										
	INSTRUMENTATION									
	Indicate the number of instruments, in full operation, installed in the dam.									
	Inclinometer		Piezometer	57	Flowmeter		Load cell		Surface frame	
	Inverted plumb		Pore pressure cell		Displacement plate		Seismograph	1	Accelerometer	
	Joint gauge		Deformimeter		Tensometer		Thermometer		Other	
	Is the existing instrumentation system in the dam sufficient for the correct monitoring of its safety?				The existing instrumentation system at the dam is:					
	Yes		No		Manual		Semi-automated		Automated	

STAGE 7				
	AUXILIARY STRUCTURES			
	What auxiliary structures are present in the dam?			
	Spillway		Bottom downloader	X
	Powerhouse		Bypass tunnel	
	Water intake	X	Floodgates	
	Others		Others	
	Can auxiliary structures compromise the stability and/or safety of the dam?			
	Yes		No	
			If yes, new computational modeling must be performed.	

STAGE 8			
	DAM SAFETY		
	Does the dam developer have the following reports and documents?		
	Periodic inspection report	Yes	No
	Risk analysis	Yes	No
	Dam Safety Plan (PSB)	Yes	No
	Emergency Action Plan (PAE)	Yes	No
	Communication plans	Yes	No
	Others		

STAGE 9			
	OPERATION		
	Does the dam entrepreneur have an operations routine that includes the following actions?		
	Identification of pathological manifestations	Yes	No
	Maintenance planning	Yes	No
	Periodic reading of instructions	Yes	No
	Periodic analysis of the dam's behavior	Yes	No
	Others		

STAGE 10			
	INTERVENTION OR DE-CHARACTERIZATION		
	Does the dam entrepreneur have a dam de-characterization plan that contains the following information?		
	Environmental management plan	Yes	No
	Risk acceptability limit	Yes	No
	Perpetual monitoring plan	Yes	No
	Definition of the useful life of the enterprise	Yes	No
	Others		

Source: Own authorship.

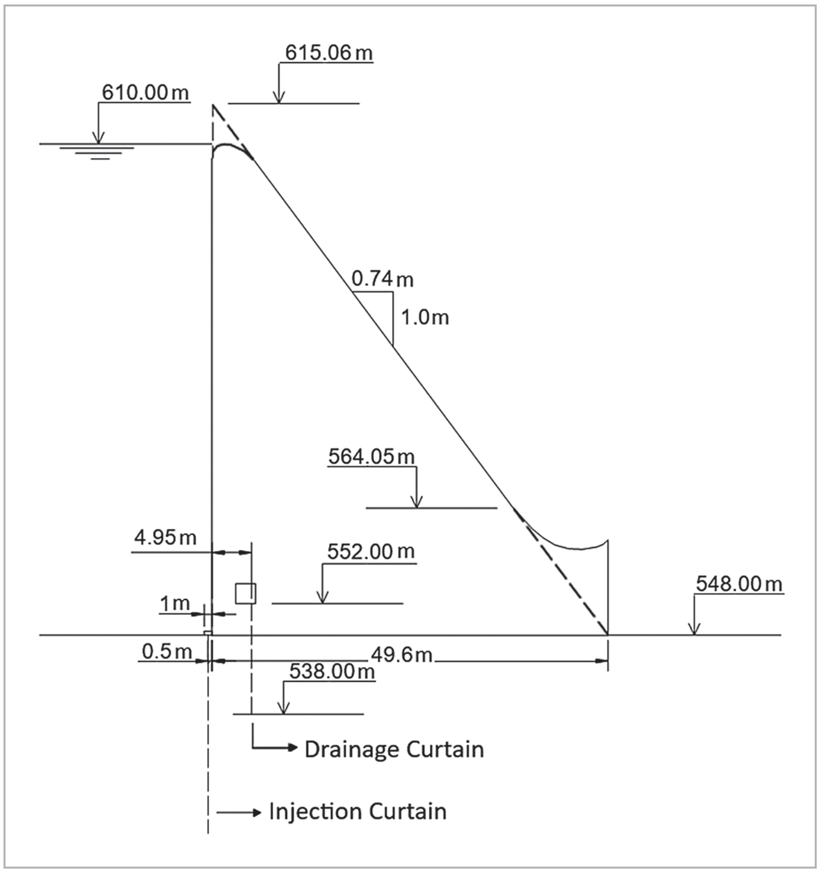

Figure 3 - Typical Cross Section of Jordan River Derivation Dam. Source: Levis, 2006.

Example 2: Rio Jordan Derivation dam

For the Rio Jordan Derivation dam, as shown in Table 7, Steps 1 to 4 of the proposed methodology involved gathering information about the dam from various sources, including Levis (2006), Andriolo, Mussi, and Oliveira (1998), COPEL (2021), and Krüger (2008). Based on this information, the author conducted a stability analysis using a typical cross-section.

The stability analysis concerning the sliding, floating, and toppling of the dam's contact with the foundation was conducted based on the loading conditions. The SF values obtained attest to the dam's stability from the statically analyzed conditions, providing values above those established by Eletrobras (2003).

To conduct the probabilistic analysis, standard deviation values were employed for several parameters, including the specific weight of the concrete, the specific weight and internal friction angle of the sediment in the reservoir, and the friction angle between the concrete and rock in the foundation.

The convergence test determined that the optimal number of Monte Carlo simulations was seven thousand, and the analysis yielded satisfactory results, with rupture probabilities smaller than 10^{-6}.

Although Stages 6 and 7 could not be executed due to a lack of information, as shown in Table 8, the final stages (8, 9, and 10) of the proposed methodology were applied to the Rio Jordan Derivation dam assuming that crucial documents existed. In doing so, the study relied on information sourced from previous works. (Levis, 2006; Andriolo, Mussi, and Oliveira, 1998; Copel, 2021 and Krüger, 2008).

Table 7 - Form of the proposed methodology to Rio Jordan Derivation dam - Stages 1 to 5.

STAGE 1	IDENTIFICATION					
	Of ENTREPRENEUR			Of INSPECTOR		
	COPEL			ANEEL		
	Basic data:		What is the type of dam?		What type of foundation?	
	Height	73 m	X	Concrete		Soft ground
	Reserve volume	109.9 hm^3		Earth		Solid ground
	Use(s)	electrical energy generation		Tailing		Fractured rock
	Age	26		Mixed	X	Sane rock
	Was there any major structural maintenance?		Other		Is there treatment on the foundations?	
	No				Yes	

STAGE 2	DATABASE					
		Pre-design		Basic design		Executive design
		Work diary(s)		As-built		Maintenance reports
	Is the volume of information sufficient to determine the parameters of the dam materials?					
	Yes			No		
	Proceed to the next step			Collect more information		

STAGE 3	MATERIALS									
	Which parameters of the dam materials have their complete definitions?									
	Soil(s)		Concrete(s)		Land(s)		Rock(s)		Other(s)	
	Specific weight		Specific weight	X	Specific weight		Specific weight	X	Specific weight	
	Cohesion		Cohesion	X	Cohesion		Cohesion	X	Cohesion	
	Angle of friction		Coefficient of friction	X	Angle of friction		Coefficient of friction	X	Coefficient of friction	
	Permeability coefficient		Permeability coefficient	X	Permeability coefficient		Permeability coefficient	X	Permeability coefficient	

STAGE 4	LOADINGS									
	Do the load cases below have their full definitions?									
	End of construction		First filling		Rapid drawdown		Earthquakes			
							Vertical acceleration		Horizontal acceleration	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	Permanent percolation								Cascade effect	
	Minimum water level		Normal water level		Maximum water level		Maximorum water level			
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No

STAGE 5	STABILITY									
	Is there sufficient information to analyze the stability of the dam?									
	Sliding		Toppling		Support capacity of foundations		Internal stresses		Effectiveness of filters and drains	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
	What is the nature of the stability analysis, based on the available data, that can be performed?									
	Deterministic					Probabilistic				

Source: Own authorship.

Table 8 - Form of the proposed methodology to Rio Jordan Derivation dam - Stages 6 to 10.

<table>
<tr><td rowspan="6">STAGE 6</td><td colspan="10">INSTRUMENTATION</td></tr>
<tr><td colspan="10">Indicate the number of instruments, in full operation, installed in the dam.</td></tr>
<tr><td>Inclinometer</td><td></td><td>Piezometer</td><td></td><td>Flowmeter</td><td></td><td>Load cell</td><td></td><td>Surface frame</td><td></td></tr>
<tr><td>Inverted plumb</td><td></td><td>Pore pressure cell</td><td></td><td>Displacement plate</td><td></td><td>Seismograph</td><td></td><td>Accelerometer</td><td></td></tr>
<tr><td>Joint gauge</td><td></td><td>Deformimeter</td><td></td><td>Tensometer</td><td></td><td>Thermometer</td><td></td><td>Other</td><td></td></tr>
<tr><td colspan="4">Is the existing instrumentation system in the dam sufficient for the correct monitoring of its safety?</td><td colspan="6">The existing instrumentation system at the dam is:</td></tr>
<tr><td></td><td colspan="2">Yes</td><td colspan="2">No</td><td colspan="2">Manual</td><td colspan="2">Semi-automated</td><td colspan="2">Automated</td></tr>
<tr><td rowspan="9">STAGE 7</td><td colspan="10">AUXILIARY STRUCTURES</td></tr>
<tr><td colspan="10">What auxiliary structures are present in the dam?</td></tr>
<tr><td colspan="4">Spillway</td><td></td><td colspan="4">Bottom downloader</td><td></td></tr>
<tr><td colspan="4">Powerhouse</td><td></td><td colspan="4">Bypass tunnel</td><td></td></tr>
<tr><td colspan="4">Water intake</td><td></td><td colspan="4">Floodgates</td><td></td></tr>
<tr><td colspan="4">Others</td><td></td><td colspan="4">Others</td><td></td></tr>
<tr><td colspan="10">Can auxiliary structures compromise the stability and/or safety of the dam?</td></tr>
<tr><td colspan="5" rowspan="2">Yes</td><td colspan="5">No</td></tr>
<tr><td colspan="5">If yes, new computational modeling must be performed.</td></tr>
<tr><td rowspan="9">STAGE 8</td><td colspan="10">DAM SAFETY</td></tr>
<tr><td colspan="10">Does the dam developer have the following reports and documents?</td></tr>
<tr><td colspan="8">Periodic inspection report</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Risk analysis</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Dam Safety Plan (PSB)</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Emergency Action Plan (PAE)</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Communication plans</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="10">Others</td></tr>
<tr><td colspan="10"></td></tr>
<tr><td rowspan="8">STAGE 9</td><td colspan="10">OPERATION</td></tr>
<tr><td colspan="10">Does the dam entrepreneur have an operations routine that includes the following actions?</td></tr>
<tr><td colspan="8">Identification of pathological manifestations</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Maintenance planning</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Periodic reading of instructions</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Periodic analysis of the dam's behavior</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="10">Others</td></tr>
<tr><td colspan="10"></td></tr>
<tr><td rowspan="8">STAGE 10</td><td colspan="10">INTERVENTION OR DE-CHARACTERIZATION</td></tr>
<tr><td colspan="10">Does the dam entrepreneur have a dam de-characterization plan that contains the following information?</td></tr>
<tr><td colspan="8">Environmental management plan</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Risk acceptability limit</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Perpetual monitoring plan</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="8">Definition of the useful life of the enterprise</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="10">Others</td></tr>
<tr><td colspan="10"></td></tr>
</table>

Source: Own authorship.

4. Conclusions

This article proposed a methodology for identifying faults in dam safety activities, which is integrated by ten verification stages and three levels of detail that indicate the volume of relevant technical information available for the investigation of the safety of a dam.

The Iraí dams and the Jordan River Derivation dams were used as examples and proved to be notorious in terms of the technical, social, and environmental responsibility of the entrepreneurs (SANEPAR and COPEL).

As all necessary information for the Iraí dam is available in the SNISB, all documents required by the PNSB are developed. The Operation and Maintenance Manual satisfies the requirements established in stage 9 of the methodology. The SANEPAR technical staff demonstrates an understanding of the importance of continuous monitoring and maintenance interventions when indicated by the analyses, taking responsibility for the safety of the dams. As a result, no safety breaches were detected in the Iraí dam. The proposed methodology assigned Level 3 (INFORMED) to the Iraí dam.

In the example of the Rio Jordan Derivation dam, values could be assigned based on other academic or technical publications. This demonstrates that the probabilistic approach can be used even when there is little or no documentation describing the construction and foundation materials of the dam under study.

Although the lack of available information prevented the completion of stages 6 to 10, the stability of the Rio Jordan Derivation dam was still evaluated. Based on the study, it was concluded that the dam is stable. However, full fault in safety detection could not be accomplished, as the methodology could only progress to stage 5.

Regarding the Jordan River Derivation dam, it was observed that it had no outstanding issues before its inspection and the SNISB, given to it Level 2 (STABLE).

The stability analyses of the two dams under study have demonstrated that the probabilistic approach can be utilized despite limited information concerning investigations or control measures during the dam's construction.

As for risk analysis, quantifying the consequences of a negative event, such as the rupture of a dam, can be a complex task, since it is not always associated with a monetary cost, but loss of life, physical damage or environmental impacts (Czap, 2022). In this sense, current legislation, based on risk analysis, requires minimum documentation to ensure risk management. In addition to the documentation required by law, the correct and sufficient characterization of the construction and foundation materials of the dams is important. Only with reliable data can risk analysis be performed.

For the proposed methodology, it is necessary to massively apply it to the most diverse types and sizes of dam, and for this, it is possible, for example, to use the data available at SNISB. Applying the proposed methodology is a helpful tool, especially for inspectors, aiming at a more effective registration process, accelerating the completion of the SNISB.

A professional, external, specialized engineer should conduct safety analyses of a dam and include the disciplines of hydrology, geology, and engineering, all relevant to dam safety issues (Adamo *et al*., 2021).

This author emphasizes the importance of an engineer with specific training and experience in dam safety being at the forefront of decision-making. This critical analysis, necessary for the planning and execution of interventions in dams, can be carried out by a trained professional or a group of professionals who add to their knowledge. However, what should be emphasized is that these professionals must have their training ensured by government bodies such as ANA, which has a range of courses that have been offered frequently, evidencing the development of the PNSB in the country.

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