SPACE OBSERVATION AND QUANTITATIVE RISK ASSESSMENT SYNERGY DELIVERS VALUE TO MINING

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ABSTRACT

In this paper we demonstrate how Space Observation and Quantitative Risk Assessment synergy delivers value to the mining industry. The term Space Observation refers to a mix of radar and optical satellite image data, as well as specific algorithms that are input into a Quantitative Risk Assessment (QRA) platform. We describe a QRA platform capable of using that “Rich Data” context to deliver an enhanced, updated risk landscape of a project or operation. The QRA platform has to be updatable, scalable, drillable and convergent to maximize benefits.

This paper provides examples of specific applications this joint technology provides to miners, allowing for better Risk Informed Decision Making, which in turn generates value.

The marriage of rich data context with an optimized risk assessment platform brings significant advantages to mining end-users, whether they are mining managers, tailings stewards, other key stakeholders, or the general public.

Preliminary quantitative risk off-line studies, using multiple data sources, deliver initial estimates regarding probability of occurrence of various failure modes, consequences of those failure modes, and preliminary alert thresholds. They also provide results that assist in the setup of emergency procedures.

Thanks to Space Observation technologies, it is then possible to confirm and gradually calibrate extant data, as well as validate old reports and their assumptions.

An additional key benefit comes from high resolution imagery which can be used to rather inexpensively perform quantitative analyses of surface features, volume measurements, and other terrain calculations. These analyses can be employed to verify the volume of mass movements, as well as whether they are man-made (construction) or natural (slides, displacements, erosion) hazards.

By virtue of this joint technology it is also possible to identify emerging crises; check and update alert thresholds and, in timely and orderly manner, update probabilities and all other significant hazards and risk parameters.

This allows to understand where projects or operations stand in term of risk mitigation at discrete and up to almost real-time pace, if and when required.

1. INTRODUCTION

1.1 Quantitative Risk Assessment (QRA) methodology

In this section we summarize the capabilities of a updatable, scalable, drillable and convergent Quantitative Risk Assessment (QRA) platform named Optimum Risk Estimates (ORE, ©Oboni Riskope Associates Inc.) developed and tested by the first two authors (Oboni, Oboni, 2016) on mining operations and restoration projects all over the world. The platform was deployed in 1999 to guide a restoration project of an orphan asbestos mine which was the object of a competitive international bid (Oboni, Oboni, 2017). Winning an international bid using Risk Informed Decision Making guided by the ORE platform confirms that this type of approach can deliver value, if properly applied and deployed.

A systematic approach to risk considerations in decision-making and project management support is indeed paramount especially when various layers of uncertainties surround alternatives, projects, operations, because decision-makers need to understand the:

- assumptions made, so that evaluations can be discussed, audited,
- uncertainties surrounding the decision,
- probabilistic future behavior (evolution),
- benefits of updating risk information during the life cycle of the system,
- benefits of a scalable (from "high level" to detailed operational, no information wasted) risk analysis system.

That is particularly important if we want to build realistic and sensible risk assessments. Because we want the model to depict reality as best as we can, the approach needs to cover:

- physical losses (human and assets),
- business interruption (BI),
- environmental damages,
- reputational damages and crisis potential.

Figure 1 shows the scheme of the ORE continuous QRA process: it is scalable and drillable from cradle to grave for any project, alternative, operation. The top left box "Rich Data Context" is where the link between rich data deriving from Space Observation (discussed in Section 2.2), historical and extant documentation, and ORE takes place. ORE evaluate risks in the drillable Data Base and delivers its results with a series of graphic representation (dashboards, in Prioritization and Displays) and other communication means agreed upon with the client. ORE delivers an updated multi-hazard risk landscapes for the studied system at each cycle allowing adaptive project enhancements from pre-feasibility to closure. The frequency of the cycles is determined with the client, based on criticality of the system, need to respond etc.

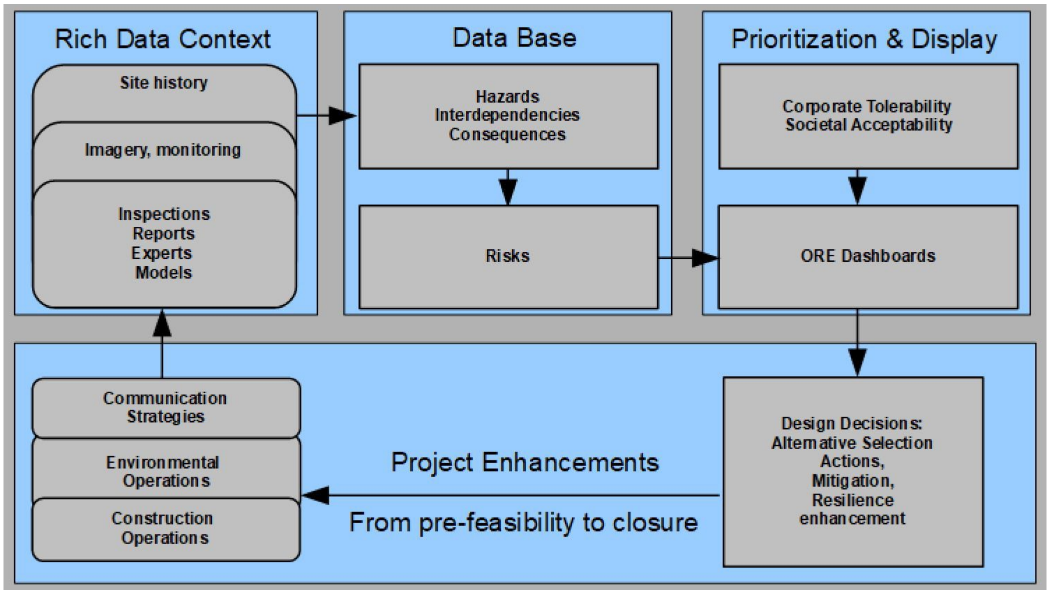

Figure 1. Scheme of the ORE (Optimum Risk Estimates) continuous process. Scalable and drillable from cradle to grave for any project, alternative, operation. The top left box is where the link between rich data and ORE takes place.

Data from extant reports, monitoring devices, expert opinion and rich data (e.g. space observation) are merged, after taking the necessary precautions, to distill new probability-magnitude estimates for the hazards and their consequences, thus allowing Bayesian updates of the risks at each cycle. At each new cycle risks are displayed in ORE dashboards to give managers and decision makers the best possible understanding of the risk landscape evolution.

Through the process uncertainties are re-evaluated in the risk register. ORE foresees the formulation of a blended consequence metric to be agreed in advance of any specific Risk Assessment with the Client. “Total risk” is defined for each record. Deliverable is a General Risk Register, sorted by decreasing “total risk” or other selected drillable filters. ORE foresees the treatment of the prior results based on proprietary methodologies as follows:

- definition of the Client's Risk Tolerance Threshold for its operations.
- A ranking based on the intolerable part of risks is developed to highlight critical areas of the operation and to guide recommendations on possible mitigations.
- This ranking leads to effective risk based/informed decisions (Oboni, Oboni, 2014).

As an option ORE foresees the probabilistic alternatives' life-cycle evaluation “from cradle to grave” with CDA/ESM (Comparative Decision Analysis/Economic Safety Margin ©Oboni Riskope Associates Inc.). In this phase risk results from the prior steps will be integrated, meanwhile avoiding the pitfalls of other project evaluation methods such as NPV (Oboni, Oboni, 2010). ORE also comes complete with a set of communication documents which allow to properly inform all the stakeholders on the outcome of the Risk Assessment. Figure 2 displays a typical ORE dashboard for a project.

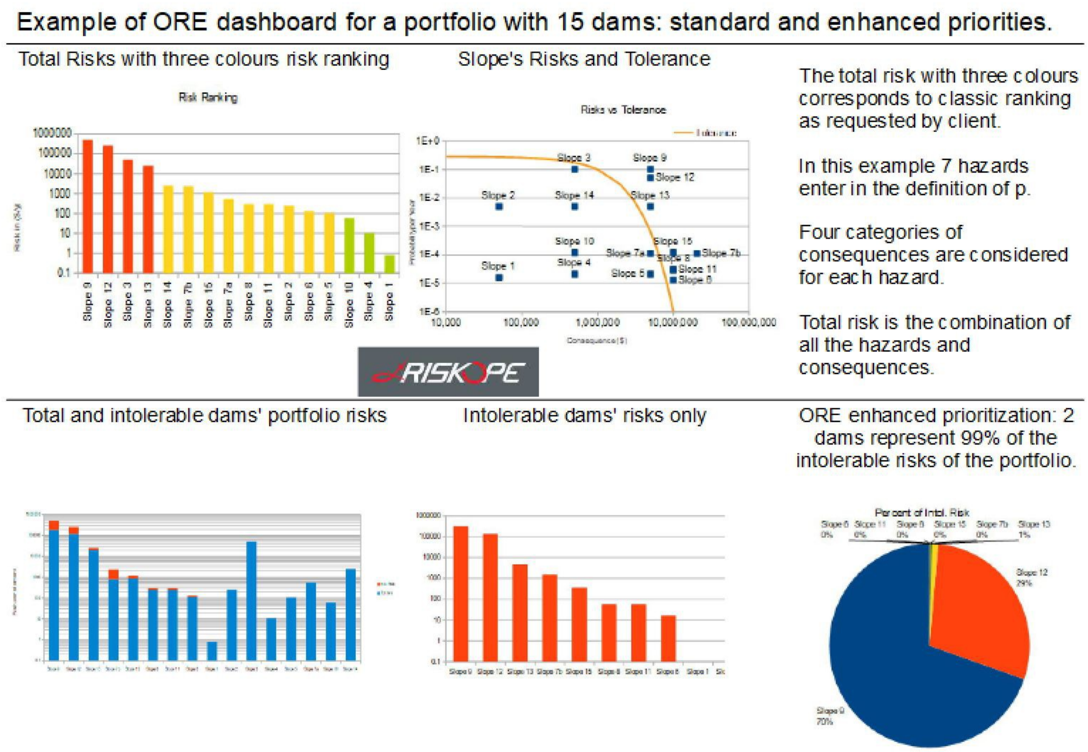

Figure 2 ORE dashboards show the most critical sources of threats to the project or alternatives, and many other data constituting the risk landscape of any endeavour.

It is possible to understand what are the most critical sources of threats to the project, which elements and hazardous sectors are loaded with the largest potential losses (split by type of loss: physical, BI, environmental, etc.), where the highest logistic risks are and even how the media vulnerabilities are distributed within several elements (projects, alternatives, operations, etc.) of a same endeavour.

1.2 Space Observation

Satellite imagery can be used for a variety of tailing dam observations. MDA and its sister company Radiant Solutions, part of Maxar Technologies Ltd., use a two pronged approach for this. To help evaluate conditions over large areas, MDA employs automated methods to identify:

- where there are potential areas of change or encroachment,
- quantitative differences in soil wetness or standing water, and
- vegetation health issues relative to similar vegetation of past years.

The second step in the analysis involves a manual search by an experienced interpreter of higher resolution imagery to identify what the nature of the change was, and to conduct a checklist search to identify any other issues of concern. The automated and manual interpretations are intended to complement each other and limit residual risk related to this element of monitoring. The automated methods are effective in drawing the interpreter's eyes to areas that might be overlooked otherwise, and the manual inspection ensures that items that may have been missed by the algorithms are caught.

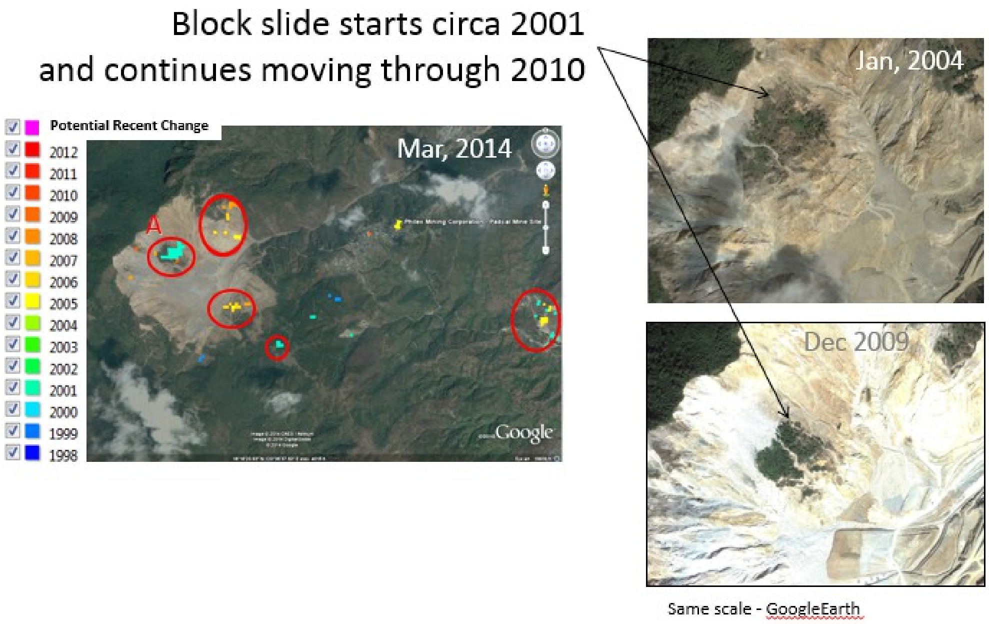

***Figure 3** Identified areas of change as well as the year in which the change occurred as a result of mining induced activities. Zone A represents large rock mass movement*

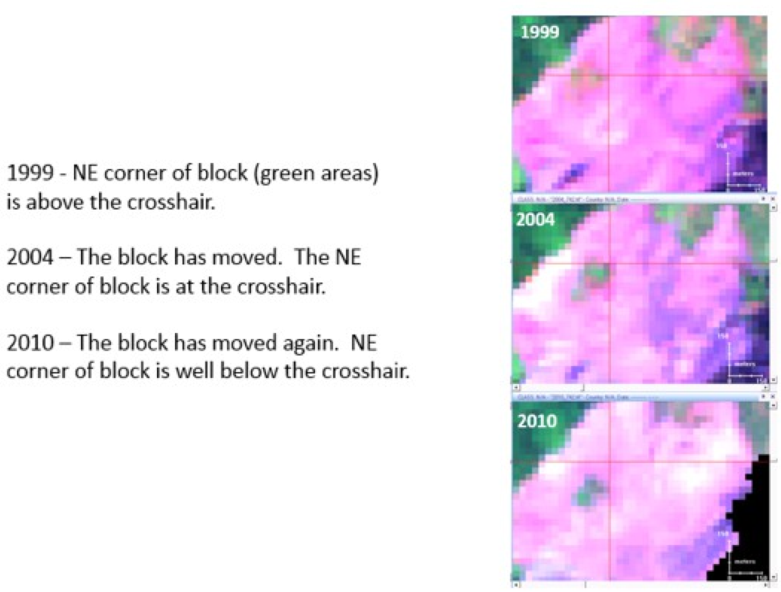

***Figure 4** PCM® methodology identifies the gradual movement of rock mass over time. Being able to identify the on-start of movement from archived images is paramount for risk assessment purposes.*

Two examples of an automated process are constituted by the Persistent Change Monitoring (PCM®) output shown in Figures 3 & 4. These examples, from the Padcal mine in the Philippines show changes in the mine area, that turned out to be related to earth movement caused by mass mining techniques. Change products created by PCM® are annotated by the date and nature of the change, and these parameters are made available to the ORE platform to evaluate/reevaluate overall risk.

2. NEW TRENDS AND REQUIREMENTS

Recent failures and related independent panels post-catastrophe comments, recent literature have highlighted common features in mining/tailings accidents. These can be summarized, but are not limited to:

- Absence of risk assessment or even of common health and safety programs. Let's note that typical, common practice, risk matrices (FMEA, PIGs) can only correctly and unambiguously compare a small fraction, reportedly less than 10%, of randomly selected pairs of hazards. Furthermore, they can assign identical ratings to quantitatively very different risks, a phenomena often referred to as "range compression" and can mistakenly assign higher qualitative ratings to quantitatively smaller risks and vice versa. These inaccuracies can lead to mistaken resource allocation. (Oboni, Oboni, 2012). Additionally we note that assessors often censor and bias risk assessments towards "credible events". However history, even recent, has shown that major failures occur when "incredible events" occur. Another cause of failure can be a long chain of apparently benign events. The public has now got these fallacies clearly in mind, generating widespread controversy and projects' opposition (Oboni at Al., 2013).
- No peer review. Independent peer review of water dams is a long-standing practice. It is disgraceful that all regulators do not insist on it. Until they do, and peer reviews become very serious endeavours, we see no hope of reducing the incidence of tailings facility failure (Morgenstern, 2010, Caldwell, 2011).
- Limited engineer involvement that appears to have been aware of potential problems but not heard or acted on. Alarming disconnect comes from the poor definition of potential consequences of mishaps and their societal ripple effects. This aspect is indeed mostly ignored in codes, leaving professionals ample room to biases and censoring applied to potential losses (Oboni at Al., 2013, CDA, 2014).
- Overconfident mining companies that did not act when prudence may have so dictated.
- Absence of significant regulatory oversight or involvement. Risks assessments are "at risk" if plagued by conflict of interest or overly optimistic cognitive biases, or censure. (Oboni, Oboni, 2014).

Furthermore it also appears that given the nature of tailings dams, their construction time and expected service life and closure, the effects of today's risk mitigation programs will only slowly become visible because the world-portfolio will contain mitigated and unmitigated (legacy) dams requiring restoration. During that period the public will perceive at best a status-quo and the industry credibility and social license to operate (SLO) will remain at stake (Oboni, Oboni, 2014; Oboni, Oboni, Zabolotniuk, 2013). It will be very difficult to evaluate progress as factors such as climate change, seismicity (not necessarily “Black Swans”, MCE), increase in population and environmental awareness (consequence side of the risk equation) will further complicate the situation. Thus public outcry and hostility toward the mining industry, fuelled by the Information and Communication Technology diffusion will likely increase if transparent, rational, and defensible approaches to dam portfolio and other mining industry's risk prioritization aren't swiftly implemented (Oboni, Oboni, 2016).

Furthermore the recent key note lecture by Henry Brehaut at TMW2017 stated that “….clearly, the need emerges to develop risk assessments that are detailed and updatable, that allow determining residual risks (after mitigations), perform risk adjusted perpetual cost estimates and draw rational and sensible mitigative roadmaps”.

It therefore not surprising to read the recent UNEP (Roche et al., 2017) report entitled “Mine Tailings Storage: Safety Is No Accident” asking mining companies to make environmental and human safety a priority in management actions and on-the-ground operations by requiring:

- detailed and ongoing evaluations of potential failure modes,
- residual risks (UNEP uses this term to indicate the risks after known mitigation)
- and perpetual costs of waste storage facilities.
- All those point go in the direction of long term monitoring and observation, updatable quantitative risk assessments which are the subject of this article.

In the next sections we will show how ORE+Space Observation support this kind of endeavours.

3. PRINCIPLES ENABLING THE COUPLING OF SPACE OBSERVATION AND ORE

Obviously the link between Space Observation and ORE is beneficial, insofar it allows feeding enhanced data into an a priori risk assessment and to deliver on a regular basis updated risk assessments with an economy of means while answering modern requirements.

The purpose of this section is not to deliver the details of the how-to connect Space Observation to, say, probabilistic analysis of dams and dykes, for obvious space limitations.

Instead, it is to explain the principle and the angle of attack leading to prepare an automated or semi-automated probability updating system, i.e. how to generate the link between Space Observation and ORE mentioned earlier.

3.1 Space Observation themes and a priori Risk Assessment

Table 1 explains how various Space Observation Themes can be approached to deliver useful data for an a priori Risk Assessment and lead to benefit. That means using historic Space Observation database on a site that requires a first Risk Assessment.

Let's now examine which data can be gathered on a regular basis over cycles of observation and the principles by which they can be used in updating probabilities and consequences of a quantitative risk assessment.

Table1 Space Observation Themes vs. data for a priori risk assessment and benefits.

Space Observation Themes	Approach	Data for a priori Risk Assessment	Benefits from enhanced data
Visual Inspection	Visual comparison of imagery at different times	Pre-existing damages, damage evolution	Increased efficiency of site visits (if still necessary) based on history
Quantitative geometry, topography data	Contour lines comparison (volumes, deformations), tension cracks, cross sections definition	Detection of potentially unstable volumes, slow creeping volumes, deposit and erosion.	Enhanced Hazard Identi-fication of existing or potential phenomena such as slides, debris flows, flash-floods, rockfalls etc. Probability estimates.
Quantitative surface hydrology data	Water/solid flows, drainage patterns, erosion patterns and deposit areas definition	Detection of potential debris flows, drainage malfunctions, overflows.	
Quantitative slope cover data	Slopes, orientation, vegetation cover health and stress definition	Detection of vegetation distress and its causes. Permafrost loss potential. Snow accumulations.	

3.2 Examples of Space Observation and Risk Assessment updating principle

This Section considers a portfolio of dams or dykes as an example. We will first review freeboard, wet spots and dams' deformations, and finally symptoms driven methodologies. In the second part of this section we will then discuss the principles of automated re-evaluation procedures.

- It is generally agreed that the amount of free-board should be increased to protect areas with high value and high loss potential. A review of different free-board requirements in various countries provides some examples of the adopted values (MacArthur, Bowen MacArthur, 1991). Furthermore the beach length (distance between the crest of the dam and the water in the tailings pond) reduction is a well know indicator of poor potential stability conditions in the dam. Both free-board and beach length can be easily measured from satellite and impact on the probability of failure from their variation estimated based on pre-determined rules.
- The same occurs with wet spots on the downstream face of a dam, at the toe. Dam's deformations (vertical and horizontal) can be compared with known height/deformation ratio to determine the state of the structure.
- Finally, symptom-driven methodologies can be applied. Space observable characteristics which reportedly alter the probability of failure of a dyke or a dam are, for example:

- Existence of low spots (not enough free-board, leading to overtopping probability increase),
- Presence of erodible material on the slopes,
- Oversteepened slopes,
- Narrow spots on the crest,
- Encroached width, toe erosion, works at toe, etc.,
- Stressed vegetation,
- Easily accessible structure, poorly secured perimeter, residences proximity,
- Lack of maintenance/repairs.

The Automated re-evaluation procedure principle allows to use Space Observation data to update probabilities of failure and consequences. As discussed earlier, the preliminary risk assessment estimates a range for the likelihood of failure of various events. The range can then be split in positive partial contributions by giving relative weights to the positive observable characteristics, based on literature results, for example as displayed in Table 3 which uses a dyke case study.

Table 2. Positive observable characteristics

	Characteristic	Relative Weight
1	Not a low spot	19.30%
2	Riprap on the “waterside”	10.50%
3	Mild pitch of the dyke on the “dry” side	6.60%
4	Extra dyke width, Crest width of the embankment	3.85%
5	Revetment of the embankment crest (paved, etc)	3.30%
6	Encroached width, toe erosion, etc.	2.75%
7	Trees on the dyke on the “waterside”	1.65%
8	Easily accessible, not private property, close from residences	1.10%
9	Low velocity at the toe of the embankment	0.55%

This lead to determining the dyke's likelihood and finally to the prioritization for each segment based on positive space observable characteristics (extant mitigative measures and features) as shown in Figure 5.

Continuing with the dam/dykes example, the next step of a risk analysis involves the evaluation of breaches which lead to downstream consequences. The first step is of course to determine the breach size.

Literature shows that dam breach size models rely on many assumptions and are mostly based on geometry of the embankment and retained water levels/volumes (Franca, M. J. & Almeida, A. B.,2004; Morris, M. W., 2005; Zagonjolli, M. & Mynett, A. E., 2005, U.S. Bureau of Reclamation, 1988).

In a 2013 study by Nourani & Mousavi (2013), 142 embankment dam breach data were collected from reliable references and dam breach equations analyzed. Dimensional analysis and multiple regression were used to predict maximum outflow from earth dam breach.

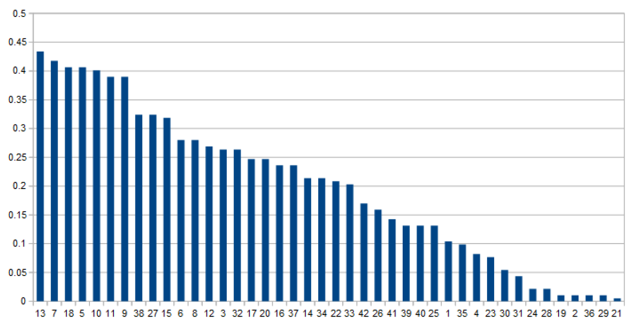

FIGURE 5 Segment prioritization based on positive observable characteristics

Uncertainty of empirical relations was determined using appropriate statistically method. The following general results were derived by Nourani & Mousavi (2013) from collected data by studying 142 embankment dam breaches:

$2*h_d <= B_m <= 3*h_d$ where
B_m=average breach width (m); h_d = dam height (m)

B_{top}/B_{bottom}= 1.13-1.64 width at top, bottom of the breach.

If we note as V_w the water volume above break point of bottom (m^3) and h_b the height of water above breach bottom the analyses performed in the study yielded the following regression:

$B_m= 2.2839* V_w^{0.0635} * h_b^{0.8481}$ with $r=0.918$

All the above data are Space Observable and lead to the results we have shown.

The final step is to develop a breach outflow analysis and through that to evaluate the downstream consequences. Let's note that unless major changes intervene it is not necessary to redo a dam break analysis each time, but variations in land use and density, which are all space observable will generate possible significant changes in consequences.

4. HOW TO USE CYCLES OF QUANTITATIVE UPDATES WITHIN THE ORE PLATFORM AND MDA

As shown in the prior section, it is possible to develop probabilistic updating of various types of data which may include, just to quote a few: deformation velocity (for example cm/year), number of events of a certain magnitude (for example number of events exceeding a certain magnitude per year), etc. The updating allows then to re-frame probabilities present in the ORE risk register and to re-evaluate the risks. In this Section we present a few techniques that can be used for the probabilities updating.

4.1 Frequency-probability updates using Poisson

Using the Poisson distribution it is possible to link the number of occurrences of an event over a selected time t to the mean occurrence rate (frequency). For example if 15 catastrophic tailings dams breaches events over 10 years have been observed (this has occurred on Earth in recent past), that means a measured frequency of 1.5 events/year.

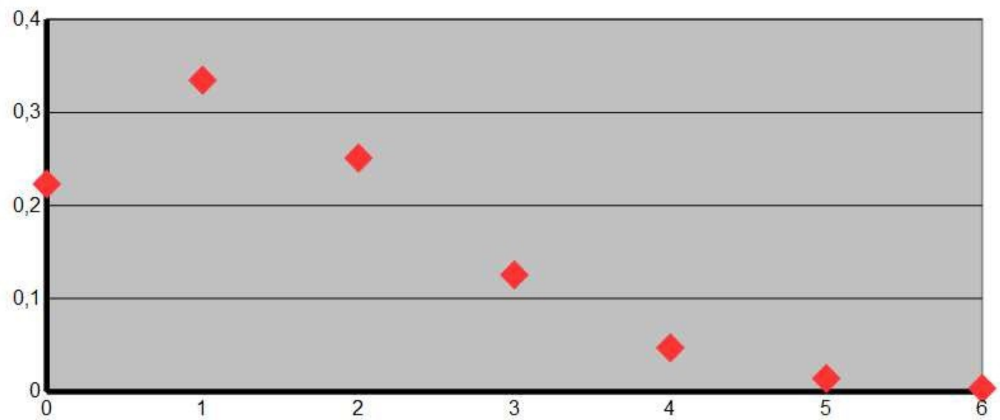

Figure 6. With a measured frequency of 1.5 events/year the probability of occurrence (vertical axis) of 1,2,3..n events next year (horizontal axis) can be evaluated using Poisson's distribution.

Using Poisson it is easy to compute and graph the probability to see any number of events (1,2,...n) during, for example, a single year. In Figure 6 the vertical axis shows the annual probability and the horizontal axis the number of events. It can be seen that with that frequency one event per year has p=0.33 to occur «next year», three events 0.12, etc.
As onsite monitoring and/or Space Observations deliver new occurrences of events, frequency and related probabilities can be updated in a new cycle, leading to updated risks yielded by ORE.

4.2 Exceedance probability updates

The exceedance probability is the probability of an event being greater than or equal to a given value, i.e. to exceed, for example a given Magnitude M. It is important to forecast the future exceedance of previously observed extremes. Based on repeated observations it is possible to re frame the probabilities of exceedance and thus to rationally update the risk register in ORE.

4.3 Bayesian updates

Bayesian analyses allow to update frequencies and probabilities as new data are generated (Ang, Tang, 1975, Straub, Grêt-Regamey, 2006) by Space Observation or other means. Consider for example the case where the available information is a set of observed n detached rocks from the slope, which are described by their volume and the time during which they occurred.

Note that the Bayesian update will be valid only insofar the observations are free of error (i.e. all rocks are recorded), reason why regular monitoring is a necessity. In order to allow later Bayesian update ORE includes the a priori estimate of frequencies or probabilities. If no data are available beyond a Min-Max range defined by models or expert opinions, the simplest and oldest rule is to assume a uniform distribution (Figure 7). However, if sufficient data were available, ORE could also be set-up with a more refined "PRIOR" distribution and then use Bayes to obtain the first "POSTERIOR" distribution... the the second posterior etc. The application of Bayes shows that one single event provokes a shift of the distribution as shown in Figure 8.

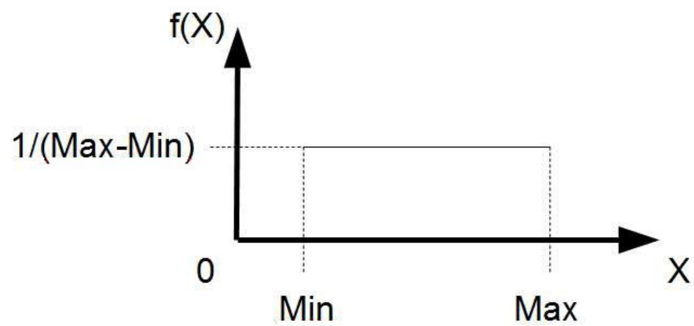

Figure 7. Uniform distribution f parameter x between its estimated extreme values Min, Max.

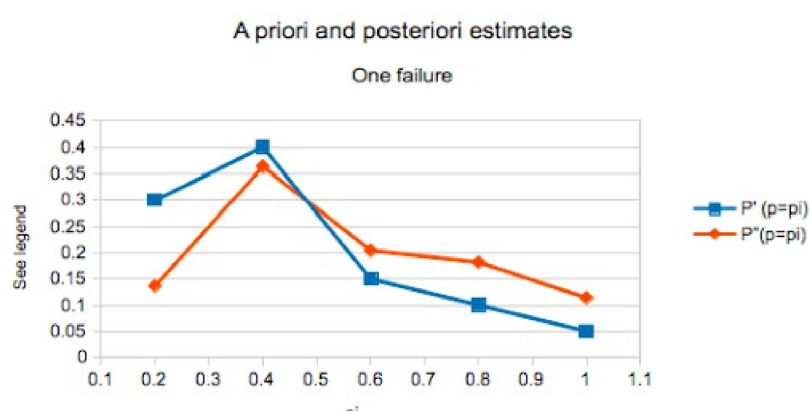

Figure 8. A priori and a posteriori distribution of a parameter x between its estimated extreme values 0.2 & 1.

5. SYNERGISTIC VALUE BUILDING

In Section 2 we saw the emerging need to develop risk assessments that are detailed and updatable, that allow determining residual risks (after mitigations), perform risk adjusted perpetual cost estimates and draw rational and sensible mitigative roadmaps. In Section 3 we showed that the link between Space Observation and ORE is beneficial, insofar it allows feeding enhanced data into a a priori risk assessment and to deliver on a regular basis updated risk assessments with an economy of means and to answer modern requirements. Finally in Section 4 we showed a few techniques allowing the probabilities updates.

In this Section we answer three basic questions related to residual risk assessment, i.e. "How, Who, How often" and for each define the Benefits/Values brought in by the ORE-Space Observation synergistic approach.

5.1 How to perform a residual risk assessment?

- First an a priori risk assessment is needed. It should detail and update evaluations of potential failure modes during the system life cycle. Defining the system is a fundamental step which requires lots of attention at inception.
- The understanding of the multidimensional consequences and the system's failure/success criteria definition are paramount. For example, oftentimes tailings dam's failure means different things to different stakeholders. e.g. engineer or regulators. Glossary has to be defined. Indeed what constitute a success from an engineering point of view might be of limited interest or value to other stakeholders (Riskope, 2016).
- The a priori risk assessment is used for risk informed decision-making on mitigation. Once mitigations are decided (and implemented) a a priori residual risk assessment is prepared. The residual risk assessment's risk register quantitatively integrates the data with mitigation leading to calculate the residual risks.

BENEFIT/VALUE: as ORE produces scalable, drillable, convergent risk assessments, no data will ever be lost or wasted. The risk register will be more detailed in areas that are better known, and uncertainties will be transparently conveyed in areas that are less known. The risk register will be ready to grow with the project/operation and will already support a priori decision making for mitigations.

5.2 Who has to perform residual risk assessment?

The UNEP report cited earlier also identifies a common practice that has to stop. The developer or design-engineers self-risk assessment has to stop as it is fraught by conflict of interest.

Independent risk assessor has to become the new norm. The report identifies this requirement in distinct ways. For example by stating: "Establish independent waste review boards to conduct and publish independent technical reviews prior to, during construction or modification, and throughout the lifespan of tailings storage facilities."

This of course must include an independent risk assessment at every step.

The report then adds:

- "Ensure any project assessment or expansion publishes all externalized costs, with an independent life-of-mine sustainability cost-benefit analysis." Including, of course the risks.
- "Require detailed and ongoing evaluations of potential failure modes, residual risks and perpetual management costs of tailings storage facilities." and

- “Reduce risk of dam failure by providing independent expert oversight” done by independent risk assessor to maintain good and unbiased oversight. This will “Ensure best practice in tailings management, monitoring and rehabilitation”.

BENEFIT/VALUE: The independent risk assessor will ensure a drastic reduction of conflict of interest and the delivery of unbiased risk reports. Space Observation and ORE will deliver to the independent risk assessor unbiased data interpreted using auditable rules, transparent risk registers. All requirements of UNEP will be met.

5.3 How often should one perform a residual risk assessment?

Ideally every-time the conditions change. This can range from weather patterns to managerial changes. Of course any addition/alteration to the overall system should trigger an update.
We have experienced that oftentimes situations change quickly and adaptive changes may require gathering different types of information from different areas. Any form of traditional (risk matrix: FMEA, PIGs) risk assessment update is too fuzzy and lacks definition to identify anomalies.

The ORE risk register will swiftly be updated depending on weather changes, water levels, wet spots etc. In theory, updates could occur in “real time”, at each satellite passage for very critical applications.
Practice and rate of movements, evolution, etc. dictate the optimum updates frequency.

BENEFIT/VALUE: Great economy of personnel, traditional instrumentation, time. Reduced risks for personnel on the ground in hazardous areas. It is possible to change frequency of monitoring to adapt to new and emerging situations.

6. CONCLUSIONS

The various examples above show the benefits found in linking multi-temporal objective Space Observation with ORE, a dynamic convergent quantitative risk assessment platform in mining projects and operations.

The deployment of Space Observation and ORE methodology developed to date enables us to “measure” and give a sense to a complex problem. It allows to:

- transparently compare alternatives,
- discuss rationally and openly the survival conditions, or to
- evaluate the premature failure of a structure.

The link between Space Observation “Rich Data” context and the risk assessment platform uses Bayesian updates of probabilities, frequencies and other selected parameters to distill the data used in the risk assessment. Connecting a dynamic quantitative risk analysis platform with a high performance data gathering technique reduces costs, avoids blunders, constitutes a healthy management practice, especially for long-term projects requiring short or long term monitoring including, of course, site restorations.

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