Recent experiences using Space Observation for quantitative risk assessment of tailings dams

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ABSTRACT: With the new requirements for tailings dams documentation and management there is a race to use remote monitoring (space, drones), sometimes coupled with machine learning and AI. Remote monitoring is often presented as a solve-all silver bullet. However, our experience is a bit more nuanced and this paper will explain why. We recently performed quantitative risk assessment (QRA) of tailings dams facilities and other geostructures in diverse geographic location. Because of confidentiality we keep the cases anonymous. The knowledge base of any dam is spread over many different documents, many authors and sources produced over time. Sometimes it is extremely poor. Building the knowledge base is a daunting task faced by anyone willing to perform a risk assessment. Space Observation offers the possibility to go back in time, using databases of satellite imagery. Our approach to QRA encompasses 30+ KPIs of which some are observable "from up above". However, a snapshot or the deformation of the last 5, 10, 20 years does not necessarily help predicting a failure. Indeed, several factors complicate the issue: normalization of deviance, human error, as well as design criteria in a divergent world that could make the structure deficient (ditch, etc., deposition patterns, beaches and pond). These can only be identified when analyzing extant reports. The available information discovery path is the file repository of the facilities. A good file repository contains a large quantity of documents allowing to grasp the state of the facilities. The access of documentation related to the construction and operations of the facilities are indeed paramount to understand their factual state and thus the likelihood of failures. Thus they cannot be neglected. With satellite imagery AND the documentation properly analyzed it is possible to understand possible deviance from the design.

1 INTRODUCTION

Dams are all exposed to natural and man-made hazards and they all have, to extents that are sometimes worrisome, gaps in their documented history, past incidents, etc. Experience shows no dam fails because of one single cause. So, beyond the intricacies of engineering analyses, humanity, with the cohort of retiring baby-boomers leaving with their knowledge, is facing an information gap which has stirred specific requirements in the recent Global Industry Standard for Tailings Management (GISTM).

Dam risks informational gap can be addressed using not a single, but a blending of wide-ranging approaches: covering archival documents; space observation (SO); Internet of Things; big data and finally Artificial Intelligence. Each approach brings in some benefits, but if poorly applied, may even be counterproductive. Considering the geographic spread of tailings dams portfolios managed by a single mining companies, the cost of travel and classic monitoring, possible travel restrictions and the apparent ease of “seeing” what is happening in a portfolio from a single control room, there is a trend to consider Space Observation as a panacea. This paper examines SO and other approaches from the point of view of a risk assessor.

2 SPECIFIC REQUIREMENTS FOR DAMS RISK ANALYSIS

A risk assessment requires the hazards to be identified. Hazards are events or conditions generating potential losses. Potential hazards may include for example: meteorological conditions; human error, human factors (normalization of deviance); poor management (lack of controls of water balance for example); poor design (inadequate drainage), and finally engineering arrogance (lack of appreciation of mechanisms that trigger failure (Hartford, Baecher, 2004; ICOLD Bulletin 121, 2001)). It is self-evident that some of these are “space observable” and some aren’t (Oboni et al., 2018). Affairs are complicated by the number of active and non-active significantly different dams around the world because of age, function, materials, construction style and care, maintenance care, and finally “behavior” or performance. Some information can only be retrieved by examining and understanding archival documents. Many Key Risk Indicators (KRIs aka KPIs) lie deep (pun intended) in the foundations and history of each structure. Dams can fail because of birth defects (e.g., insufficient depth of investigation, geology understanding, etc.), poor management (e.g., normalization of deviance, etc.) among many other causes that will neither be understood by reading only the latest third-party inspection, nor detected by space observation until, unfortunately, too late to allow mitigation.

As we expressed in an ICOLD 2019 paper (Oboni et al., 2019) KRIs generate from choices and historic evolution related for example to: material; berms & erosion; cross section; supervision; maintenance; monitoring; divergence from plans; and finally known errors and omissions. Monitoring is oftentimes considered the panacea, and its latest development, based on Space Observation even a better medicine. But is this true? This is the question we will try to answer in this paper. Furthermore, there are many possible ways to create the necessary knowledge-base for a GISTM conforming risk assessment and we believe that only a blending of these approaches is capable of bringing the answers needed for high quality risk assessments (e.g. benchmarking, causality analyses, etc.). Of course, the proportion of blending and the intensity of the efforts must be scaled as a function of the project size and resources available, and potential consequences.

3 SPACE OBSERVATION

Dam structure can be monitored using traditional instruments such as inclinometers and piezometers; ground-based methods such as ground-based SAR, photogrammetry and global navigation satellite system (GNSS). Remotely based methods include airborne Laser Imaging Detection and Ranging (Li-DAR) and space-borne InSAR. The Canadian company MDA started using InSAR for mining in the early 90s. We started using InSAR data for slope monitoring in 2004, when we used a 6-8 year long observation program for the risk assessment of a deep seated landslide in the Italian Alps. Numerous papers have summarized InSAR (Ulaby et al., 1986; Sousa et al., 2014) and our Tailings Management book includes a chapter on the subject (Oboni, Oboni, 2020). Reproducible measurements of ground movement have been demonstrated to be within 2 millimeters in a month (Henschel, Lehrbass, 2011; Henschel et al, 2015; Mäkitaavola et al, 2016) in optimal conditions.

Recent papers (Scaioni et al. 2018; Maltese et al., 2021) reviewed the available technologies for hydro dam deformation monitoring. Di Martire et al. (2014) compared the displacements estimated via a Differential SAR (DIn-SAR) interferometry technique, the “coherent pixels” technique (Blanco-Sánchez et al. 2008) with those recorded by a network of conventional ground-based sensors to monitor an earth dam.

3.1 *Concepts*

Space Observation offers numerous possibilities to re-create the history of a facility. However it is possible that on specific sites good quality stereo pairs going back many years may be available. Starting in the second half of the seventies, US spy-satellites started bringing back to Earth stereo imagery of various parts of the globe. The US has declassified those images allowing civilians to build, step by step, the history of a tailings facility. We listened to a presentation on this subject by Edumine/Photosat where they showed a real-life example. The precision is reportedly 15cm, acceptable to gain a general understanding of what happened on a site, e.g.: beach lengths, overall slope angle, dam construction phases and finally deposition history, but not enough for evaluating the deformations of a dam.

Radar interferometry and optical observation allow to gain a more in depth understanding of, for example: micro-deformations, humidity, ground temperatures and finally vegetation stress. Analyses can also go back in time using existing databases. We believe there is great value in approaching the study of a site from an historic point of view using both optical and radar imagery to build the history of the site.

3.2 *Some details on Space Observation*

Optical satellite technologies can be used to determine variation of water level by quantifying the extent of the water surface (Yue et al., 2019). Applying a single-channel algorithm to Landsat 4, 5, and 8 thermal images can extend monitoring to the past (from 2018 back to 1984) to perform a pond surface temperature analysis (Sharaf et al., 2019). In our recent studies bearing on a portfolio of inactive dams in Northern Ontario (confidential client) we have shown the effects of freezing thawing cycles, i.e. seasonal effects and long term deformation of the dams, emerging solifluction and erosion patterns, first detected by space observation, and then confirmed by site visits. Sources of inaccuracies are both the baseline of a given interferogram, compared to the critical value (Li et al., 1990; Zebker et al., 1992), and the precision of the ephemeris (Copernicus Sentinels POD Data Hub). The baseline controls the coherence of the interferogram, while the ephemeris accuracy has an influence on the conversion of interferogram phases to absolute height (Reigber et al., 1996). Water levels can be indirectly determined by mapping the reservoir water surface extent using optical images (Yue et al., 2019; Ma et al., 2019; Li et al., 1990).

3.3 *Recent case study*

We recently developed additional experiences on a number of dams in various locations, including semi-Arctic conditions. The satellites used were Sentinel-1B & Radarsat 2 for InSAR deformation and Landsat 5, 7, 8 for Normalized Difference Vegetation Index (NDVI). Below we present a summary of our findings.

NDVI with medium-resolution optical imagery was aimed at analyzing whether a target area contains live green vegetation and to perform a qualitative assessment of the vigor of that vegetation. The process used to perform the analysis consists of: acquiring and processing archive optical satellite image data over each site in order to establish a “history” of the site; processing the imagery to calculate the NDVI and highlight plant vigor and areas of standing water to determine the relative water level; completing an assessment of each considered tailings facility. Note, the calculation of the NDVI value may be sensitive to a number of factors including atmospheric effects, clouds and cloud shadow, soil moisture variation and anisotropic effects. Our comments can be summarized as follows: good vegetation health can be linked to possible drainage on the dams bodies and vicinities; visible changes in vegetation can be linked to changes in relative water levels; whenever possible, space observation results should be checked on the ground with visual inspection and instruments data analysis, especially if there is no observation history of the site.

Deformation monitoring (InSAR) program aimed to identify areas where ground motion patterns are: changing over time; remaining consistent over time; and related to the development of new deformations (i.e. previously unobserved deformations beside seasonal variations). The program initially included one year backward looking analysis and one year forward looking observation. It quickly became obvious that there was significant value in extending the backward analysis as far as possible to understand seasonal effects (freezing-thaw cycles), the effects of meteorology and thus to filter out false positives. At the end the study allowed to identify deformations related to: freeze thaw cycles; areas of potential deformation along dams spillways and the dams themselves; potential subsidence that combined with toe heave could highlight a potential developing instability areas.

Short-Wave InfraRed (SWIR) and near-infrared bands in the Landsat 8, were used to determine the relative water levels during the same periods of time of the NDVI program. Using this band combination makes the water appear darker and the effects of shallow versus deep water and relative water levels for each site were determined from this processing.

Overall, the study showed the great potential of SO on TSF areas, with specific reference to ground movements, vegetation health and water levels within the ponds. The process allowed to drive onsite observations requests including in locations where subsequent site visit confirmed signs of solifluction not previously identified and to draw information allowing to update the a priori ORE2_Tailings™ probability of failure estimates and the NDVI analysis detected anomalies in one of the dams area where some materials were deposited.

The following final comments can then be summarized.

Pros of space observation (SO). SO allows to analyze deformations and movements of wide areas starting from “historic” perspective. This constitutes a significant advantage when undertaking an analysis (risk assessment) of sites with poor archival documentation. SO can easily cover an entire multi-dam area, where a more traditional, costlier ground or drone systems would only make local or fragmentary observations. It can detect deformations and incipient phenomena that would escape a site visit visual observation. It gives clues on potential issues which would not otherwise be visible from the ground via a more traditional “punctual” monitoring system. SO allows to go back in time to detect past behaviors and seasonal effects. It can help to overcome bad weather and difficult or hazardous access conditions. It can reach a higher efficiency if reflectors are installed on the ground in critical spots, to improve the quality of the signal and the reliability of the data. NDVI coupled with meteorological data allow an integrated understanding of the evolution of the site environment.

However, SO also has drawbacks, particularly when related to vegetation cycle interpretation and to measurements taken in nonstandard conditions (water surfaces or very wet areas for example) which may be difficult to interpret. It is sometimes impaired by persistent significant vegetation which makes the measurements interpretation uncertain; can be negatively affected by signal noise disturbances; is negatively affected by the presence of ice and snow.

Thus our experience is that:

1) In difficult ground conditions the use of fixed reflectors should be considered to enhance precision.

2) Any study should start with an extended historic approach, vital to build a solid knowledge basis.

3) The measurements need to be constantly interpreted with great care by expert personnel to address further data requests or more detailed ground interpretation.

4) Analysts should try to correlate unusual behaviors with physical events, as a sudden jump in deformation could for example be linked to a significant meteorological event or to seismic activity, by pursuing attentive visual monitoring and geological survey after unusual readings with cross-checks between ground-based and space-based results.

5) Reading area should be extended to dam slopes and surrounding areas and focus on details near sensitive structures or geological features, thus making the most of the capacity of space monitoring to inspect wide areas which could not be easily and cheaply seen from the ground.

6) Always try to establish cumulative long-term deformations and deformation vectors and avoid as much as possible interruptions in the sequence of the space monitoring.

7) InSAR observation data should not be delivered “as they come” to a wider audience or be used to automate alert systems as attentive expert analysis is required for correct interpretation. Neither should they be used to establish “alert” thresholds without an overall simultaneous understanding of the observation results and the structures’ conditions and behavior. Indeed false positive can make the alarm system “cry wolf” and lead to normalization of deviance.

8) If activities are foreseen on a closed site and no in situ observation is performed it is advisable to deliver a schedule of possible work that will be conducted onsite, or any changes foreseen on the ground.

9) Blending techniques is highly effective. Pay attention to any potential changes in the satellite orbital schedule, changes of satellite (over time) to avoid data misinterpretations.

10) InSAR results are displayed at the center of the pixels thus the “colored dot” position is not precise. Beware “over-interpretation” of the results!

11) No analysis should be attempted without climatological and meteorological context pairing, particularly in view of the significant ongoing climate changes.

12) Changes of density in water/tailings, including partially frozen areas, may lead to interferences.

13) Space Observation, like any other monitoring program, cannot shelter its users against fragile failures such as for example those generated by static or dynamic liquefaction, undetected brittle layers, etc.

4 MONITORING RECORDS

Each time we start a new risk assessment we go through monitoring records. It is long and tedious, and generally very frustrating. Even the exact location of boreholes and monitoring instruments is oftentimes not clearly mapped, let alone their elevation. In those conditions it is even difficult to understand if, for example, an inclinometer is indeed anchored in bedrock or not. Thus, we see the benefit in using databases and business intelligence platforms, big data and Internet of things (IoT) but we also see the hazards linked to this practice. They produce beautiful graphics that may be anchored in “alternate reality” rather than in rock, pun intended. And then, of course, instruments break down and may not be replaced as they should. Sometimes their placement follows ease of installation rather than the needs of knowledge-building.

Big data and IoT are indeed becoming common features in all sorts of business activities. They will help define better ranges for reliability and failure of a system’s elements, and make it possible to search world-wide occurrences of near-misses, losses, news, etc. At the other end of the spectrum, Thick data are useful to understand deep motivations and can foster SLO, CSR and ESG by fostering proper communication (Oboni, Oboni 2021).

Big data and Thick data are actually two sides of the same coin (Fig. 1). It is essential to understand their differences.

- Big data is a term for large or complex data sets that traditional software has difficulties processing. Processing generally involves, for example, capture, storage, analysis, curation, searching, sharing, transferring, visualizing, querying, updating, etc. However, big data also often refers to the use of predictive analytics, behavior analytics or certain other advanced data analytic methods. Analysis of data sets can find new correlations to spot trends, prevent emerging issues, etc. but focusing solely on Big data can reduce the ability to imagine how a system might be evolving. Big data only is not sufficient for risk assessment, and in particular hazard identification. It can create a distorted view of the risk landscape surrounding an entity. Big data relies on machine learning, isolates variables to identify patterns, reveals insight. Big data gains insight from scale of data points, but loses resolution details. It does not tell you why those patterns exist and is unprepared to cope with new extremes, divergences.
- Thick data requires careful observation of human behavior and its underlying motivations. Thick data is qualitative information that provides insights into the everyday emotional lives of a given population, i.e. how a facility is managed and decisions taken. Thick data relies on human learning, accepts irreducible complexity, reveals social context of connections between data. Thick data gains insight from anecdotal, small sample stories, but loses scales. It tells you why, but misses identifying complex patterns or future behavior.

To date, big data and thick data have been used and supported by different groups. Organizations grounded in the social sciences tend to use thick data, while corporate IT functions and data scientists tend to favor big data. This constitutes a perfect example of silo culture. Ideally, big data and thick data should “talk to each other”, but most of the time do not because of siloed approaches.

If one is seeking a map of an unknown risk territory (risk landscape) and data are scarce, then thick data is the tool of choice. As data availability grows on its way to becoming big data, integrating both types of data becomes important. In the case of innovative companies, that combined insight can be highly inspirational.

When performing risk assessments, we always collect and analyze stories, anecdotes and loss reports to gain insights into pre-existing states of the system. The combined insight may tell us that a system that “looks wonderful” actually has a congenital defect that may raise its probability of failure. Big data would not be capable of highlighting that aspect but could probably reveal a pattern between third-party observations and, say, meteorology. In fact, it could identify patterns among any other groups of variables, which could sound an alarm on shorter-term emergent hazards.

Working successfully with integrated big and thick data certainly enhances any risk assessment. Over the years we have found ways to integrate data from multiple sources and of various natures in our risk assessments. We routinely use incomplete thick data sets in conjunction with expert opinions and literature to generate a first, a priori estimate of the probability of occurrence of hazards and failures. This immensely increases the value of the first-cut risk assessment, which can then be updated using big data and Bayesian techniques.

The combined approach also makes it possible to enhance the value of big data, avoid capital squandering, and reduce the running cost necessary to obtain big data.

Recent studies have shown that without that approach data oftentimes remain virtually unused.

Integrating big data and thick data brings value and should be fostered. Thus, it is crucial to explore how big data and thick data can supplement each other. This demands the integration of qualitative evaluation and expert-based judgments with hard quantitative data.

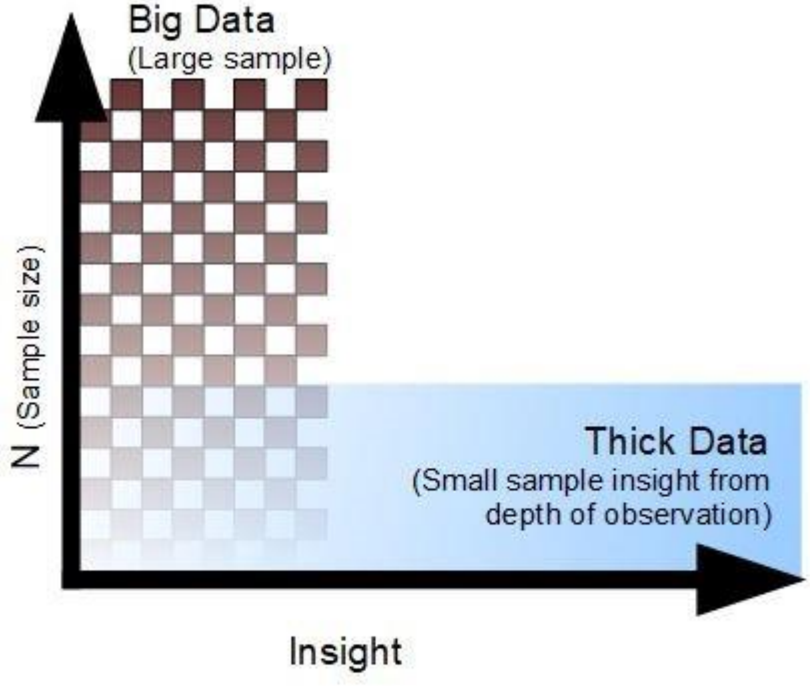

Fig. 1 Big data vs. thick data

Nowadays, measurements, space observation results can be broadcasted to a central record which in turn can deliver them to a “control room” where graphic displays render the global situation in real time. Internet of Things adds wonderful data and Artificial Intelligence may gobble all of this and tell us… what exactly? Let’s remember that AI builds its knowledge on what it feeds on. Indeed, AI is not good, as far as we know, in forecasting something it has never “seen” and is highly unusual.

In that sense it is not better than a human being confronted with a new situation. The key to allowing IoT and AI to deliver a better job lies in blending backward space observation with as long as possible monitoring history. Do not start with today’s data and hope AI can help you tomorrow morning!

5 ADVANCED DOCUMENTS SEARCH FOR KNOWLEDGE BASE CREATION

Once the space observation and monitoring records are gathered we are left with the annoying, and less glamorous, yet paramount part of tailings dams knowledge base creation. That is to ingest, check and understand the mass of reports that may exist to document a tailings dam since inception and cross check it with SO, if possible. When clients tell us to go visit a tailings operation in order to start a risk assessment, we always try to dissuade them from starting the deployment that way. We want to know the dam system before we visit it. As a result, when we go to the site we want to be able to reconnect what we see with what we have learned. Thus, we start by spending days reading and annotating extant reports. That's the only way we know to discover hidden deficiencies, to evaluate uncertainties and to come up with the KPIs we need to feed our quantitative risk assessment platform (Oboni, Oboni, 2020).

As volumes of global data increase exponentially risk analysts have to review larger volumes of information quickly and accurately to increase process efficiencies and avoid paralysis. Fortuitously, the capabilities of technology and machine learning to augment human review have been growing at a rate comparable to that of data (Oboni, Oboni, 2021). Today, we find ourselves with highly developed technological approaches, but it can be difficult to know which technology to utilize and why.

In this section we highlight technologies and tools commonly implemented to drive proactive strategies and work in partnership with reactive tools, in order to aid in risk identification. We also touch on the importance of project management for effective technology implementation in this field.

Please note that the list provided is not exhaustive, as there are many other analytics and machine learning tools that can be deployed to help streamline the ability to identify hazards. However, these are the most common tools used, for instance, in the legal discipline and scientific research and that can be tweaked for risk assessment purposes.

Let's note for a start that there is no one information governance strategy, but professionals in this space commonly refer to it as "getting your data house in order". The process of information governance removes junk data (Fig. 2), reduces the risk of errors in your data and/or alleviates the downstream work of having to sift through stacks of digital hay to find that needle.

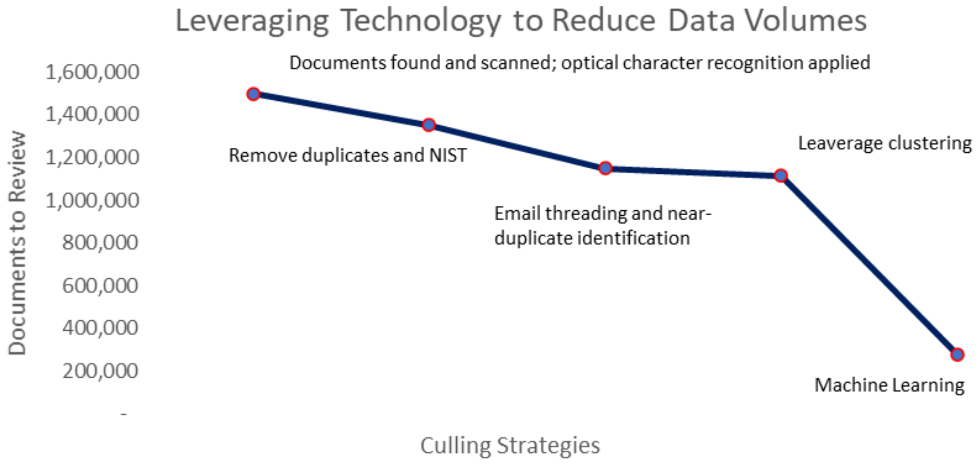

Fig. 2 Leveraging technology to reduce data volumes: stepped approach can reduce documents number five- to six-fold (Oboni, Oboni, 2021)

Due to the age of archival documents, optical character recognition is of course a must. Beyond that, here is a sample of analytic and machine-learning tools, what they do, and why we use them:

- Email threading: identifies and groups together emails that are part of the same conversation/thread: useful to suppress duplicates.
- Near-duplication: groups documents that are highly similar to each other and identifies differences, similar to track-changes. It is useful for identifying documents that have undergone revisions, or for finding 100% text-similar documents of different formats.

- Categorization: allows many documents or paragraphs to be submitted as examples and returns documents that are conceptually similar to those examples: similar to concept searching, but on a larger scale.
- Keyword expansion: identifies different language used to express the same or similar concepts.
- Supervised machine learning and continuous active learning: uses input from reviewers to categorize documents in the database and predict whether they are likely to be relevant. Data volumes can be substantially reduced using this technology.

There are many reasons to incorporate these tools into Quantitative Risk Assessments (QRA) workflows, including providing early access to key information, organizing information faster than ever before, decreasing the time needed for review, reducing costs associated with review, and the ability to handle more work while keeping headcount the same.

Below, we briefly highlight the execution and monitoring/controlling aspects of the implementation of technology in tailings dams risk assessment.

- "Garbage in, garbage out". The phrase skillfully articulates that, in the sense of training continuous active learning tools, the end result directly correlates to user input (human reviewer). The software continues to learn as more documents are coded by human reviewers and uses advanced statistics to determine when reviewers can stop based on the probability and predicted number of documents that directly correlate to human training may remain in the unreviewed set. Therefore, human input remains so far the most essential piece of any machine learning workflow.
- As you embark on your technology implementation journey, it is important to remember that there is not a "magic button" that will completely remove the human element of review. There are tools to help augment human review so identifying hazards/anomalies can be done faster and more accurately. The ultimate goal of incorporating technology into human review is to weed out irrelevant documents and focus on the pertinent issues, while minimizing time spent and concentrating efforts on high value tasks.

Like for monitoring, archival documents search and interpretation is paramount to complete the knowledge base necessary for a rational and sensible risk assessment.

6 CONCLUSIONS

Tailings dams risk assessment must be performed in a rigorous way where systems under scrutiny, their hazards and potential divergence must be clearly and transparently identified to avoid meaningless results. We have first discussed space observation monitoring, a method that, when properly implemented, can bring significant advantages to the analyses, particularly with respect to the past behavior of a structure, which cannot be investigated with any other method. We have of course also stressed the importance of monitoring and archival documents reviews showing how blending these techniques is important to support rational risk assessments. Pros and cons have been highlighted and some recommendations have been suggested: in particular, measurements and results need to be interpreted with great care by expert personnel. Space Observation does not substitute any other monitoring system and the usual on-site visual controls and like any other monitoring program, cannot shelter its users against fragile and sudden failures. In the second part we have concentrated our attention on the need of creating a knowledge-based database of past documentation via modern advanced search techniques by highlighting the new technologies and tools available to us for a proactive strategy in documental review.

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