Application of Risk Analysis Methods on Tailings Dams

T. Espósito, L.R. Palmier

Abstract. One of the procedures adopted in a Safety Management System is the use of Risk Analysis for which analytical, iterative, descriptive and qualitative methods, such as the FMEA "Failure Modes and Effects Analysis", have been applied in order to identify and analyse potential failures from a given failure mode, its causes and consequences, as well as the means of detection and prevention of failure modes and mitigation of their effects. In Brazil the FMEA method has been used to evaluate the safe conditions of tailings dams. On the other hand a specific tool for the Risk Analysis of dams, the LCI "Analysis by Diagrams Location, Cause and Failure Indicators" semi-quantitative method, has been developed and in the United Kingdom under the name of "Risk Management for UK Reservoirs" and applied in Europe but not for tailings dams. Recently the LCI MOD-REJ version – an adaptation of the LCI method – has been proposed and applied to one Brazilian tailings dam to explicit deal with the Risk Analysis of this type of structure. Considering the promising results of the former application, the aim of this paper is to evaluate the LCI MOD-REJ version applicability and efficiency by comparing the results of its and the FMEA method applications to two Brazilian tailings dams.

Keywords: tailings dams, risk analysis, LCI, LCI MOD-REJ, FMEA, safety management.

1. Introduction

Tailings are the inevitable consequences of the ore treatment processes, being generated in parallel to the product of interest. Nowadays, these tailings are produced in large amounts, affecting qualitatively and quantitatively the environment. The large production of tailings has generated a growing concern in companies that seek to minimize environmental impacts and costs associated with the processes of containment and disposal of this material. Thus, the tailings have been the subject of great interest of mining companies, which have been looking for inexpensive and safe alternative disposal of these materials. Among the various methods, the deposition of tailings surface using containment of tailings dams has been a preference of Brazilian mining companies. Such dams may be constructed in stages, with successive and raisings over time and in many cases the tailings may constitute the building material (Esposito, 2000). Nonetheless, tailings dams failures continue to occur despite the modern technology available for their design, construction and operation. The consequences of these failures have been economic losses and environmental degradation, and, in many cases, loss of human life. The main causes of the failures include, in some cases, complex geotechnical characteristics that require special care to overcome the adverse conditions.

However, the causes are also possible situations to be solved with the use of already available technologies. This demonstrates the necessity of a more systematic application of the current specialized knowledge. In this sense, "Tailings Dams Engineering" must act in the design, construction, operation, monitoring and maintenance, as well as in emergency situations, and deactivation and decommissioning of tailings dams. The dam security can be achieved in the light of an effective Safety Management. In this context it is worth the use of the Risk Analysis procedure on the Safety Management System of Tailings Dams, which aims to estimate the probabilities of failure events of the components or system and the magnitude of the consequences. However, that application in Geotechnics is not common, although users of this tool in conventional dams (except tailings dams) perceive an increase in the practice of these structures safety, as well as a better understanding of their behaviour. It is concluded that the Risk Analysis in Geotechnics, although not yet a routine application, can be extremely useful in works whose potential risks are high and associated with important consequences such as in tailings dam, as it allows to manage the risks efficiently.

In light of these considerations the aim of this paper is to discuss the application of two Risk Analysis methods, the FMEA and an adapted version of the LCI method (LCI MOD-REJ), to two Brazilian tailings dams.

2. Principles and Procedures of the LCI Method "Analysis by Diagrams Location, Cause and Failure Indicators"

In the past, risk assessment methodologies, as developed for use in other industries, have not been applied to dams and reservoirs on a regular basis. According to Hughes *et al.* (2000), this fact can be explained by the following reasons: the data inadequacy, the uniqueness nature of each dam, the complex interactions involved in the dam behaviour, the wrong perception of negligible risk of dam failure, the concern about the cost of risk assessment, the scepticism, the difficulties of understanding or applying the

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output resulting from any form of risk assessment, and, finally, the lack of knowledge of risk assessment techniques by the dam community. According to Hughes *et al.* (2000), the application of risk assessment should help to improve existent dam and reservoir safety, would be useful in identifying the potential consequence of failure and would allow risk classification of reservoirs and prioritization of the future interventions. It is essential that the dam risk assessment should include the primary mechanisms associated with dam incidents and failures, such as seepage/internal erosion, overtopping, instability/overstress, and settlement/deformation. In this context, taking into account the failure mechanisms and the actual maintenance of the embankment dams with different ages, the LCI method was developed for scoring the individual hazard, vulnerability and acquired knowledge of those structures, constituting one phase of a risk portfolio assessment.

The Location, Cause and Indicator (LCI) diagrams have been used for the risk assessment of reservoirs in the United Kingdom, specifically for risk analysis of dams with storage volumes greater than or equal to 25,000 m^3. These three diagrams include the location of the dam component under study, the cause of failure of that component and signs or evidences (indicators) of failure effects in terms of the response of the system, and exclude the consequences evaluation. As an example, Pimenta *et al.* (2005) and Pimenta (2009) discussed the application of this method in Portugal, but without considering tailings dams, which is one of the aims of the current paper.

2.1. Principles and procedures of the LCI Method

Hughes *et al.* (2000) produced a series of Location, Cause, Indicator (LCI) Diagrams, based on known failure modes of different types of dams and on historical data and engineering judgment of existing dams in order to assist the FMECA (Failures Mode, Effects and Criticality Analysis) process in the risk assessment. Each LCI diagram analysis is performed on the basis of the dam characteristics, such as: type (concrete or embankment), height (less than 15 m, 15-30 m, greater than 30 m) and age (pre 1840, between 1840 and 1960, post 1960).

It should be noted that the FMECA complements the FMEA (Failure Modes and Effects Analysis) and is a systematic approach to analyse how a system can fail (failure mode), to determine the effects associated to each failure mode and to assess the likelihood of its occurrence and the severity of its effects to the system operation, through a criticality index, in other words, how critical that type of failure will be to the operation of the system.

Hughes *et al.* (2000) related that to characterize the causes and the indicators three score categories were used (scores from 1 to 5):

i Effects or consequences in the system (Cons.) to reflect the way as the failure of the element is directly related to complete (or partial) failure of the dam;

ii Likelihood (Like.) corresponding to the likelihood of the failure of the element;

iii Confidence degree (Conf.) of the analyst in its consequences and likelihood estimatives, to take into account the uncertainty in knowledge of the dam or of its components; this factor allows the consideration of an uncertainty measure.

During the process, the consequences in the downstream valley are evaluated through a Global Impact Index (GII) and the product of the score of each category (Cons., Like. and Conf.) gives a Criticality index for each set of causes or indicators of problems related to dam elements. The product of those indexes (Criticality index and Global Impact Index) gives the risk score.

Outputs include Location, Cause, Indicator (LCI) Diagram, indicating problematic areas and a list of criticality and risk scores associated with specific problem causes and indicators, allowing prioritisation of resources for single or multiple sites. The stages of this method are:

Stage 1: Impacts evaluation, that includes: information gathering, site visit, prediction of discharge and potential floodwater levels caused by dam failure, assessment and scoring of specific impacts from flooding and combination of scores.

Stage 2: Calculation of the Global Impact Index by the reduction of the different impact scores to a single value impact.

Stage 3: Development and application of LCI diagrams by considering the components of a dam and its contribution to its possible failure. Dam failure with different causes and with different indicators is considered. A criticality score is calculated for each cause/indicator element thus accreting for the overall dam safety.

In the first stage, information is collected along a stretch of 30 km in the downstream valley, including the main characteristics of land occupation, structures and infrastructure, and environmental resources. It is recommended to perform an inspection visit to the near valley along the first 5 km from the dam.

The identification of consequences involves the estimative of the discharge at the dam section, the rupture time and the levels reached by the flood wave in the valley sections previously defined. In order to achieve this, numerical models of dam-break type or simplified techniques are used for calculations of the hydrographs along the valley, as described by Hughes *et al.* (2000). Once the occupation of the valley and the downstream water levels, as affected by the flood wave, are estimated, stage 2 is initiated with the evaluation of the Global Impact Index (GII) by a weighted combination of the potential loss of human life (PLL) and economic losses (EL), along the near valley (first 5 km) and the remaining valley (until 30 km).

To calculate the PLL, the number of people at risk (PAR) is calculated taking into account the types of land occupations, *i.e.*, residential properties, non-residential properties, transportation infrastructure and recreational sites potentially affected by the flood, and considering the estimates presented in Table 1. In formal terms, the PLL is calculated by the following equations:

$$\text{PLL} = 0.5\ \text{PAR (near valley)} \tag{1}$$

$$\text{PLL} = \text{PAR}^{0.6}\ \text{(far valley)} \tag{2}$$

The figure for the EL is obtained from the weighted sum of the scores associated with losses in the near and in the far away valleys. In this context, the following weights are used: 0.15 for residential properties; 0.15 for non-residential properties; 0.10 for transportation infrastructure; 0.05 for recreational sites; 0.25 for industrial sites; 0.25 for utilities; and 0.05 for agriculture areas and natural habitats.

The GII is then determined by this equation:

$$\text{GII} = 100\ \text{EL}_{<5\,\text{km}} + \text{PLL}_{<5\,\text{km}} + 30\ \text{EL}_{5\text{-}30\,\text{km}} + \text{PLL}_{5\text{-}30\,\text{km}} \tag{3}$$

After calculating the GII, the next step (stage 3) is to classify the causes and subsequent effects through the application of the LCI diagrams, in order to estimate and classify the Ordination, Confidence, Criticality and Risk indexes.

The causes and the failure indicators are classified within a scale ranging from 1 to 5 by using the previously described three attributes: i) Consequences on the dam (Cons. 1 low, 5 high); ii) Likelihood (Like. 1 low, 5 high); and iii) degree of Confidence (Conf.) (5 low, 1 high).

According to Hughes *et al.* (2000), Caldeira (2005), Pimenta *et al.* (2005) and Pimenta (2009) after the classification of the attributes it is possible to calculate four indexes for each set Location/Cause/Indicator:

- Ordinance Index (Ind_{Ord}), as determined by the product of attributed ratings to the Consequence and Likelihood.
- Confidence Index (Ind_{Conf}), taken equal to the Confidence score.
- Criticality Index (Ind_{Crit}), defined by the product of the ratings assigned to the Consequence, Likelihood and Confidence.
- Risk Index (Ind_{Risk}), as determined by the product of Criticality Index and the Global Impact Index.

2.2. Proposal of a version of the LCI method for tailings dams (LCI MOD-REJ)

An adapted version of the LCI method – the LCI MOD-REJ version – has been proposed in order to adjust a former structure developed specifically for dams to an even more explicit one to focus on the risk assessment of tailings dams by including a "Tailings impoundment" item in the general analysis. The main aim of this adapted version is to identify the structural elements that most contribute for the total collapse of tailing dams. So far the LCI MOD-REJ version was applied to just one Brazilian tailings dam with promising results – Esposito *et al.* (2011a) and Esposito (2011b). It is important to emphasize that the LCI MOD-REJ version does not constitute a new system as specific and common adaptations were considered over the LCI method.

Pimenta *et al.* (2005) emphasize that when GII is below 175 (from the original LCI method) it is not recommended to apply the second step of the original method and therefore there is no need to estimate the Ordinance Index (Ind_{Ord}), the Criticality Index (Ind_{Crit}), the Confidence Index (Ind_{Conf}) and the Risk Index (Ind_{Risk}). In the LCI MOD-REJ version, based on a more conservative approach, the failure modes and the rates of risk must always be estimated. Tailings dams do not always have effective construction control, which also occurs in stages, following the generation and disposal of tailings. These tailings, in turn, have characteristics that change over time, making the quality control of the construction even more necessary. As in practice, since there is not yet a systematic control for these structures, especially in small and medium-sized mining companies, the suggestion is to always apply the proposed LCI MOD-REJ version following the three mentioned stages.

Another aspect is that LCI MOD-REJ diagrams considered the item "Location" with its subdivisions "Dam body, foundations and abutments" and "Spillway and its components", like the original LCI method, adding, as mentioned before, the "Tailings impoundment" subdivision.

3. Principles and Basic Procedures of the "Failure Modes And Effects Analysis" (FMEA) Method

In order to evaluate the LCI MOD-REJ version applicability and efficiency it is proposed a comparison of the results from its application with those from the use of the FMEA method, a much diffused one, to two Brazilian tailings dams. In this item only the basic procedures of the latter method will be shown as it is very well known and has been normally applied by Brazilian mines companies in the evaluation of the risk assessment on tailings dams. The FMEA method is a technique suited to define, identify and analyze potential failures from a given failure mode, its causes and consequences of effects, as well as the means of detection and prevention failure modes and mitigate their effects. To apply the FMEA method it is important to constitute a group of people to identify the product/process in question, in order words, to identify the system with its elements considering theirs functions, the types of failures that can occur, the effects and possible causes of this failure in each element (Hartford & Baecher, 2004).

The FMEA method can be conducted primarily in six steps (Caldeira, 2005 and Santos, 2006): (i) Structuring the system; (ii) Definition of features/requirements of each system component; (iii) Identification of potential failure modes associated with each function of each component; (iv) Identification of potential causes; (v) Description of the direct effects, and other components in the system; and (vi)

Table 1 - Economic losses (PE) and people at risk estimated PAR (Hughes *et al.*, 2000).

Impact 1 – Residential properties			
Properties flooded	Number of properties flooded	Score	PAR
None	0	0	0
Minor	1 to 15	1	30
Appreciable	16 to 50	2	100
Significant	51 to 250	3	500
Major	> 250	4	2 x estimate
Impact 2 – Non-residential properties			
Disruption	Number of people affected	Score	PAR
None	0	0	0
Minor	1 to 150	1	150
Appreciable	151 to 500	2	500
Significant	501 to 1000	3	1000
Major	> 1000	4	Estimate
Impact 3 – Transportation infrastructure			
Disruption	Infrastructures affected	Score	PAR
None	None	0	0
Minor	Minor roads only	1	25
Appreciable	Major regional	2	50
Significant	Major national	3	100
Major	Major international	4	Estimate
Impact 4 – Recreational sites			
Disruption	Number of people affected	Score	PAR
None	0	0	0
Minor	1 to 10	1	10
Appreciable	11 to 50	2	50
Significant	51 to 100	3	100
Major	> 100	4	Estimate
Impact 5 – Industrial sites			
Disruption	Type of industrial site	Score	
None	None	0	
Minor	Light industrial	1	
Appreciable	Public health industries	2	
Significant	Heavy industry	3	
Major	Nuclear petrochemical	4	
Impact 6 – Utilities			
Disruption	Impact on utilities	Score	
None	None	0	
Minor	Local loss of distribution	1	
Appreciable	Local loss of distribution/supply	2	
Significant	Regional loss of distribution/supply	3	
Major	Significant impact on national services	4	
Impact 7 – Agriculture/habitats			
Disruption	Type of site	Score	
None	Uncultivated/grassland	0	
Minor	Pasture	1	
Appreciable	Widespread farming	2	
Significant	Intensive farming/vulnerable natural habitats/monuments	3	
Major	Loss of internationally recognise habitats/monuments	4	

Identification of measures available to detect the causes or failure modes and to control or mitigate their effects. It is common to present the FMEA results by calculating the RPNi (Risk Priority Number) and elaborating the Risk Matrix.

4. Main Characteristics of the Tailings Dams A and B

The data used in the applications of the LCI (the LCI MOD-REJ version) and FMEA methods were based on actual information obtained from Tailings Dams A and B. Technical visits for visual inspection have been done and full dam-break studies were used to assess the floodplain in the downstream valley. The characteristics of both tailings dams are shown in Table 2. It should be noted that Tailings Dam A is currently receiving iron ore tailings differently from Tailings Dam B that is not receiving tailings and its reservoir is full of bauxite tailings.

5. Results and Discussions

5.1. Application of the LCI MOD-REJ diagrams

The purpose of applying the Location, Causes and Indicators of Failure diagrams is to identify and assess the failure modes in terms of likelihood and effects in the global system, based on exterior signs or deficiencies in the dam performance. This section illustrates the application of the LCI-MOD REJ diagrams to two tailings dam, named, in this paper, as Tailings Dam A and Tailings Dam B. Previously to the application of the LCI MOD-REJ diagrams, the GII was calculated. In the sequence, the causes and indicators of failures modes were classified according to the consequences (Cons.), likelihood (Like.) and confidence (Conf.) attributes (Figs. 1 and 2). Then, the following four indices were calculated: I_{Ord}, I_{Crit}, I_{Conf} and I_{Risk}.

The GII (Global Impact Index) was calculated considering the potential loss of lives (PLL) and the economic losses (EL), as estimated for the near downstream (< 5 km) and the far away valleys (5 to 30 km), as shown in Tables 3 and 4. The GII values are showed in Table 5.

The causes and indicators were classified according to three attributes (Figs. 1 and 2): Consequence (Cons.); Likehood (Like.); Confidence (Conf.).

The Tables 6 and 7 present the justification of the values of attributes. In addition, the four indices, Ordinance Index (Ind_{Ord}), Criticality Index (Ind_{Crit}), Confidence Index (Ind_{Conf}), and Risk Index (Ind_{Risk}), were calculated as shown in Table 8.

5.2. Tailings dams A and B: The LCI MOD-REJ diagrams results

The Tailings Dam A and B Safety Reports were consulted and both dams were visited in order to elaborate their LCI MOD-REJ Diagrams. In the Tailings Dam A the Safety Reports was consistently emphasized great concerns about the freeboard, which explains the highest value of the Risk Index (Ind_{Risk}) for overtopping presented in Table 8 for

Table 2 - Characteristics of Tailings Dams A and B.

Characteristics/Dam	Tailings Dam A	Tailings Dam B
Section	Homogeneous	Homogeneous
Function storage reservoir	Iron ore tailings	Bauxite tailings
Classification of tailings stored (according FEAM – State Foundation of Environment)	III	III
Downstream human occupancy	Medium	Medium
Downstream environmental interest	High	High
Concentration of facilities in the downstream area	High	Medium
Analysis	Stability flow	Stability flow
Final dam height (m)	53	64
Crest	Width: 7.50 m Length: 267.97 m	Width: 5.00 m Length: 145.0 m
Upstream slope	1V:2H	1V:2H
Downstream slope	1V:2H	1V:2H
Surface drainage system	Concrete channels on the verges	Concrete channel on the verges and cut-water on the abutments
Internal drainage system	Vertical sand filter type chimney connected to a horizontal drainage and a foot drain	Vertical sand filter connected to a horizontal drainage. It has drains at the bottom of the valley and on the abutments
Spillway system	Channel side	Stop logs
Final volume of the reservoir (m^3)	6.72×10^6	3.87×10^6

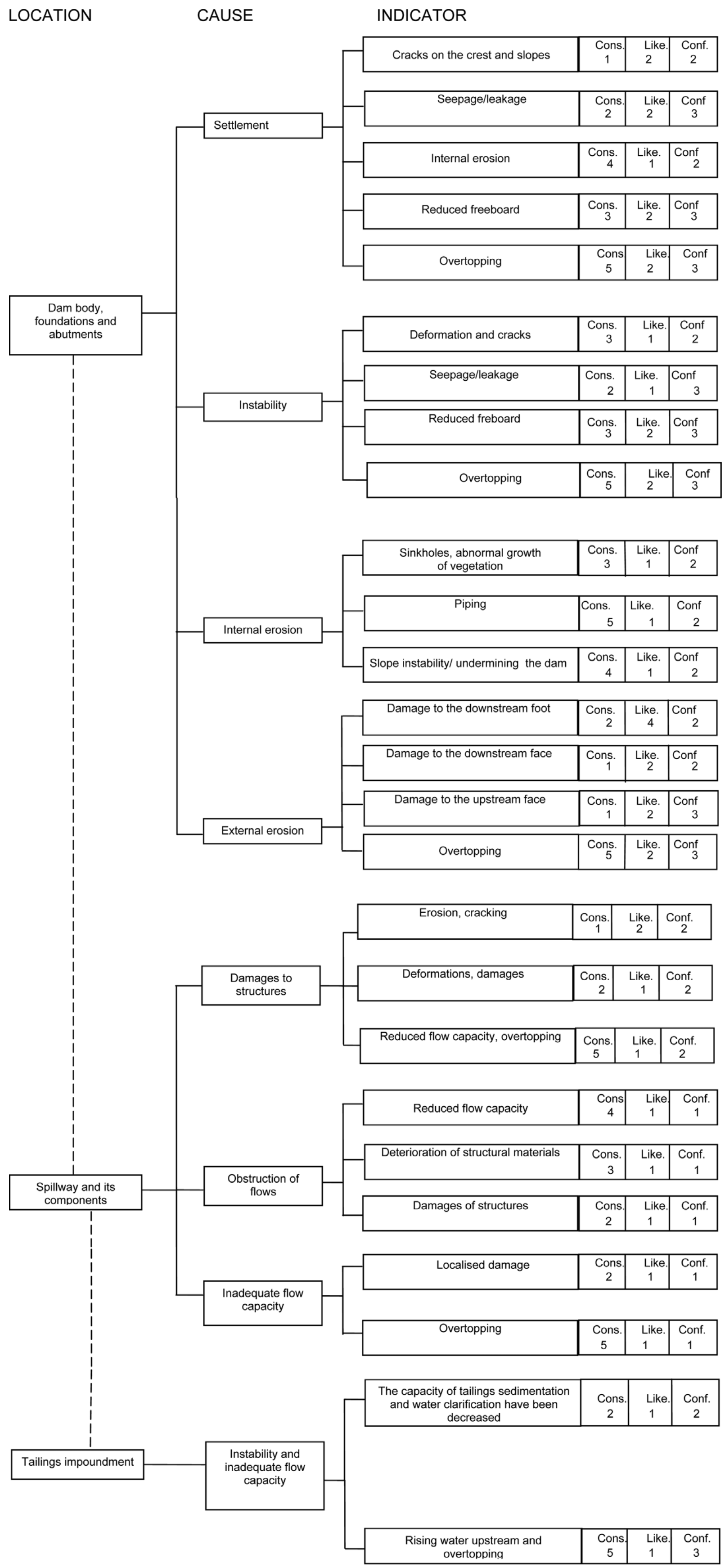

Figure 1 - Diagram LCI MOD-REJ Tailings Dam A - Attributes Consequence (Cons.), Likelihood (Like.) and Confidence (Conf.).

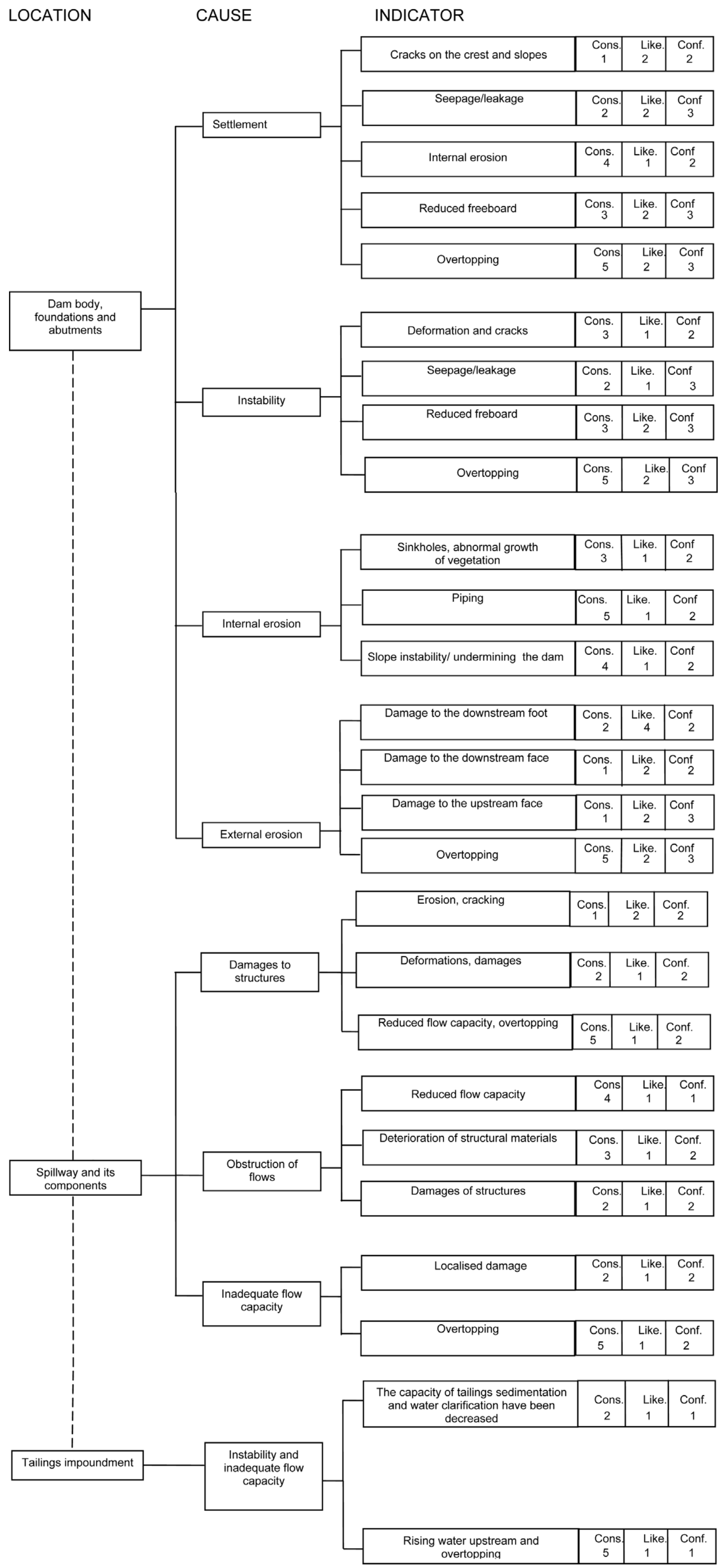

Figure 2 - Diagram LCI MOD-REJ Tailings Dam B - Attributes Consequence (Cons.), Likelihood (Like.) and Confidence (Conf.).

Table 3 - Near valley (< 5 km) – Tailings Dams A and B.

Impact	Dam A Impact score	Dam B Impact score	Value	Dam A Final score	Dam B Final score	Dam A *PAR*	Dam B *PAR*	Dam A *PLL*	Dam B *PLL*
1	4	4	0.15	0.60	0.60	600	800	300	400
2	2	3	0.15	0.30	0.45	500	1000	250	500
3	3	4	0.10	0.30	0.40	100	200	50	100
4	4	4	0.05	0.20	0.20	200	450	100	225
5	1	4	0.25	0.25	1.00	-	-		
6	2	2	0.25	0.50	0.50	-	-		
7	4	4	0.05	0.20	0.20	-	-		
Total				2.65	3.35			700	1225

Table 4 - Far valley (5 to 30 km) – Tailings Dams A and B.

Impact	Dam A Impact score	Dam B Impact score	Value	Dam A Final score	Dam B Final score	Dam A *PAR*	Dam B *PAR*	Dam A *PLL*	Dam B *PLL*
1	2	4	0.15	0.30	0.60	100	150000	16	1275
2	0	4	0.15	0	0.60	0	60000	0	736
3	4	4	0.10	0.40	0.40	10000	200	251	24
4	4	4	0.05	0.20	0.20	500	50000	42	658
5	4	4	0.25	1.00	1.00	-	-		
6	2	2	0.25	0.50	0.50	-	-		
7	4	4	0.05	0.20	0.20	-	-		
Total				2.60	3.50			511	2693

Table 5 - Global Impact Index – Tailings Dams A and B.

Tailings Dam A	GII = 1002.65 + 700 + 302.60 + 511 GII = 1554
Tailings Dam B	GII = 1003.35 + 1225 + 303.50 + 2693 GII = 4358

Dam A, although the probability of its occurrence is low. On the other hand the biggest concern for Tailings Dam B is due to internal erosion because it could generate a significant effect on this dam.

As no evidence of this phenomenon was detected, the probability of occurrence appears to be very small, especially considering the dam long operation time and the good practice used during its construction. However, as there are no monitoring devices, it has been assigned in this paper (Table 8) a high level for the Risk Index (Ind_{Risk}) for this indicator.

Another indicator associated with a high level for the Risk Index (Ind_{Risk}) for the Tailings Dam B was the overtopping. But it should be remembered that its probability of occurrence is low. It is interesting to note that the GII value is almost three times greater for Tailings Dam B than the same for Tailings Dam A even though the former is no longer in operation. This reflects the importance given by the method to the overall consequences on the downstream valley.

The determination of a threshold value for the Risk Index (Ind_{Risk}) may allow an overall picture over a state of alert. Considering the results for Dams A and B, just as an example, the Location/Cause/Indicator for Ind_{Risk} values greater than 40,000 are presented in Table 9. This could be considered a preliminary estimate and it is recommended the application of the method to a great number of tailings dams to make it possible to establish a more reliable reference number for this index.

5.3. Application of the FMEA method

This section illustrates the application of the FMEA method to two tailings dams, named, in this paper, as Tail-

Table 6 - LCI MOD-REJ Tailings Dam A - Justification of the values of Cons., Like. and Conf.

Location	Cause	Indicator	Justification
Dam body, foundations and abutments	Settlement	Cracks on the crest and slopes	No cracking observed.
		Seepage/leakage	No resurgences or wetlands observed, however the inspection was carried out in a dry season.
		Internal erosion	No internal erosion detected. There are no monitoring devices.
		Reduced freeboard	There is no evidence.
		Overtopping	There is no evidence; however there are no monitoring devices.
		Deformations and cracks	There is no evidence; however there are no monitoring devices.
	Instability	Seepage/leakage	There is evidence of vegetation, but no resurgences or wetlands. However, the inspection was carried out in a dry season.
		Reduced freeboard	There is no evidence of reduction of freeboard. The probability is small, but it is an important concern of the design related in the reports.
		Overtopping	There is no evidence; however there are no monitoring devices.
	Internal erosion	Sinkholes, abnormal growth of vegetation	There is evidence of vegetation, but no resurgences or wetlands. However, the inspection was carried out in a dry season.
		Piping	Considering that the dam was built following all the technical requirements and piezometers were installed, the piping probability is very small.
		Slope instability/undermining the dam	The instability of slopes could create the dam global destabilization, so the effect would be significant. The probability is very small, since the dam was built following all the technical requirements. However, there are no monitoring devices.
	External erosion	Damage to the downstream foot	The deterioration of the downstream foot caused by erosion external could generate instability in the dam.
		Damage to the downstream face	The deterioration of the downstream face would not cause significant effects on the dam. The probability of occurrence is very small.
		Damage to the upstream face	The deterioration of the downstream face would not cause significant effects on the dam. The probability of occurrence is very small.
		Overtopping	There is no evidence; however there are no monitoring devices.
Spillway and its components	Damages to structures	Erosion cracking	There is no evidence.
		Deformations damages	There is no evidence.
		Reduced flow capacity overtopping	There is no evidence.
	Obstruction of flows	Reduced flow capacity	There is no evidence.
		Deformations of structural materials	There is no evidence.
		Damages of structures	There is no evidence.
	Inadequate flow capacity	Localised damage	There is no evidence.
		Overtopping	There is no evidence.

Table 7 - LCI MOD-REJ Tailings Dam B - Justification of the values of Cons., Like. and Conf.

Location	Cause	Indicator	Justification
Dam body, foundations and abutments	Settlement	Cracks on the crest and slopes	No cracking observed
		Seepage/leakage	No resurgences or wetlands observed, however the inspection was carried out in a dry season.
		Internal erosion	No internal erosion detected. There are no monitoring devices.
		Reduced freeboard	There is no evidence.
		Overtopping	There is no evidence.
	Instability	Deformations and cracks	There is no evidence; however there are no monitoring devices.
		Seepage/leakage	There is evidence of vegetation, but no resurgences or wetlands. However the inspection was carried out in a dry season.
		Reduced freeboard	There is no evidence of reduction of freeboard.
		Overtopping	There is no evidence; however there are no monitoring devices.
	Internal erosion	Sinkholes, abnormal growth of vegetation	There is evidence of vegetation, but no resurgences or wetlands. However the inspection was carried out in a dry season.
		Piping	Considering that the dam was built following all the technical requirements and piezometers were installed, the piping probability is very small.
		Slope instability/undermining the dam	The instability of slopes could create the dam global destabilization, so the effect would be significant. The probability is very small, since the dam was built following all the technical requirements. However, there are no monitoring devices.
	External erosion	Damage to the downstream foot	There is no evidence.
		Damage to the downstream face	There is no evidence.
		Damage to the upstream face	The deterioration of the downstream face would not cause significant effects on the dam. The probability of occurrence is very small.
		Overtopping	There is no evidence; however there are no monitoring devices.
Spillway and its components	Damages to structures	Erosion, cracking	There is no evidence.
		Deformations, damages	There is no evidence.
		Reduced flow capacity, overtopping	There is no evidence.
	Obstruction of flows	Reduced flow capacity	There is no evidence.
		Deformations of structural materials	There is no evidence.
		Damages of structures	There is no evidence.
	Inadequate flow capacity	Localised damage	There is no evidence.
		Overtopping	There is no evidence.
Tailings impoundment	Instability and inadequate flow capacity	The capacity of tailings sedimentation and water clarification have been decreased	The effects caused by the non-sedimentation of the tailings and the non-clarification of the water are small. This dam is not in operation.
		Rising water upstream and overtopping	There is no evidence; however there are no monitoring devices. This dam is not in operation.

Table 8 - LCI MOD-REJ Tailings Dams A and B - Ordinance Index (Ind_{Ord}), Criticality Index (Ind_{Crit}), Confidence Index (Ind_{Conf}), and Risk Index (Ind_{Risk}).

Location	Cause	Indicator	Dam A Ind_{Ord}	Dam B Ind_{Ord}	Dam A Ind_{Crit}	Dam B Ind_{Crit}	Dam A Ind_{Conf}	Dam B Ind_{Conf}	Dam A Ind_{Risk}	Dam B Ind_{Risk}
Dam body foundations and abutments	Settlement	Cracks on the crest and slopes	2	1	4	2	2	2	6216	8716
		Seepage/leakage	4	2	12	4	3	2	18648	17432
		Internal erosion	4	4	8	8	2	2	12432	34864
		Reduced freeboard	6	3	18	6	3	2	27972	26148
		Overtopping	10	5	30	10	3	2	**46620**	**43580**
	Instability	Deformations and cracks	3	3	6	9	2	3	9324	39222
		Seepage/leakage	2	2	6	4	3	2	9324	17432
		Reduced freeboard	6	3	18	6	3	2	27972	26148
		Overtopping	10	5	30	10	3	2	**46620**	**43580**
	Internal erosion	Sinkholes abnormal growth of vegetation	3	3	6	6	2	2	9324	26148
		Piping	5	5	10	10	2	2	15540	**43580**
		Slope instability/undermining the dam	4	4	8	8	2	2	12432	34864
	External erosion	Damage to the downstream foot	8	2	16	2	2	1	24864	8716
		Damage to the downstream face	2	1	4	2	2	2	6216	8716
		Damage to the upstream face	2	3	6	9	3	3	9324	39222
		Overtopping	10	5	30	5	3	1	**46620**	21790
Spillway and its components	Damages to structures	Erosion, cracking	2	2	4	4	2	2	6216	17432
		Deformation, damages	2	2	4	4	2	2	6216	17432
		Reduced flow capacity, overtopping	5	5	10	10	2	2	15540	**43580**
	Obstruction of flows	Reduced flow capacity	4	4	4	4	1	1	6216	17432
		Deformations of structural materials	3	3	3	6	1	2	4662	26148
		Damages of structures	2	2	2	4	1	2	3108	17432
	Inadequate flow capacity	Localised damage	2	2	2	4	1	2	3108	17432
		Overtopping	5	5	5	10	1	2	7770	**43580**
Tailings impoundment	Instability and inadequate flow capacity	The capacity of tailings sedimentation and water clarification have been decreased	2	2	4	2	2	1	6216	8716
		Rising water upstream and overtopping	5	5	15	5	3	1	23310	21790

ings Dam A and Tailings Dam B. Firstly the Systems of the Tailings Dam A and B (Table 10) were defined. The dams are very similar, so the same system was used for both dams and only the item "1.1.6.4 Drain on the abutments" was incorporated in Tailings Dam B. For each element of the system the FMEA method incorporates its Function, Failure, Final Effect, Severity Index (Si), Cause, Occurrence Index (Oi), Control, Control Type, Detection Index (Di) and

Table 9 - Location/Cause/Indicator with associated Risk Index (Ind_{Risk}) higher than 40,000.

Location	Cause	Indicator
Dam body foundations and abutments	Settlement	Overtopping (Tailing Dam A and B)
	Instability	Overtopping (Tailing Dam A and B)
	Internal erosion	Piping (Tailing Dam B)
	External erosion	Overtopping (Tailing Dam A)

Table 10 - System of the Tailings Dams A and B

System of the Tailings Dams A and B	
1.1	Dam body
1.1.1	Crest
1.1.2	Core
1.1.3	Upstream slope
1.1.3.1	Free board
1.1.4	Downstream slope
1.1.5	Surface drainage system
1.1.5.1	Concrete channels
1.16	Internal drainage system
1.1.6.1	Bottom drain
1.1.6.2	Vertical filter
1.1.6.3	Foot drain
1.1.6.4	Drain on the abutments (only in Tailings Dam B)
1.2	Spillway system
1.3	Abutments
1.3.1	Abutment right
1.3.2	Abutment left
1.4	Foundation
1.5	Tailings impoundment

RPNi (Risk Priority Number). It is emphasized that the Severity Index (Si) shows how severe are the consequences (effects) of each failure mode, the Occurrence Index (Oi) shows how often occurs the cause of failure and the Detection Index (Di) shows what is the chance to be detected the cause of failure (Table 11). RPNi is equal to the product of Si, Oi and Di for each failure mode. The results are presented in Tables 12 and 13.

5.4. Tailings Dams A and B: the FMEA method results

The variation range for the RPNi numbers was from 4 to 225. The following criterion is proposed based on the RPNi values: 1 < RPNi < 50 Acceptable Risk; 50 < RPNi < 120 Tolerable Risk; and RPNi > 120 Intolerable Risk. The Table 14 shows the locations where the values of RPNi were greater than 120 (Intolerable Risk), to both dams.

Moreover the Risk Matrix may be plotted considering the Severity Index (Si) and the Occurrence Index (Oi). For the current cases both indexes would appear on the far left and higher positions, which can be interpreted as an alert situation. The critical items were “1.1.3.1 Free board” (Tailing Dam A) and “1.1.6.3 Foot drain” (Tailing Dam B).

Table 11 - Severity Index (Si), Occurrence Index (Oi) and Detection Index (Di).

Severity index (Si)		Occurrence index (Oi)		Detection index (Di)	
Si	Effect	Oi	Probability	Di	Probability
1	Very low	1	Improbable (0.1%)	1	Almost right
2 3	Low	2 3	Remote (0.1 to 1%)	2	Very high
4 5	Medium	4 5 6	Occasional (1 to 10%)	3	High
6 7 8	Severe	7 8 9	Probable (10 to 20%)	4	Moderately high
9	Very severe	10	Frequent (> 20%)	5	Moderate
10	Catastrophic			6	Low
				7	Very low
				8	Remote
				9	Very remote
				10	Almost impossible

Table 12 - FMEA Results: System of the Tailings Dam A.

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.1 Dam body									
Containment of tailings	Insufficient capacity to contain tailings	Global instability of the dam	10	Inadequacy of the project and/or construction	2	Adjustment of the project	Prevention	3	60
						Visual Inspection and Instrumentation	Detection		
1.1.1 Crest									
Allow access to dam	Not allow access to dam	Inability to carry out inspections	4	Inadequacy of the project and/or construction	2	Adjustment of the project	Prevention	1	8
						Visual Inspection	Detection		
1.1.2 Core									
Reduce the hydraulic conductivity	Excessive seepage	Piping	9	Alterability of the materials	2	Recompaction	Prevention	6	108
						Visual Inspection	Detection		
				Dissolution of the materials	4	Recompaction	Prevention	6	216
						Visual Inspection and Instrumentation	Detection		
				High hydraulic load increase the saturation line	4	Recompaction	Prevention	2	72
						Visual Inspection and Instrumentation	Detection		
				Hydraulic fracturing	2	Recompaction	Prevention	4	72
						Visual Inspection and Instrumentation	Detection		
1.1.3 Upstream slope									
Confer mechanical stability	Instability associated with movements of the soil mass	Global instability of the dam	10	Deficient compaction of the embankment	4	Adequacy of the geometry	Prevention	2	80
						Recompaction	Prevention		
						Instrumentation	Detection	6	120
				Alterability of the materials	2	Adequacy of the geometry	Prevention		
						Recompaction	Prevention		
						Visual Inspection	Detection		
	Excessive deformation	Overtopping	9	Alterability of the materials	2	Recompaction	Prevention	6	108
						Visual Inspection	Detection		
				Collapse	2	Recompaction	Prevention	3	54
						Visual Inspection and Instrumentation	Detection		
				Deficient compaction of the embankment	4	Recompaction	Prevention	2	72
						Visual Inspection and Instrumentation	Detection		
1.1.3.1 Free board									
Not allow over-topping of the dam	Allow overtopping of the dam	Overtopping	9	Inadequacy of the project and/or construction	7	Adequacy of the geometry	Prevention	1	63
						Adjustment of the project	Prevention		
						Visual Inspection and Instrumentation	Detection		
1.1.4 Downstream slope									
Confer mechanical stability	Instability associated with movements of the soil mass	Global instability of the dam	10	Deficient compaction of the embankment	4	Adequacy of the geometry	Prevention	2	80
						Recompaction	Prevention		
						Instrumentation	Detection	6	120
				Alterability of the materials	2	Adequacy of the geometry	Prevention		
						Recompaction	Prevention		
						Visual Inspection	Detection		
	External erosion	Local instability of the dam	5	Deficient compaction of the embankment	4	Recompaction	Prevention	2	40
						Visual Inspection and Instrumentation	Detection		
	Excessive deformation	Overtopping	9	Alterability of the materials	2	Recompaction	Prevention	6	108
						Visual Inspection	Detection		
				Deficient compaction of the embankment	4	Recompaction	Prevention	2	72
						Visual Inspection and Instrumentation	Detection		

Table 12 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.1.5 Surface drainage system									
Collect surface water that flow through the embankment	Insufficient capacity to collect surface water that flow through the embankment	Local instability of the dam	5	Inadequacy section	1	Structural maintenance of channels	Prevention	4	20
						Visual Inspection	Detection		
				Obstruction of channels	2	Unblocking of channels	Prevention	2	20
						Visual Inspection	Detection		
Collect surface water outside the dam	Insufficient capacity to collect surface water outside the dam	Local instability of the dam	5	Inadequacy section	1	Unblocking of channels	Prevention	4	20
							Detection		
				Obstruction of channels	2	Visual Inspection	Prevention	2	20
							Detection		
1.1.5.1 Concrete channels									
Collect the surface water that flow through the embankment	Insufficient capacity to collect surface water that flow through the embankment	Local instability of the dam	4	Inadequacy section	1	Structural maintenance of channels	Prevention	4	16
						Visual Inspection	Detection		
				Obstruction of channels	2	Unblocking of channels	Prevention	2	16
						Visual Inspection	Detection		
Collect the surface water outside the dam	Insufficient capacity to collect surface water outside the dam	Local instability of the dam	4	Inadequacy section	1	Unblocking of channels	Prevention	4	16
							Detection		
				Obstruction of channels	2	Visual Inspection	Prevention	2	16
1.1.6 Internal drainage system									
Collect the seepage	Inadequate functioning of the internal drainage	Piping	9	Inadequacy of the project and/or construction	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection and Instrumentation	Detection		
1.1.6.1 Bottom drain									
Collect the seep-age from dam	Insufficient drainage capacity	Piping	9	Inadequate particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
Collect the seep-age from nature mass	Insufficient drainage capacity	Piping	9	Inadequate particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Visual Inspection	Prevention	6	108
							Detection		
Collect the seep-age from founda-tion	Insufficient drainage capacity	Piping	9	Inadequate particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Visual Inspection	Prevention	6	108

Table 12 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.1.6.2 Vertical filter									
Collect the seepage from dam	Insufficient drainage capacity	Piping	9	Inadequate of particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
Collect the seepage from nature mass	Insufficient drainage capacity	Piping	9	Inadequate of particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
1.1.6.3 Foot drain									
Collect the seepage from dam	Insufficient drainage capacity	Piping	9	Inadequate of particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
Collect the seepage from nature mass	Insufficient drainage capacity	Piping	9	Inadequate of particle size	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	2	Adequacy of particle size	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
1.2 Spillway system									
Conduct water	Insufficient drainage capacity	Overtopping	9	Inadequate dimensioning of the spillway	3	Correct dimensioning of the spillway	Prevention	2	54
						Visual Inspection and Instrumentation	Detection		
Not allow overtopping of the dam	Allow overtopping of the dam	Overtopping	9	Inadequate dimensioning of the spillway	3	Correct dimensioning of the spillway	Prevention	2	54
						Visual Inspection and Instrumentation	Detection		
1.3 Abutments									
Confer stability of embankment	Instability associated with movements of the soil mass	Local instability of the dam	4	Reduction of strength	3	Sealing of cracks	Prevention	3	36
						Adequacy of the geometry	Prevention		
						Visual Inspection and Instrumentation	Detection		
1.3.1 Abutment right									
Confer stability of embankment	Instability associated with movements of the soil mass	Local instability of the dam	4	Reduction of strength	3	Sealing of cracks	Prevention	3	36
						Adequacy of the geometry	Prevention		
						Visual Inspection and Instrumentation	Detection		

Table 12 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.3.2 Abutment left									
Confer stability of embankment	Instability associated with movements of the soil mass	Local instability of the dam	4	Reduction of strength	3	Sealing of cracks	Prevention	3	36
						Adequacy of the geometry	Prevention		
						Visual Inspection and Instrumentation	Detection		
1.4 Foundation									
Provide support for dam	Instability associated with movements of the soil mass	Global instability of the dam	10	Foundation treatment insufficient	2	Reinforcement in the foundation treatment	Prevention	4	80
						Visual Inspection and Instrumentation	Detection		
Confer global stability of embankment	Excessive seepage	Piping	9	Foundation treatment insufficient	2	Reinforcement in the foundation treatment	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
1.5 Tailings impoundment									
Store water	Insufficient capacity for store water	Overtopping	9	Inadequacy of the project and/or construction	4	Visual Inspection and Instrumentation	Prevention	2	72
Retain sediments	Insufficient capacity for retain sediments	Reduction temporary of the storage capacity	5	Inadequacy of the project and/or construction	4	Visual Inspection and Instrumentation	Prevention	2	40
Water clarification	Insufficient capacity to clarify the water	Reduction temporary of the storage capacity	4	Inadequacy of the project and/or construction	3	Visual Inspection and Instrumentation	Prevention	2	20

Table 13 - FMEA Results: System of the Tailings Dam B.

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.1 Dam body									
Containment of tailings	Insufficient capacity to contain tailings	Global instability of the dam	10	Inadequacy of the project and/or construction	2	Adjustment of the project	Prevention	3	60
						Visual Inspection and Instrumentation	Detection		
1.1.1 Crest									
Allow access to dam	Not allow access to dam	Inability to carry out inspections	4	Inadequacy of the project and/or construction	2	Adjustment of the project	Prevention	1	8
						Visual Inspection	Detection		
1.1.2 Core									
Reduce the hydraulic conductivity	Excessive seepage	Piping	9	Alterability of the materials	2	Recompaction	Prevention	6	108
						Visual Inspection	Detection		
				Dissolution of the materials	4	Recompaction	Prevention	6	216
						Visual Inspection and Instrumentation	Detection		
				High hydraulic load increase the saturation line	4	Recompaction	Prevention	2	72
						Visual Inspection and Instrumentation	Detection		
				Hydraulic fracturing	2	Recompaction	Prevention	4	72
						Visual Inspection and Instrumentation	Detection		

Table 13 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.1.3 Upstream slope									
Confer mechanical stability	Instability associated with movements of the soil mass	Global instability of the dam	10	Deficient compaction of the embankment	4	Adequacy of the geometry	Prevention	2	80
						Recompaction	Prevention		
						Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of the geometry	Prevention	6	120
						Recompaction	Prevention		
						Visual Inspection	Detection		
	Excessive deformation	Overtopping	9	Alterability of the materials	2	Recompaction	Prevention	6	108
						Visual Inspection	Detection		
				Collapse	2	Recompaction	Prevention	3	54
						Visual Inspection and Instrumentation	Detection		
				Deficient compaction of the embankment	4	Recompaction	Prevention	2	72
						Visual Inspection and Instrumentation	Detection		
1.1.3.1 Free board									
Not allow overtopping of the dam	Allow overtopping of the dam	Overtopping	9	Inadequacy of the project and/or construction	4	Adequacy of the geometry	Prevention	1	36
						Adjustment of the project	Prevention		
						Visual Inspection and Instrumentation	Detection		
1.1.4 Downstream slope									
Confer mechanical stability	Instability associated with movements of the soil mass	Global instability of the dam	10	Deficient compaction of the embankment	4	Adequacy of the geometry	Prevention	2	80
						Recompaction	Prevention		
						Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of the geometry	Prevention	6	120
						Recompaction	Prevention		
						Visual Inspection	Detection		
	External erosion	Local instability of the dam	5	Deficient compaction of the embankment	4	Recompaction	Prevention	2	80
						Visual Inspection and Instrumentation	Detection		
	Excessive deformation	Overtopping	9	Alterability of the materials	2	Recompaction	Prevention	6	108
						Instrumentation	Detection		
				Deficient compaction of the embankment	4	Recompaction	Prevention	2	72
						Visual Inspection and Instrumentation	Detection		
1.1.5 Surface drainage system									
Collect surface water that flow through the embankment	Insufficient capacity to collect surface water	Local instability of the dam	5	Inadequacy section	1	Structural maintenance of channels	Prevention	4	20
						Visual Inspection	Detection		
				Obstruction of channels	2	Unblocking of channels	Prevention	2	20
						Visual Inspection	Detection		
Collect surface water outside the dam	Insufficient capacity to collect surface water	Local instability of the dam	5	Inadequacy section	1	Unblocking of channels	Prevention	4	20
							Detection		
				Obstruction of channels	2	Visual Inspection	Prevention	2	20
							Detection		
1.1.5.1 Concrete channels									
Collect the surface water that flow through the embankment	Insufficient capacity to collect surface water	Local instability of the dam	4	Inadequacy section	1	Structural maintenance of channels	Prevention	4	16
						Visual Inspection	Detection		
				Obstruction of channels	2	Unblocking of channels	Prevention	2	16
						Visual Inspection	Detection		

Table 13 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
Collect the surface water outside the dam	Insufficient capacity to collect surface water	Local instability of the dam	4	Inadequacy section	1	Unblocking of channels	Prevention Detection	4	16
				Obstruction of channels	2	Visual Inspection	Prevention	2	16
1.1.6 Internal drainage system									
Collect the seepage	Inadequate functioning of the internal drainage	Piping	9	Inadequacy of the project and/or construction	3	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	6	162
1.1.6.1 Bottom drain									
Collect the seepage from dam	Insufficient drainage capacity	Piping	9	Inadequate particle size	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Insufficient thickness	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Alterability of the materials	2	Adequacy of particle size Visual Inspection	Prevention Detection	6	108
Collect the seepage from nature mass	Insufficient drainage capacity	Piping	9	Inadequate particle size	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Insufficient thickness	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Alterability of the materials	2	Visual Inspection	Prevention Detection	6	108
Collect the seepage from foundation	Insufficient drainage capacity	Piping	9	Inadequate particle size	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Insufficient thickness	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Alterability of the materials	2	Visual Inspection	Prevention	6	108
1.1.6.2 Vertical filter									
Collect the seepage from dam	Insufficient drainage capacity	Piping	9	Inadequate of particle size	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Insufficient thickness	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Alterability of the materials	2	Adequacy of particle size Visual Inspection	Prevention Detection	6	108
Collect the seepage from nature mass	Insufficient drainage capacity	Piping	9	Inadequate of particle size	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Insufficient thickness	2	Adequacy of particle size Visual Inspection and Instrumentation	Prevention Detection	5	90
				Alterability of the materials	2	Adequacy of particle size Visual Inspection	Prevention Detection	6	108

Table 13 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.1.6.3 Foot drain									
Collect the seepage from dam	Insufficient drainage capacity	Piping	9	Inadequate of particle size	5	Adequacy of particle size	Prevention	5	225
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	5	Adequacy of particle size	Prevention	5	225
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
Collect the seepage from nature mass	Insufficient drainage capacity	Piping	9	Inadequate of particle size	5	Adequacy of particle size	Prevention	5	225
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	5	Adequacy of particle size	Prevention	5	225
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
1.1.6.4 Drain on the abutments									
Collect the seepage from dam	Insufficient drainage capacity	Piping	9	Inadequate of particle size	3	Adequacy of particle size	Prevention	4	108
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	3	Adequacy of particle size	Prevention	4	108
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
Collect the seepage from nature mass	Insufficient drainage capacity	Piping	9	Inadequate of particle size	3	Adequacy of particle size	Prevention	4	108
						Visual Inspection and Instrumentation	Detection		
				Insufficient thickness	3	Adequacy of particle size	Prevention	4	108
						Visual Inspection and Instrumentation	Detection		
				Alterability of the materials	2	Adequacy of particle size	Prevention	6	108
						Visual Inspection	Detection		
1.2 Spillway system									
Conduct water	Insufficient drainage capacity	Overtopping	9	Inadequate dimensioning of the spillway	1	Correct dimensioning of the spillway	Prevention	3	27
						Visual Inspection and Instrumentation	Detection		
Not allow over-topping of the dam	Allow overtopping of the dam	Overtopping	9	Inadequate dimensioning of the spillway	1	Correct dimensioning of the spillway	Prevention	3	27
						Visual Inspection and Instrumentation	Detection		
1.3 Abutments									
Confer stability of embankment	Instability associated with movements of the soil mass	Local instability of the dam	4	Reduction of strength	2	Sealing of cracks	Prevention	2	16
						Adequacy of the geometry	Prevention		
						Visual Inspection and Instrumentation	Detection		
1.3.1 Abutment right									
Confer stability of embankment	Instability associated with movements of the soil mass	Local instability of the dam	4	Reduction of strength	2	Sealing of cracks	Prevention	2	16
						Adequacy of the geometry	Prevention		
						Visual Inspection and Instrumentation	Detection		

Table 13 (cont.)

Function	Failure	Final effect	Si	Cause	Oi	Control	Control type	Di	RPNi
1.3.2 Abutment left									
Confer stability of embankment	Instability associated with movements of the soil mass	Local instability of the dam	4	Reduction of strength	2	Sealing of cracks	Prevention	2	16
						Adequacy of the geometry	Prevention		
						Visual Inspection and Instrumentation	Detection		
1.4 Foundation									
Provide support for dam	Instability associated with movements of the soil mass	Global instability of the dam	10	Foundation treatment insufficient	2	Reinforcement in the foundation treatment	Prevention	4	80
						Visual Inspection and Instrumentation	Detection		
Confer global stability of embankment	Excessive seepage	Piping	9	Foundation treatment insufficient	2	Reinforcement in the foundation treatment	Prevention	5	90
						Visual Inspection and Instrumentation	Detection		
1.5 Tailings impoundment									
Store water	Insufficient capacity for store water	Overtopping	9	Inadequacy of the project and/or construction	1	Visual Inspection and Instrumentation	Prevention	1	9
Retain sediments	Insufficient capacity for retain sediments	Reduction temporary of the storage capacity	5	Inadequacy of the project and/or construction	1	Visual Inspection and Instrumentation	Prevention	1	5
Water clarification	Insufficient capacity to clarify the water	Reduction temporary of the storage capacity	4	Inadequacy of the project and/or construction	1	Visual Inspection and Instrumentation	Prevention	1	4

Table 14 - Intolerable Risk - RPNi > 120.

Location	Function	Failure	Final effect	Cause	Tailing Dam
1.1.2 Core	Reduce the hydraulic conductivity	Excessive seepage	Piping	Dissolution of the materials	A and B
1.1.6 Internal drainage system	Collect the seepage	Inadequate functioning of the internal drainage	Piping	Inadequacy of the project and/or construction	B
1.1.6.3 Foot drain	Collect the seepage from dam	Insufficient drainage capacity	Piping	- Inadequate of particle size - Insufficient thickness	B
	Collect the seepage from nature mass	Insufficient drainage capacity	Piping	- Inadequate of particle size - Insufficient thickness	B

6. Conclusions

Risk analysis methods have been recently applied to dams, also including tailings dams however there is still a lack of confident threshold risk values to subsidize general analysis of risk situations. A preliminary attempt was carried out in this paper for the LCI (LCI MOD-REJ version) and the FMEA methods (Ind_{Risk} greater than 40,000 and RPNi were greater than 120, respectively).

It can be concluded that those two methods allowed a better understanding of the behaviour of the analyzed dams proving that the use of risk analysis methods is a tool for the decision on making process of the risk management.

In a general view the results of both methods are similar in terms of risk situations though there are specific differences on the determination of failure modes for the two dams considered in this study case. The emphasis for the LCI MOD-REJ version was the indications of failures caused by overtopping while for the FMEA method only problems with piping were detected. It should be reinforced that by no means there is an immediate evidence of failures as both methods only specify to which aspects one must concentrate efforts in order to diminish the risk associated to potential failures of the structures.

These differences in the results are probably related to the way the methods were proposed and have been applied on risk analysis. The LCI one, the basis for the LCI MOD-REJ version, is more general and the calculation of the risk is carried out after an evaluation of the impacts on the downstream valley. On the other hand the evaluation process of the FMEA method is more detailed as the risk for each element of the system is considered in the analysis.

Based on the current results a preliminary recommendation is to apply, whenever possible, these two risk analysis methods to a single or a portfolio of tailings dams. In the first case the idea is to allow the elaboration of an ordination hierarchy and a list of procedures for security. In the latter case the combined application may define the dams that should be prioritized to an immediate maintenance and repairs.

It is important to emphasize the importance to extend the applications of these methods to several tailings dams for a real evaluation of their suitability and effectiveness. For the case of the LCI MOD-REJ version, this extension would be essential to its calibration and verification.

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