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Methodology for the Definition of Geotechnical Monitoring Thresholds for Tailings Dams - A proposal

Metodología para la Definición de Umbrales de Monitoreo Geotécnicos para Depósitos de Relaves

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ABSTRACT: Geotechnical monitoring thresholds are essential to evaluate the safety and physical stability of the tailings dams. They enable the development of action plans in case these thresholds are exceeded and serve as a fundamental tool for dam safety. This paper presents a methodology for defining critical values or thresholds associated with geotechnical instrumentation for implementation in tailings dams, following global industry standards.

Examples of specific thresholds are given for each type of critical control, such as pore pressure monitoring, deformations, and other variables. In addition, general guidelines are given to define effective action plans in the event of non-compliance with the established criteria and thresholds. The minimum responsibilities of the various roles involved in tailings management are also described.

KEYWORDS: Tailings Dams, Thresholds, TARP, GITSM.

1 INTRODUCTION.

Tailings Storage Facilities (TSF) are structures that can store large volumes of mine waste (tailings), with an extended period of operation and even longer post-closure period. These sites require high standard geotechnical monitoring of critical variables that could affect the physical stability of the site.

Geotechnical monitoring allows to evaluate the behavior of critical variables associated with the stability of the structure and the identification of potential deviations, which could lead to failure or collapse, enabling timely intervention. This is possible due to the capability of modern geotechnical instrumentation systems to provide information almost in real time, thus being able to automate most of the measurement and information management processes.

The available monitoring technology allows an evaluation of the entire life cycle of the dam, detecting the need for optimization or correction of the design, construction, or operation in a timely manner, resulting in greater efficiency, cost reduction and early risk mitigation.

In this context, the availability of geotechnical monitoring performance thresholds, together with action plans that indicate the steps to follow when they are exceeded (Trigger Action Response Plans, TARP) is essential for an adequate follow-up of critical variables and assurance of physical stability.

2 CONTEXT

2.1 *International Best Practices*

Global Tailings Standard (GISTM)

One of the main tools developed worldwide for tailings management is the Global Industry Standard on Tailings Management (GISTM), developed by a multidisciplinary panel of experts based on current good practice guidelines and the findings of failures that have occurred at tailings facilities.

Regarding the monitoring of tailings impoundments in particular, Principle 7 of the Standard corresponds to design, establishment and operation of monitoring systems for risk management throughout all phases of a tailings impoundment's life cycle. In terms of monitoring, the following requirements are highlighted:

1. Design, implement, and operate a tailings facility performance monitoring program that verifies design assumptions and credible failure modes.
2. Establish specific and measurable performance objectives, indicators, criteria and metrics, and include them in the design of the monitoring program that measures performance throughout the life cycle of the tailings facility.
3. Evaluate the performance of the facilities, clearly identifying any deviations, and presented their evidence with respect to the expected performance and their deterioration over time.
4. Performance outside expected ranges should be addressed through response implementation action plans or critical controls.

In addition, it considers the importance of monitoring in emergency response and long-term recovery, indicating that it is necessary to facilitate the monitoring and public disclosure of progress associated with actions following failure events, aligned with the thresholds and indicators described in the reconstruction, restoration, recovery plans, adapting the activities to the findings and recommendations received.

2.2 *Regulations in force in Chile*

Supreme Decree N°248 (Ministry of Mining)

Articles 14, 51 and 52 of D.S. 248 require that each mining company must identify the critical parameters that require monitoring during the life cycle of the tailings deposit, defining as a minimum the monitoring of the water table within the dam. A description of the instrumentation systems and associated controls that will be used to evaluate the performance of the deposit during its operation, both in compliance with the design intent and the requirements that may be requested by the regulatory authorities, must be included.

Supreme Decree N°50 (General Directorate of Water)

D.S.50 in articles 31, 34, 37, associated to the structural design of tailings dams and industrial dams, indicates that all dams must be instrumented to monitor their behavior during construction and operation. This instrumentation is defined according to the state of the art and must be oriented to the verification of the safety and operation of the work (performance evaluation).

2.3 *Good practices in Chile*

In line with the provisions of Article 52 of DS 248, mining companies operating in Chile have developed internal standards for the management of tailings deposits, specifically the Operation, Maintenance and Surveillance Manuals (OMV), which define critical parameters and thresholds to evaluate their performance, together with their respective action plan in case of overcoming them (*Trigger Action Response Plan*, TARP).

The following are the most important points of interest associated with the development of TARP, considered by the mining companies during the preparation of the operation and monitoring manuals (OMV):

- Identify critical controls associated with the TSF. Each critical control should have performance criteria, measurable performance indicators and monitoring requirements. Actions to be taken when performance is outside normal ranges, such as emergency preparedness and response plans, should also be defined.
- The thresholds defined to assess performance should be associated with different levels, depending on the associated risk.
- The OMV must clearly describe the notification requirements necessary upon detection of a performance parameter outside normal operating ranges.
- The performance criteria or thresholds defined to evaluate critical controls must have an impact on the operating condition, according to the level of risk they represent, and may change from normal to eventual or critical operation.
- When thresholds are defined for detecting performance deviations, they must have associated predefined actions (TARP).
- For the determination of critical controls in a tailings deposit, it is suggested to start with FMEA studies, and then evaluate additional specific failure mode studies.
- TARPs should be defined for both variables associated with instrumental monitoring and variables associated with visual monitoring.
- Alert and escalation levels associated with surveillance must be fully aligned with deviation and emergency response plans.

3 MONITORING PARAMETERS

Based on the criteria presented by national and international best practices, together with the recommendations provided by current mining standards, it can be observed that the methodology for establishing a performance threshold is based on the identification and evaluation of critical parameters related to the physical stability of tailings deposits.

This process is supported by the results obtained from the FMEA (*Failure Modes and Effects Analysis*) study, which provides a comprehensive view of potential credible failure modes and scenarios and their consequences. Thus, by using the potential failure modes for the choice of critical monitoring parameters, the performance thresholds and associated actions focus on the most significant and priority aspects for the safety and stability of the deposits.

The critical parameters associated with the most observed credible failure modes globally are presented below.

3.1 *Water Table and Pore Pressures*

The water table corresponds to the upper water level, where the pore pressure is equal to the atmospheric pressure. The water table within a tailing dam is critical for physical stability. In fact, variation in water level decrease or increase the effective pressures and thus the shear strength in the same way. In addition, significant variations can accelerate the consolidation of fine saturated soils that may exist, both at the foundation level and in the body of the dam.

3.2 *Deformations*

Deformations can be subdivided into horizontal and vertical displacements (generally settlements).

- Horizontal displacements: movements expected mainly in the body of the structure, transversal to the axis of the dam. Tailings deposited in the basin and the self-weight of the dam can generate sufficient stresses to cause horizontal displacements, under static and seismic loads.
- Vertical displacements (settlements): these are generated in soils because of external loads (static or seismic) or by self-weight that induce volumetric changes.

3.3 *Freeboard*

The freeboard corresponds to the difference in elevation between the crest of the dam and the tailings or lagoon in direct contact with it. It is measured to verify that the difference in elevation is associated with a volume available in the deposit that allows managing the Probable Maximum Flood (PMF), settlements due to static and seismic loads and other factors.

3.5 *Flow rate and Turbidity at the outlet of the drainage system*

The flow rate is measured to evaluate the efficiency of the drainage system, validating the assumptions and predictions made at the design stage.

Turbidity corresponds to the number of suspended particles in the outflow, it is generally measured in NTU (Nephelometric Turbidity Units), and the detection of high levels may indicate that there is migration of particles inside the dam and, eventually, that piping is occurring.

3.6 *Leaks and/or humidity*

Seepage is generated when the drainage, waterproofing or channeling system does not work properly, or flows move through sectors not foreseen according to the design intention.

Table 1 presents the relationship between the critical geotechnical monitoring parameters and the main failure modes observed globally in tailings impoundments. These critical parameters have a major impact on the physical stability of the dam and are usually monitored with geotechnical instrumentation. However, when performing this type of study, it is necessary to consider all those parameters that are obtained from the FMEA study.

Table 1. Relationship between critical parameter and typical failure modes in tailings impoundments

Parameter (2) Reviewer	*Typical potential failure modes (1)*		
	Overflow (Overtopping)	*Slope instability*	*Internal Erosion*
Water table		X	X
Deformations	X	X	X
Freeboard	X		
Drainage flow rate			X
Turbidity flow drains		X	X
No leaks controlled		X	X
Crack formation		X	X

(1) The 3 typical credible failure modes generally identified in tailings impoundments have been selected. (2) The critical parameters presented in this table correspond to the most frequent indicators in tailings dams; however, there may be additional critical parameters depending on the specific characteristics of each tailing storage facility (for example, deposition plan, construction plan, size and position of the lagoon, among others).

In Table 1, seismic acceleration measurements are omitted, because is not a direct indicator of performance. However, the perception and damage observed during the seismic event are key elements to determine an immediate action plan. Nevertheless, it is essential to carry out acceleration measurements to validate design assumptions and ensure the structural integrity of the dam.

4 DEFINITION AND CLASSIFICATION OF PERFORMANCE THRESHOLDS

4.1 *Threshold definition*

To identify deviations in the performance of monitoring parameters, thresholds or evaluation criteria are established. These correspond to conditions or rules defined to detect the level of compliance with a critical parameter.

4.2 *Threshold Classification According to Type of Monitoring*

Regardless of the associated critical parameter, it is always possible to classify a threshold in one of the following three groups:

- Thresholds by limit values: Corresponds to a threshold associated to a single numerical value, with which the monitoring data will be compared. This type of threshold is used in exclusively quantitative monitoring by means of direct measurements of the critical parameter.
- Thresholds by condition: Corresponds to a binary evaluation (yes or no), associated to the description of a specific event. It is associated to qualitative conditions and is generally used to detect the occurrence of events that cannot be directly measured by instrumentation, or that are more feasible to detect by visual inspections. For example, the detection of a sinkhole in a certain sector of a dam (binary condition).
- Mixed threshold: Considers both compliance with a binary evaluation and comparison with a predefined numerical value. They are commonly used for detecting events that cannot be measured by installed instrumentation in the deposit, but once detected, the event can be followed up by measuring a quantitative parameter. For example, the appearance of a crack (binary condition), and that the crack has dimensions below or above a predefined threshold (predefined numerical value).

4.3 *Risk Level of a Threshold*

Whenever a threshold is assigned or defined to a critical control, failure to meet this condition constitutes a "deviation" and must be managed according to the level of risk associated with it.

To assess the risk level of the detected deviation, the following criteria should be considered:

- Direct or indirect relationship of the critical control to the failure mode for which it was defined.
- Level of impact of the deviation with respect to the overall failure mode.
- Degree of deviation from the expected design or performance.

If the threshold involves more than one critical control, the following must also be evaluated:

- Whether there is a relationship between all critical controls bypassed and any of the credible failure modes.
- If it is coherent to assume that the detected deviations are related to each other given their spatial location, then it is possible to assume that they are related to each other.
- The number of deviations detected.

With all the above criteria, it is possible to assign a risk level to each defined threshold. It is suggested to use 4 risk levels when defining the thresholds, which are generally represented by colors: green (preventive); yellow (slight deviation); orange (severe deviation); red (imminent danger of failure).

5 THRESHOLDS DEFINITION PROPOSAL

Criteria and methods are proposed for the definition of thresholds of a general point of view, which can be used as a guide in defining the threshold for a particular tailings deposit.

5.1 TREND CHANGE THRESHOLDS

5.1.1 *General Description*

An unfavorable trend is defined as the change in the rate of variation of a monitoring variable over time. This change considers a historical rate of change, which represents the normal behavior of the instrument, and the rate of change of the last period of analysis, as illustrated in Figure 1.

Depending on the type of variable, the historical rate of change may consider monitoring data from the last months, years, or since the instrument was installed. The determination of the time window to be considered (historical and last period) should be evaluated based on the reliability of the information and is specific to the tailing facility. The same applies to the rate of variation of the last period, which can vary from months, weeks to days.

5.1.2 *Methodology for calculating variation rates*

To determine the variation rates, the following methodology is proposed, which is schematically shown in Figure 1:

a) Determine the rate of change (trend) of an instrument's records associated with a measurement period "n". This value will be called the historical rate of change and can be a linear approximation of the variation of the record over time; it is represented by equation (1)

$$\textit{Measured value (time)} = a + b\_1 \cdot time. \quad (1)$$

Where:

a [unit]: Corresponds to a constant obtained from linear regression.
b_1 [unit/time]: Corresponds to the historical rate of change of the measurement variable over time, in period "n".

b) Following this, the same procedure will be performed, but for a second period of data, corresponding to period "m", where m must be less than n. This rate will be associated with the current behavior of the instrument.

$$\textit{Measured value (time)} = a + b\_2 \cdot time. \quad (2)$$

Where:

a [unit]: Corresponds to a constant obtained from linear regression.
b_2 [unit/time]: Corresponds to the current rate of change of water table over time, in period "m".

c) The difference in the calculated exchange rates (B_3) indicates how much the current rate (period "m") has varied with respect to the historical rate (period "n"), which can be increasing (+) or decreasing (-) with respect to the historical behavior of the instrument.

$$B\_3 = b\_2 - b\_1 \quad (3)$$

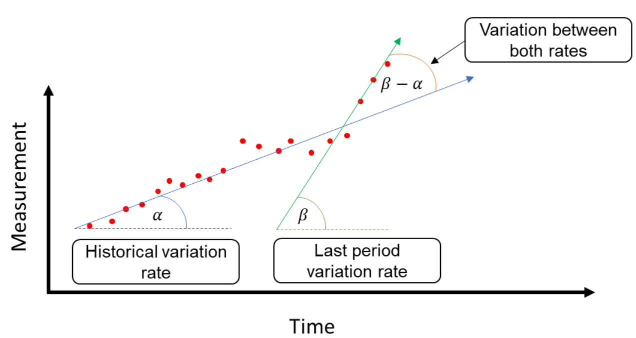

Figure 1. Variation rate estimation scheme

5.1.3 *Trend Threshold Value Definition Methodology*

A normal range of measurement is understood as the historical dispersion of readings from one or more instruments that remain within the range considered by design and whose variations have not caused instabilities or effects that are indicative of any type of risk. The methodological proposal for defining trend thresholds for an instrument is as follows.

a) Select instruments with reliable data over a significant time window and with relatively low dispersion.
b) Apply the methodology described in section 5.1.2, for all available data, this will generate a database of rates of change over time for each instrument.
c) Generate a histogram with the results, which should resemble a Gaussian distribution (Bell curve), where most of the records close to the average value will be concentrated. The records should be separated between increasing and decreasing trends, considering 0 as the inflection point.
d) Define the acceptance percentage. It is recommended to select values between 75 and 99% depending on the desired sensitivity regarding the threshold. With an acceptance value of 75%, 25% of the historical data would trigger the unfavorable trend threshold, whereas with 99%, only 1% of the data would have triggered the threshold. This must be defined based on expert judgment, both for data associated with an increasing trend and a decreasing trend.
e) Determine the rate of change corresponding to this value.

As an example, we present the case of measurement records of 16 displacement monitoring instruments, which have at least 2 years of historical data. Applying the methodology described above, different ranges of values for the rate of change over time were obtained. Figure 2 presents a histogram with the rate of change of the selected instruments.

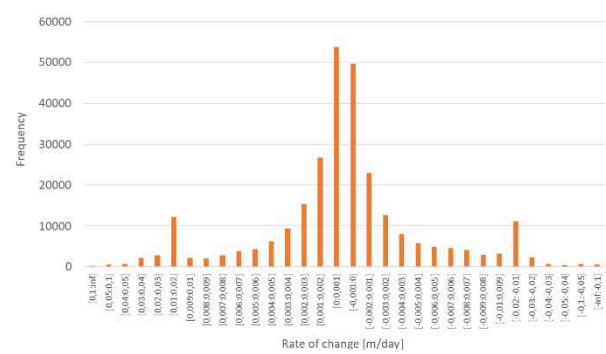

Figure 2. Histogram of the Rate of Change - Example

Table 2 presents the criteria determined to define the threshold values to be evaluated. The results have been segmented between positive (increasing growth rate) and negative (decreasing growth rate) values. The criterion chosen, for this situation, considers that 87% and 88% of the values within each segment will define the threshold limit value respectively, in the case of an increasing change the value 0.01 m/day has been defined, and for the case of a decreasing change the value defined is -0.01 m/day.

Table 2. Threshold Value Definition Criteria - Example.

Parameter	*Value*
Number of increasing records (>0)	145.577
Percentage of acceptance [%].	87
Threshold value increasing rate [m/day].	0,01
Number of decreasing records (<0)	134.899

Percentage of acceptance [%].	88
Threshold value decreasing rate [m/day].	-0,01

5.2 THRESHOLDS PER LIMIT VALUE (MAXIMUM AND MINIMUM)

5.2.1 *General Description*

This type of threshold is used to alert when a monitoring parameter reaches a fixed target value, which is usually obtained from the design basis of the facility. It is usually combined with trend thresholds, alerting when the change in the monitored variable has deviated enough to reach a next alert level.

In general, it is recommended to consider thresholds associated with different alert levels, as schematically illustrated in Figure 3.

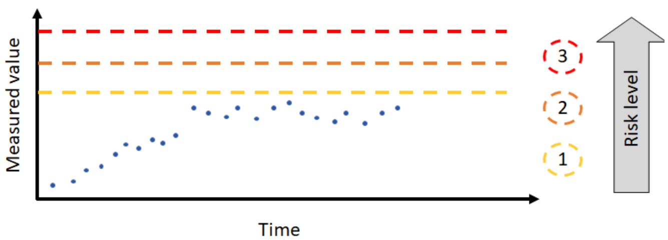

Figure 3. Example of threshold limit value for 3 levels of risk

5.2.2 *Criteria for defining limit value thresholds*

The methodological proposal for defining limit value thresholds for an instrument is as follows:

a) Identify the monitoring variable. Consider that the selected variable must provide relevant information when exceeding a given target value.
b) Identify the risk level(s) for which the limit value is to be defined. This step requires expert judgment, as a variable alone may not generate a high level of risk.
c) Based on the design basis of the facility, define threshold limits for different risk levels. For example, consider the water table used in the stability analyses that support the design as the maximum tolerable value threshold, and define other thresholds for lower levels. A similar approach can be applied to define thresholds for deformation based on dynamic analysis results. The same can be done for maximum and minimum flow values associated with the design ranges of the drainage system, among others.

It should be considered that these thresholds need to be evaluated and updated over time, as they are often modified by changes in the deposit, such as dam raised, basin growth, dam performance or even climate change.

5.3 THRESHOLDS PER CONDITION

5.3.1 *General Description*

When the alteration of a parameter or condition of the deposit cannot be quantified with the available instrumentation, qualitative or mixed (qualitative and quantitative) conditions must be applied.

A qualitative condition corresponds to the verification of a specific event, which can be quickly identified and classified by any operator. The description of a qualitative condition must include the description of a minimum of elements for its correct evaluation, which can also be complemented with secondary descriptions as indicated in Table 3.

5.3.2 CRITERIA DEFINITION OF THRESHOLDS BY CONDITION

The proposed criteria for determining a threshold associated with a qualitative condition are as follows:

a) Identify the event to define a qualitative threshold condition. Consider that the event must directly or indirectly affect the stability of the deposit. To do this, it is recommended to review the credible failure modes defined by the current FMEA and identify those that are currently partially or not monitored at all by the operational geotechnical instrumentation.
b) Generate a description of the event, its location, development, classify it or indicate a risk level. The purpose of this description is to enable a repository operator to validate whether (or not) the event that has occurred corresponds to the described threshold condition.

Some examples of descriptions are given in Table 3. It should be noted that the more specific the description of the event, the higher the likelihood of identifying the root cause.

An annual update is recommended, reviewing the descriptions, and verifying with the operators whether the indicated characteristics correspond to the actual conditions in the field.

6 SUMMARY OF PROPOSED THRESHOLD APPLICATION BY PARAMETER

The methodology for the definition of three types of performance thresholds has been presented: trend-based; limit value-based and qualitative condition-based.

The selection of the threshold type will depend on the critical variable being monitored and the behavior of the measurements, and multiple thresholds per variable may be applied.

Table 4 provides a recommendation for the type of threshold to be applied for each of the main critical variables. This recommendation is based on the frequency of existing monitoring to optimize the use of these methodologies according to the available information. It is important to note that more complex threshold definition may lose their reliability when there is a limited monitoring data available.

7 FINAL COMMENTS

It is highly recommended that these systems are not fully automated, meaning that there should be a human team involved. Ideally, this team should have proper training in soil and tailings geotechnics to continuously review, analyze and interpret the quality and reliability of the readings from the instrumentation during the operation of the dam. They should also be trained in applying performance thresholds.

It is essential that the implementation of geotechnical instrumentation performance thresholds and action plans (TARPs) is intuitive and understandable for field personnel. Clear and well-defined values are fundamental to define appropriate actions in the event of significant variations in the monitoring indicators.

While this publication has selected the most relevant critical parameters associated with the stability of the deposits, it is important to consider all those parameters that are obtained from the FMEA study. These parameters allow for monitoring the occurrence of credible failure modes in the deposit.

In defining and applying performance thresholds and corresponding action plans, it is crucial to involve all roles responsible for tailings stability, including the Responsible Tailings Facility Engineer (RTFE), the Engineer of Record (EoR) and the operations teams.

Lastly, a plan for evaluating and updating performance thresholds throughout the lifespan of the deposits, including closure and post-closure, should be considered. This ensures that the monitoring controls are adjusted to the operational conditions and geometric characteristics of all phases of the project´s life cycle.

7 REFERENCES

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Table 3. Main and secondary elements associated with the des

Table 4. Methodology Proposal

Note: The monitoring frequencies indicated in this table are referential and are associated with the type of monitoring (manual or automatic).