ABSTRACT:
Many actors need a screening level reliability ranking tool for earth hydro-dams, dykes, tailings dams portfolios. UNEP, authoritative voices in the industry recommend evaluating residual risks and perpetual costs of waste storage facilities.

Screening level evaluations have to be refined enough to grasp complex realities, yet operable enough to avoid paralysis by analysis. Tools have to be efficient, affordable, accommodate extant data and ready to adapt to new data.

A subset of the ORE (Optimum Risk Estimates) quantitative risk assessment methodology, covers those needs. The principles of ORE and its dams' subset have been tested, published and taught. ORE can also use Space Observation data to deliver historic background, first estimates and regular updates of the probability of failure of dams.

This wide spectrum approach delivers balanced view of the expected reliability, allows bench-marking each dam with respect to the world-wide portfolio of dams, including recent failures. Furthermore it allows for semi-automated regular updates of the risks.

This paper describes the dams' application while referring to numerous prior publications and courses delivering its theoretical backbone. Ample space is devoted to case histories and results with examples of radar and optical contributions to risk analysis.

RESUME:
Des méthodes d'analyse des barrages hydrauliques, pour résidus et digues sont requis par de nombreux agents. Les dernières recommandations par l'UNEP et des auteurs respectés demandent des méthodes d’évaluation des risques résiduels et des coûts totaux. Au vu du nombre d'ouvrages au monde, ou dans certain pays, il faut des méthodes assez fines, mais rapides pour éviter la paralysie par l'analyse. Il faut des méthodes efficientes, économiques, adaptables aux données disponibles dans le temps.

Les deux premiers auteurs ont développé sur un arc de vingt ans une approche de risque quantitative nommée ORE (Optimum Risk Estimates) qui correspond a ces besoins. ORE a été publiée et enseignée par le monde, ses applications couvrant de nombreux thèmes. Dernièrement ORE2_Tailings, dédiée aux barrages a résidus a vu le jour, ainsi que ORE2_Dykes. Elle permet l'utilisation de Observations Satellitaires pour l'analyse historique, premières estimations et mises a jour des probabilités de rupture.

Cette approche a large spectre donne une vue balancée de la fiabilité attendue, permet des comparaisons de performances, des mises a jour semi-automatiques régulières. Avec le temps les expériences constituent une nouvelle base actualisée.

Cet article décrit des case histories en donnant les références qui constituent l'ossature théorique de la méthode. Des cas d’étude montrent aussi la contribution des observations satellitaires radar et optiques aux études des risques.

Innovation in Dams Screening Level Risk Assessment

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1. INTRODUCTION

Lessons learned from recent tailings dams failures and related independent panels have been summarized by various authors over the last decade.

Absence of risk assessment oftentimes paired with fuzzy and misleading risk assessment approaches is considered by some as an important factor related to poor risk awareness. Indeed, typical, common practice, risk matrices (Failure Modes and Effects Analysis (FMEA), Probability Impact Graphs (PIGs)) end-up assigning 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 (Oboni, Oboni, 2012). Additionally assessors often censor and bias risk assessments towards "credible events" while history has shown that major failures are due to "incredible events" or long chains of apparently benign events, through normalization of deviance. Even though the public does not necessarily clearly understand those fallacies a growing distrust generating widespread controversy and projects' opposition (Oboni at Al., 2013) is rampant.

Morgenstern states (Morgenstern, 2018) the dominant cause of these failures arises from deficiencies in engineering practice associated with the spectrum of activities embraced by design, construction, quality control, quality assurance, and related matters. No surprise that the absence (or inadequacy) of peer review is a limiting factor in reducing the incidence of tailings facility failures (Morgenstern, 2010, Caldwell, 2011). Limited engineer involvement and alarming disconnect coming from the poor definition of potential consequences of mishaps and their societal ripple effects, an aspect indeed mostly ignored in codes, leaves professionals ample room to biases and censoring applied to potential losses (Oboni at Al., 2013, CDA, 2014). Inadequate understanding of undrained failure mechanisms leading to static liquefaction with extreme consequences is a factor in about 50% of the cases (Morgenstern, 2018). Inadequacies in site characterization, both geological and geotechnical, is a factor in about 40% of the cases. Regulatory practices, considered appropriate for their time and place, did not prevent those accidents (Morgenstern, 2018). Other failures have been generated by overconfident mining companies that did not act when prudence may have so dictated, the absence of significant regulatory oversight or involvement. Finally, 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", Maximum Credible Earthquakes (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, fueled 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, 2016a).

The recent key note lecture by Henry Brehaut at TMW2017 summarized the above, stating that "….clearly, the need emerges to develop risk assessments that are detailed and updatable, that allow determining residual risks (after mitigation), perform risk adjusted perpetual cost estimates and draw rational and sensible mitigative road-maps". The recent UNEP (Roche et al., 2017) report entitled "Mine Tailings Storage: Safety Is No Accident" reinforced these concepts 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) assessments and

- perpetual costs evaluation 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.

Additionally the UNEP report cited earlier identifies a common practice that has to stop. The developer or design-engineers self-risk assessment is indeed fraught by conflict of interest and thus is deeply non geoethical.

Independent risk assessor basing their assessment on auditable, repeatable selections of parameters have to become the new norm. The UNEP 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".

The independent risk assessor will ensure a drastic reduction of conflict of interest and the delivery of unbiased risk reports.

To end this review with a positive note, Morgenstern (Morgenstern 2018) states that "the success of the dam safety system applied to the Alberta oil sands industry relies on responsibilities shared by the owner, the Engineer-of-Record, the regulator, and various levels of independent review. However, given the relative small portfolio and the short temporal window of observation, we would be more cautious and talk about success "this far". We also note that to provide guidance on the extent to which external review boards are required, a third party risk assessment would be indicated as it would bring the clear benefit of creating a risk-based, rational classification of facilities.

The "good old ways" (a.k.a. Common practices, unfortunately still considered by some "best practices") do not make the cut anymore in tailings and other dams management.

In this paper we show how to deliver to the independent risk assessor unbiased data interpreted using auditable rules, transparent risk registers, so that the requirements of UNEP will be met. In particular, in the next sections we show how using quantitative risk assessment (QRA) techniques (Oboni, Oboni, 2016b) and Space Observation support this kind of endeavours for tailings dams, levees and other embankments.

2 WHAT CAN BE ACHIEVED THROUGH SPACE OBSERVATION TODAY

2.1 Technologies review

Available space observation relating to the monitoring of geo-structures includes Synthetic Aperture Radar (SAR), Interferometric SAR (InSAR), and specialized satellite sensors supplying high resolution imagery in the visible and near-visible wavelengths. Products available in the market place that relate these observations to applications include MDA's InSAR ground movement and Radiant Solutions' PCM® technology for deriving permanent change from optical sensors. A combination of these technologies is being used to strengthen and confirm data from on-site geotechnical and environmental instrumentation and allow seamless integration with risk assessments using ORE.

Obviously the link between Space Observation and QRA is beneficial insofar it allows feeding enhanced data into an a priori quantitative risk assessment and to deliver on a regular basis updated risk assessments with an economy of means while answering modern requirements. Indeed, the Space Observation techniques described in the sections above seamlessly integrate with the ORE risk approach.

The following steps are often included in the analysis of an embankments or a portfolio of structures and become integral part of the ORE risk approach:

- Historical InSAR Deformation Analysis - historical InSAR deformation analysis covering historical observation period (depends on extant coverage) using archived RADARSAT-1 satellite images designed to establish historical deformation trends within the area of interest.
- Forward InSAR Deformation Monitoring Program - forward InSAR deformation monitoring can be deployed for a selected observation period (for example one year) using RADARSAT-2 satellite images.

- Persistent Change Monitoring (PCM®) Analysis.
- Intermittent Water Analysis -IW- layers characterize water extent on the Earth's landscape over time.

2.2 Principles leading to a semi-automated risk assessment updatable system

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, due to 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 QRA mentioned earlier as the backbone of ORE2_Tailings and, of course also ORE2_Dykes.

ORE2_Tailings looks for example at thirty diagnostic points using a modified version of the semi-empirical methodology described by Silva and later Altarejos (Silva et Al. 2008, Alterejos et Al. 2015) custom tailored to the needs of tailings dams. Each diagnostic point is expressed by a weight, following a similar approach to the original methodologies referenced above. In order to allow swift, affordable analyses the symptom-driven methodology anchored by hundred years of failure history and in depth calibration has proven to offer the best solution. Table 1 summarizes the key Space Observable elements considered in ORE. These contribute among others to the probability of failure and allow swift updates of the risks generated by a single dams or a portfolio of dams.

Table1 ORE2_Tailings diagnostic points summary

Elements	General diagnostic nodes
Dam System Description	Tailings (beaches slopes, surface irregularities); Water (size and position of pond with respect to dam crest, bathimetry, volume); Reclaim pumps barge; Equipment on crown (Transport Lines, Spigotting, Traffic); Weir; Intake tower/pennstock; Diversion ditch.
Construction	Material; Berms & erosion; Cross Section; Supervision; Divergence from plans; Known errors and omissions.
.....	.....
Stability analyses	This data will come from client (if they have any records...), but possible instabilities (deformations, cracks, slumps) may be visible from Space Observation
Instability symptoms	Wet spots on the D/S face; Streaming, Ponding at toe (Temperature differential); Tailings deposited at toe.
Settlements analyses	All this data will come from client (if they have any records...) but settlement may be visible from Space Observation
.....	.....

As per the consequences analyses, the useful Space Observable data are topography precise enough to allow detailed calculations (the presence of man made fills, ditches, even only a couple meters high/deep, a few meters wide brings significant influence on the flooding behavior). If water bodies are present bathymetry is important as well. Finally, data on land use/occupation, residences, infrastructure, lines, pipes, storage facilities, parkings, etc. can also be integrated.

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 a recent paper we presented a few techniques that can be used for the probabilities updating:

- Frequency-probability updates using Poisson (Oboni et Al., 2018)
- Exceedance probability updates (Ang, Tang, 1975)
- Bayesian updates (Dezfuli et Al. 2009)

2.3 Examples of Space Observable data used in the case studies

2.3.1 Radar Observations

The use of SAR to study the earth's surface was made popular by the launch of the Earth Resources Satellite (ERS-1) and RADARSAT in 1990 and 1991, respectively. The current generation of satellites, including RADARSAT-2 can be programmed to provide a robust set of data over a mine site with observations that are not dependent on cloud cover.

From complex mine-related movement in the Swedish Arctic to long term multiple satellite observations of oil reservoir depletion in California, MDA has been providing InSAR solutions since the 1990s. InSAR solutions derive ground movement from a precise observation of the time that it takes for a radar pulse to be returned to the satellite sensor.

Radar reflections (Ulaby et al., 1986) are the result of the type of surface and the geometry of the observation. For instance, flat calm water will redirect the radiation away from the radar and an image will show low back-scatter values. A metal roof, oriented to reflect radiation toward the radar, is a very bright target while a ceramic structure would be basically invisible to a radar. With the understanding of the reflective properties of the structures to be observed, the dependability of radar means that it is possible to make long time series of observations that allow the automated detection of changes, for instance, from 1) construction, 2) soil wetness or standing water, and 3) vegetation health issues relative to year over year changes. Reproducible measurements of ground movement have been demonstrated to within 2 millimetres in a month (Henschel, Lehrbass, 2011, Henschel et al, 2015, Mäkitaavola et al, 2016). As an example, the movement on a tailings dam over a period of years is shown in Figure 1.

The graphic demonstrates a small range of movement over a long period of time. The accuracy of the InSAR and the consistency of radar measurements make it possible to watch for the development of movement trends altering prior risk estimates. The InSAR is particularly useful for the development of baseline movement before storage or mining activities begin, i.e. at prefeasibility risk assessment level.

Figure 2 depicts at left a raw InSAR image of a mining dump impinging on a pond (black rectangle). At right the figure shows the topographic surface variations over a period of two months. In this case a deformation of 25mm over two months was picked-up by Space Observation in an area where no other instrumentation was present. Based on experience, it is obvious that even the most experienced inspector would have missed that deformation during a standard inspection, should successive inspections have occurred at the same frequency. In Tailings 2.0 (Oboni et al., 2018) that deformation impacts a number of diagnostic nodes (see later Sections) and alters the probability of failure of that slope, possibly triggering an early alert.

2.3.2 Optical Observations

There are a multitude of optical satellite systems available for monitoring large areas and small scales to very high resolution. From the Landsat series of satellites supported by the United States Geological Service (USGS) to the high resolution sensors from Maxar's Digital Globe, optical satellites provide images of the planet in visible and near visible frequencies. Visible pictures of the surface are available with resolutions of a few centimeters and can provide instantaneous descriptions of a tailings dam and its surroundings.

Optical satellites can be very powerful. The immediate recognition of objects from the imagery, helps the human brain to provide context and quickly exploit the image information. Understanding change can be very quick from one image to the next but understanding the difference between a persistent change or a particular type of change can be more challenging. Fig. 1.Example of movement seen on a tailings dam by the long term use of InSAR. The movement is shown both as a cumulative image and as a progression of the labeled square over time.

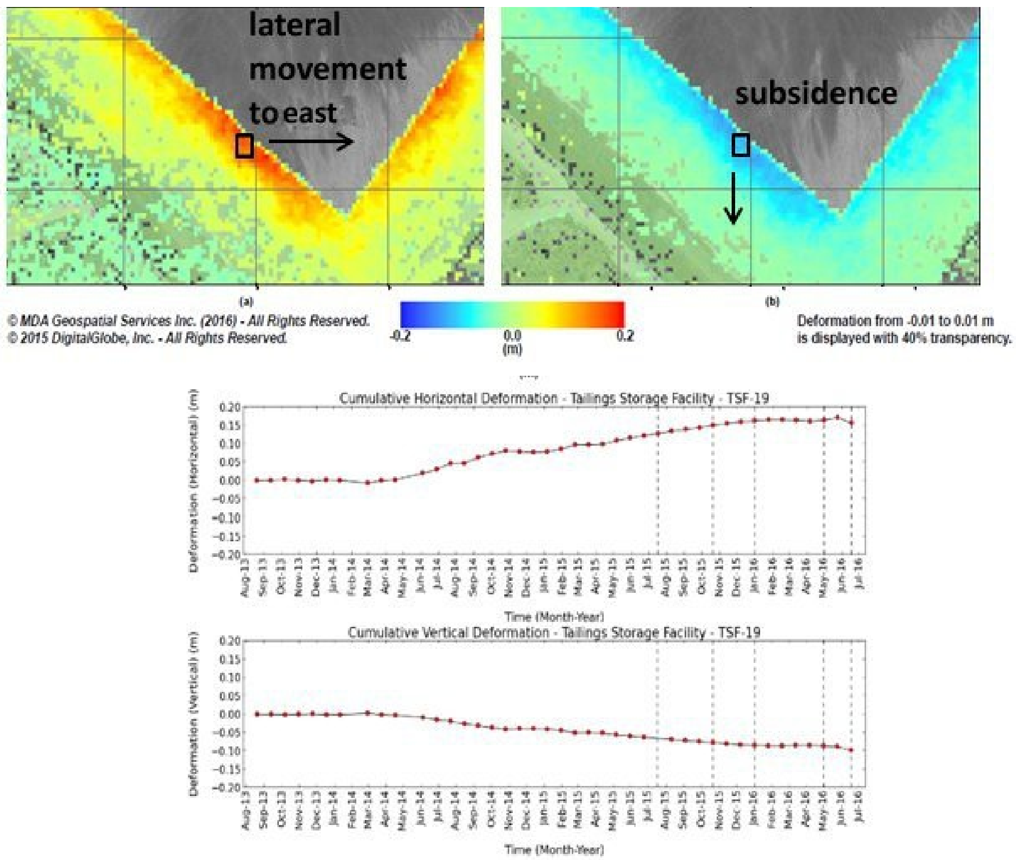

Fig. 1.Example of movement seen on a tailings dam by the long term use of InSAR. The movement is shown both as a cumulative image and as a progression of the labeled square over time.

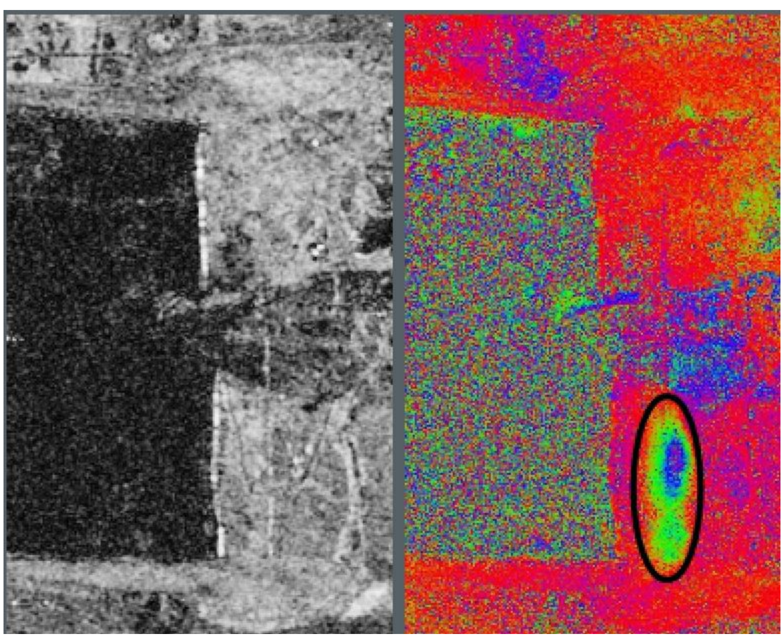

Fig. 2. Left: raw InSAR image of a dump impinging on a pond. Right: the ellipse encircles a zone of vertical settlement (0 to 25mm) which appeared over two months period.

PCM® and Intermittent Water Analysis (IW) help with the automated understanding of the magnitude and persistence of infrastructure or land use change and with the measurement of standing water cover and periodic surface water changes.

- Persistent Change Monitoring ("PCM") is an automated detection algorithm that identifies multi-date change within a series of optical satellite imagery. Some of the changes that PCM detected in other studies include: significant slumps or block (earth) movement; new standing water; new encroaching infrastructure such as roads, buildings, powerlines or pipelines; de-vegetation; and revegetation (from barren). Based on a Maxar Technologies-patented process, the algorithm is highly accurate and not affected by temporary features like clouds, crop changes, or data gaps. It is now being used by commercial companies, government agencies, and organizations for a variety of applications, such as identifying areas of potential encroachment risk/features and map updating.

  PCM requires a stack of imagery to initially establish baseline conditions, followed by a series of looks over the evaluation period. Reporting includes an indication of areas where change is verified (due to its persistence over time) and also an indication where there has been potential change that has not yet been verified.

  PCM requires imagery that is automatically tightly co-registered and, as a result, is limited to medium-resolution imagery (5 to 30m), such as LANDSAT or Sentinel. Pending suitable image availability PCM provides information on historic change which is a useful input for predictive risk assessment.

  PCM delivers data useful for ORE risk analysis such as:
    - When and where did historic change first or most recently occur?
    - Which change is definite vs. less likely based on the strength of the spectral difference and other factors?
    - What is the probable type of change?

  That information can be directly used within ORE to update the probabilities and consequences values in the risk assessment.

  Figure 3 displays an example of PCM outputs in the vicinity of the Jim Bridger Power Plant in Wyoming. It shows two dates of imagery indicating change near the dams. The containment areas behind some of these dams have alternately been filled with water and sediment over time.

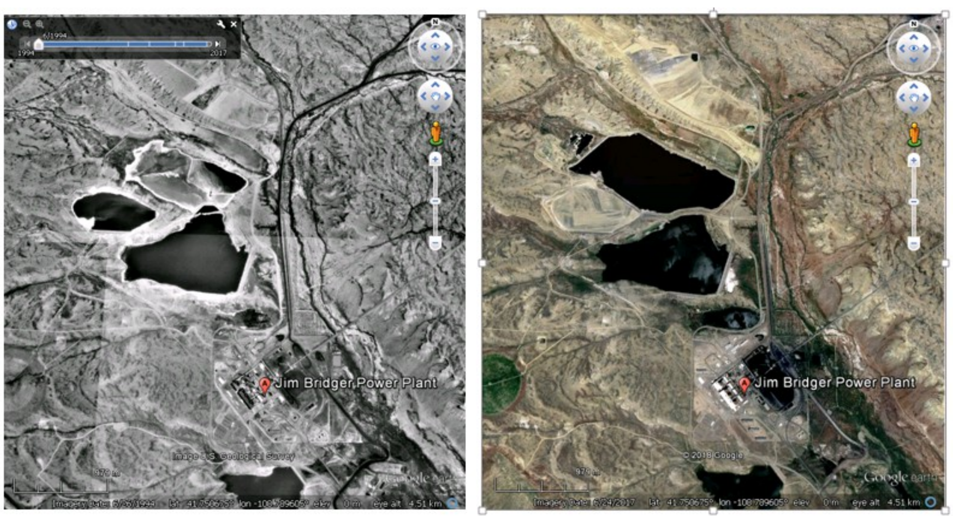

Fig. 3 Two data comparison of dam-related changes near the Jim Bridger Power Plant in Wyoming.© Maxar Technologies Ltd. (2018) – All Rights Reserved

  Figure 4 shows the PCM-confirmed change results over that region.

- Intermittent Water Analysis IW layers characterize water extent on the Earth's landscape over time. IW products are derived from a stack of 30+ years of LANDSAT imagery often totaling upwards of 500 historical images per location. A sophisticated process for very accurately extracting water at the pixel level is used to map water extent on each image individually. The individual water masks are then stacked and analyzed to count the number of water observations and frequency at each pixel. Frequency is summarized on the full dataset, decadal subsets of the images, and monthly subsets of the images. Finally, the frequency derived from the full set of imagery is used to generate a vector geodatabase of the naturally occurring lakes and ponds in the footprint.

There are three general categories of deliverable layers for each 30m pixel:

- layers related to the frequency that standing water is detected;
- layers related to the frequency that snow or ice is detected; and
- relative soil moisture.

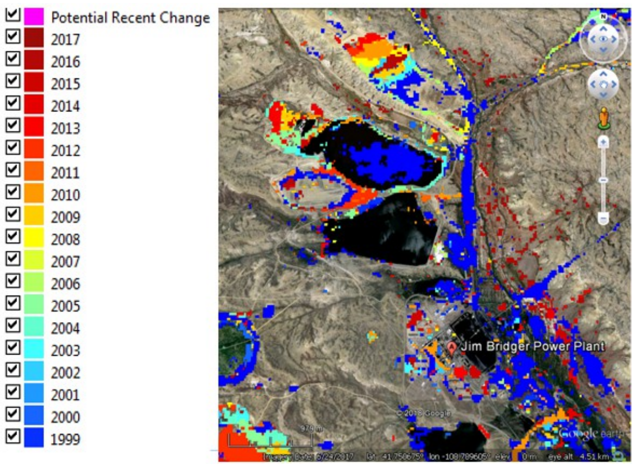

Fig. 4 PCM result for confirmed change Each of these categories has additional statistical layers related to observations clustered by month or decade, as well as average or extreme values per pixel. © Maxar Technologies Ltd. (2018) – All Rights Reserved

The above leads to probabilistic analysis of dams and dykes with an automated or semi-automated probability updating system, based on the dynamic link between Space Observation and QRA mentioned earlier as the backbone of Tailings 2.0. Of course, like all systems of this kind, caution will have to be exerted during all phases of the deployment. This is not a universal panacea, but to use a car metaphor, a good set of lights to drive through the night and a couple more instruments in the cockpit to alert the driver in case of a emerging problem in a impartial, fact driven, emotionless manner. Thus, if we cannot ensure that sudden, unforeseeable failures will never occur, we can certainly say that the results of Tailings 2.0 will enhance planning and mitigation capabilities. It is indeed 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 Tailings 2.0 risk register and to re-evaluate the risks. As mentioned earlier, in a recent paper we presented a few techniques that can be used for the probabilities updating:

- Frequency-probability updates using Poisson (Oboni et Al., 2018)
- Exceedance probability updates (Ang, Tang, 1975)
- Bayesian updates (Dezfuli et Al. 2009)

3 CASE STUDY: TAILINGS DAMS PORTFOLIO

This case study bears on a portfolio of 15 tailings dams of various makes and state, namely:

- Center line/modified center line rock-fill dams with no anomalies detected to date.
- Upstream dams of excellent quality with no anomalies reported to date.
- Dams of various types presenting seepage problems, ongoing deformation (lateral and vertical).

Figure 5 shows in the vertical axis the annual probability of failure results for the portfolio. The horizontal axis shows the various dams as well as four bench-marking values. Those are: Mount Polley and Samarco annual probability of failure evaluated with ORE2_Tailings methodology (Oboni, Oboni, 2017a), the min-max values of the world-wide portfolio based on historic records and the values obtained by a Ph.D. thesis (Taguchi, 2014) at UBC.

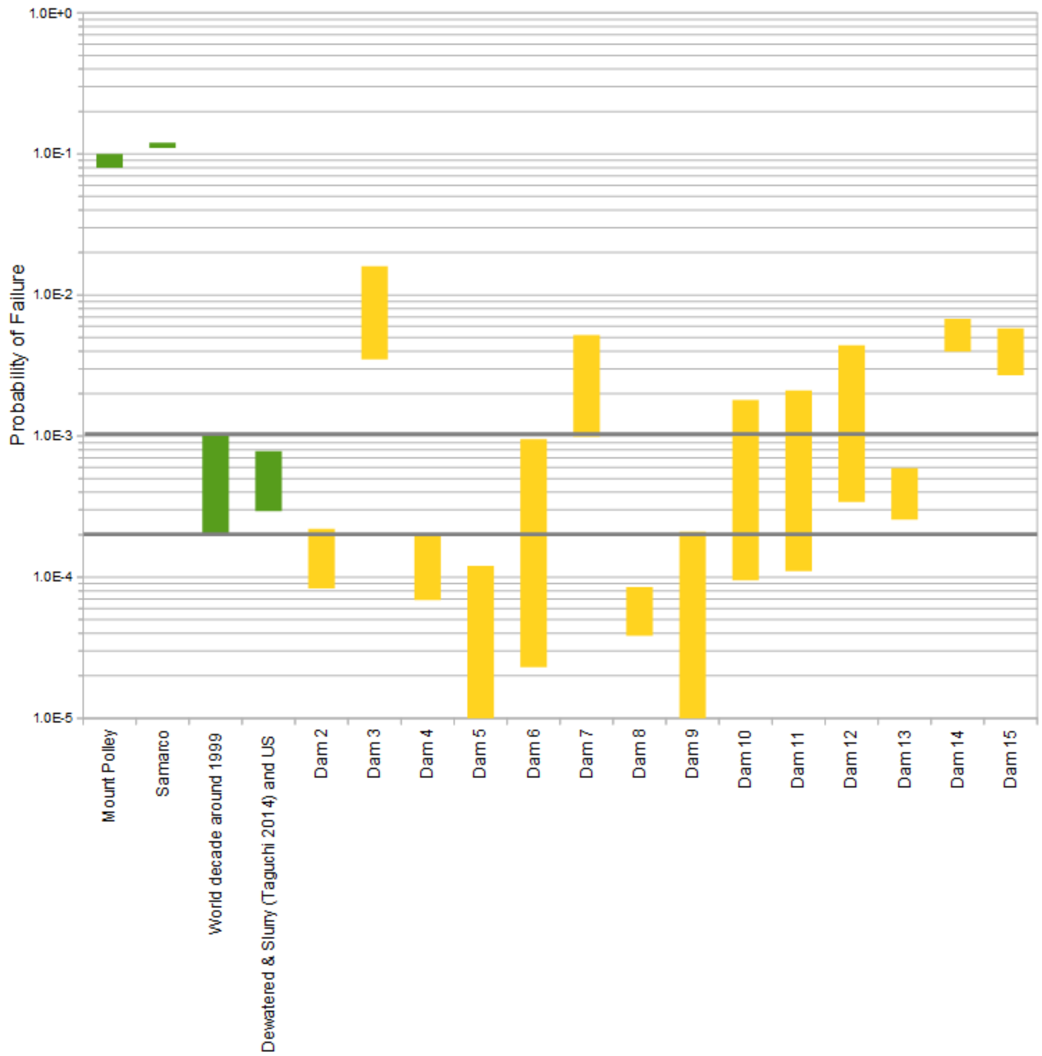

Fig. 5 Annual probability of failure results for a real life tailings dams portfolio with 15 dams.

The thesis attempted a theoretical estimate of the annual probability of failure of standard and dewatered tailings. For each structure the yellow bar in Figure 5 depicts the uncertainty related to the probability estimate.

Dam failures generally are the result of a series of “original sins” (Oroville Independent Forensic Team Report 2018, Mount Polley Independent Expert Engineering Investigation and Review Panel, 2015) and “normalized” deviances. ORE examines thirty diagnostic nodes (from inception to the date of analysis (Oboni et al., 2018) to deliver the estimated annual probability of failure of dams. This wide spectrum approach gives a balanced view of the expected performances and allows ORE2_Tailings to benchmark each dam in respect to world-wide portfolio of dams and also well known failures.

Here is a summary of the case study portfolio notes and results:

- Dams 2 and 4 are water dams with some reported defects.
- Dam 5 and 9 are modified center-line rock-fill dams. The difference is that the extent and depth of the investigations for Dam 9 were not as developed as for Dam 5.
- Dam 8 is an upstream dam on excellent foundation, well studied, built, monitored and managed.
- Dams 3 is a upstream dam on weak foundation undergoing active deformations.
- Dams 14 and 15 are similar to Dam 3, but at an earlier stage.
- Dams 10 to 13 are "average dams", predicted to behave as the world-wide portfolio.

As it can be seen in Figure 5, the effect of uncertainties brings many dams to "straddle" the benchmarks.

The combination of the results of Figure 5 with the cost functions for each dam gives the risks (Figure 6) of individual dams. Figure 6 depicts the results for Dam 1 (and Dam 1 & 2 with interdependence, see Section 3.2, 3.3).

3.1 Portfolio bench-marking

The portfolio bench-marking shows that in the considered case there are dams below the historic benchmark. Some overlap the benchmarks limits and some are above the upper limit, however still significantly lower than Mount Polley or Samarco estimates. Additional studies and information allow to narrow the uncertainties (length of the yellow bars) and finally deliver a clearer bench-marking.

Mitigation will push the bar down. Long term lack of maintenance, climate change effects will tend to push the bars up.

3.2 Inter-dependencies and consequences

Interdependent dams can be analyzed and their effect included in the portfolio analysis as shown in Figure 6 for Dams 1, 2.

Furthermore, as inter-dependencies can cause amplification effects within a dam portfolio, ORE elegantly tackles this problem and delivers a meaningful vision by evaluating the probability of dominoes effects and their amplified consequences.

Also, ORE foresees the development of a portfolio-specific risk tolerance threshold, allowing users to determine which risks actually really matter in a portfolio based on multi-dimensional criteria.

Indeed ORE includes a multidimensional consequence function as consequences are generally multifaceted. This enables the integrated comparison of Project Execution, Community, Legal, Environmental, Financial, Technical and H&S Risks. This convergent risk vision fosters healthy discussions and helps organizations to build consensus on decisions at operational, tactical and strategic level.

3.3 Specific dam's assessments

In Figure 6 various scenarios for Dam 1 are displayed. Dam 1 mitigation shifts the risks downwards. Climate change effects increase the risks. Lifts will also increase the risks as losses will also increase. Finally inter-dependency between Dam 1 and 2 will generate the largest losses, but at a lower annual probability (of simultaneous breach).

It is therefore possible to understand which are the most critical sources of threats to the tailings dam in the portfolio or compare each tailings dam's risks, e.g. which dam and hazard are loaded with the largest potential losses (split by type of loss: physical, BI, environmental, etc.).

If the methodology applied to this case study is implemented though an application, then it becomes updatable, scalable, drillable. It can become part of a convergent Corporate Quantitative Risk Assessment (QRA) platform (Riskope 2018).

In order to avoid any misunderstanding it is necessary to define the terms we used above:

- Updatable. As soon as implementation or design selections are made risks can be updated quickly and affordably.
- Scalable. Whether the project is at pre-feasibility or at reclamation the same data base and model is progressively scaled-up.
- Drillable. Users get exactly the data they are looking for — quantified and prioritized.
- Convergent. Users get all the risks relative one to another. No more silo with Health and Safety risks separated from Community risks or Strategic risks, etc.

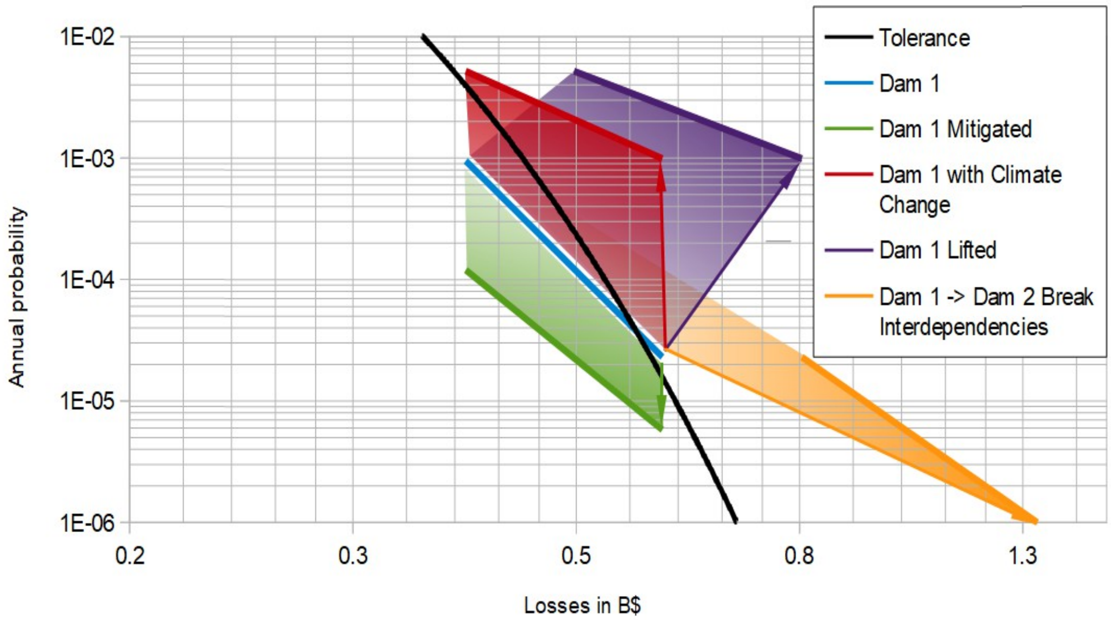

Fig. 6 Various risk scenarios for Dam 1 of the sample portfolio.

4 CASE STUDY: FLOOD PROTECTION DYKE

Assistance to an insurance company was provided in performing a probabilistic risk breach prioritization of a 50 kilometers long flood-protection dyke of a fluvial-marine area requiring flood and surge protection (Oboni, Oboni, 2018b). ORE2_Dykes was deployed.

Uncertainties and incomplete information were considered in the risk prioritization as detailed engineering analyses and testing were either not available or couldn't be performed due to various issues. The study goal was to show how fast the surface protected by the dykes would flood, in case of one or multiple failures, and estimate the actual capping water depth, i.e. show the influence of topography and tidal pulses on the flooding risks. Indeed, potential consequences, thus risks, of flooding strongly depend on water depth and velocity.

Crest chainage of the dyke had considerably changed over time due to settlement, reinforcements, construction. The location of low spots was investigated using LIDAR imagery which allowed to build the protected surface 3-D topographic model. Based on available data an approach was developed to determine the relative failure likelihood of the dyke's "homogeneous" segments. Actual failure locations were forecast in terms of relative probability. Thanks to the ORE updatable and scalable structure, the risk register can then evolve and be refined as information is collected, as actions need to be focused on the highest risks structures.

4.1 Dykes breach modelling

A great deal of data is needed to allow the application of various analytical methods to dykes stability and breach, including information about the sub-soil under the dykes and engineering works. However, in this case study data sets were incomplete or just non-existent. ORE2_Dykes is designed to cope with scarce data. It evaluates the relative likelihood of failure of apparently "homogeneous" segments of the levees. The approach detail is commensurate to available data.

ORE2_Dykes is based on a subjective, symptom-driven evaluation of the relative probability of failure calibrated on historic records from Netherlands.

A site visit was first carried out leading to observations useful in the selection of driving parameters for the probability estimates. The typical earth dyke sections were defined and homogeneous sections amenable to analysis defined.

Actual likely failure locations were predicted based on relative probabilities. Indeed, for each homogeneous sector, the likelihood of failure was estimated. A list of ten "highest hazard (likelihood)" segments prepared.

The next step was to evaluate breach characteristics using empirical literature relations based on more than one hundred dam breaches. Initial and “final” breach dimensions were estimated (from 16m up to 200m). At this point the hydraulic modeling started with the aim of understanding the development of maximum flooding levels including tidal pulses effects.

4.2 Dyke failure likelihood and prioritization

ORE2_Dykes differentiates cross sections based on (ground and/or space) observable characteristics which reportedly alter the probability of failure of a dyke. These are listed below:

- Not a low spot.
- Riprap present on the “waterside.”
- Mild pitch of the dyke on the “dry” side.
- Extra dyke width, wide crest width of the embankment.
- Finish of the embankment crest (paved, etc.).
- Encroached width, toe erosion, etc.
- Trees on the dyke on the “waterside.”
- Easily accessible, not private property, close to residences.
- Low velocity at the toe of the embankment.

The estimated range of the failure likelihoods was split in positive partial contributions by giving relative weights to the positive observable characteristics, based on literature results.

This lead to determining the segments' likelihood and finally to the prioritization for each segment breach probability based on positive observable characteristics (extant mitigative measures and features) as shown in Figure 7.

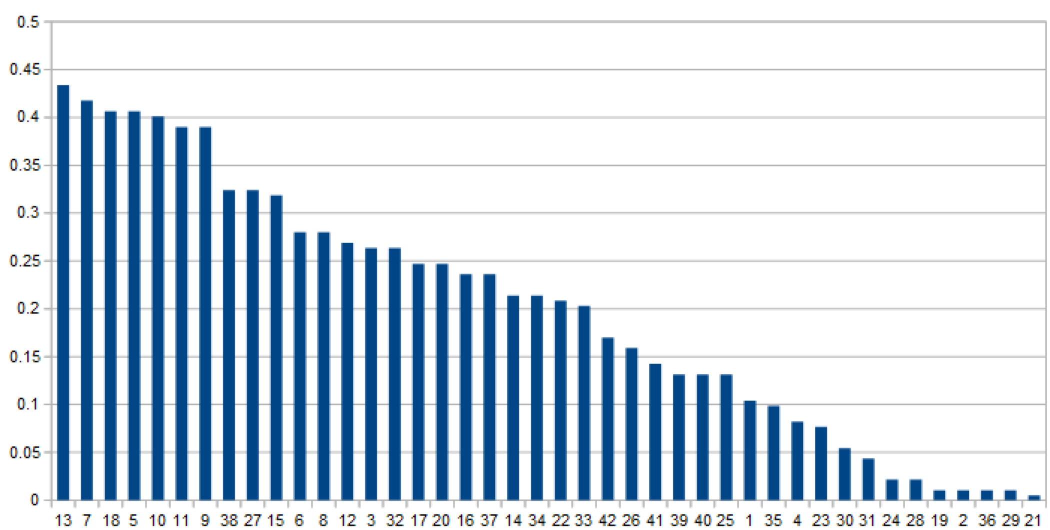

Figure 7 segment based on positive observable characteristics

5. SYNERGISTIC VALUE BUILDING

At the beginning of this paper we described the emerging need to develop risk assessments that:

- are detailed and updatable,
- allow determining residual risks (after mitigation),
- perform risk adjusted perpetual cost estimates and
- draw rational and sensible mitigative road-maps.

In Section 2 we showed that coupling and updating QRA thanks to Space Observation is synergistic and 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 and to answer modern requirements. We closed that section by reminding a few techniques allowing the probabilities updates and showing examples of observable data.

In this Section we describe the five general steps necessary to build such a system using the ORE concept.

1) After defining the list of dams/embankments sections to be evaluated, the analyst need to receive all available documentation, coordinates, reports, etc. 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).

2) Based on the documentation and observations the analyst performs a preliminary quantitative risk assessment. During this deployment existing and missing information are evaluated and a request for further information is sent to the client. If that information is definitely not available or becomes available, it enters in the evaluation either in negative or positive way. Of course an historic approach using Space Observation databases is possible, to attempt to gain a better level of knowledge.

3) After the second round the image of the relative risks generated by the portfolio is delivered to the client, with recommendations relative to future monitoring and possibly mitigation ideas. The a priori risk assessment is used for risk informed decision-making on mitigation. Once mitigations are decided (and implemented) an 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.

4) Future monitoring recommendations can follow classic instrumentation, or Space Observation (Optical, InSAR), or any blend of the two approaches. Thanks to Space Observation the updates of the risks and monitoring of the structures can be very competitive. It is possible to convene dates for regular updates during specific duration.

5) Whether the client is a regulatory agency or a miner, the results foster rational and healthy discussions on a transparent base the analyst can facilitate if required. In many cases, this will help fostering Corporate Social Responsibility (CSR) and maintaining Social License to Operate (SLO), while covering some of the needs of NI 43-101 (Oboni, Oboni, 2017b).

As this ORE approach 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.

6 CONCLUSIONS

At the end of the day, in order to fill the gaps and reach the results outlined in the introduction ORE2_Tailings and ORE2_Dykes propose a synergistic approach encompassing an updatable, scalable, drillable and convergent Quantitative Risk Assessment (QRA) platform and Space Observation monitoring as main or complementary to extant classic monitoring programs.

Preliminary QRA deployment, 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.

The examples and case studies presented in this paper show the benefits found in linking multi-temporal objective Space Observation with a dynamic convergent quantitative risk assessment platform in mining projects and operations, and more specifically in ORE risk assessment.

The two pronged approach enables the analysts 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.

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.

REFERENCES

Ang, A., H-S., Tang, W., H., 1975. Probability concepts in Engineering Planning and Design, Vol. I, John Wiley and sons.

Altarejos-García, L. , Silva-Tulla, F., Escuder-Bueno, I., Morales-Torres, A., 2015. “Practical risk assessment for embankments, dams, and slopes” Risk and Reliability in Geotechnical Engineering, 437.

Caldwell, J., 2011. Slimes dam - aka tailings storage facility - failure and what it meant to my mining mindset, april 19, 2011 , http://ithinkmining.com in “Long term risks of tailings dam failure”, Chambers, D. M., Higman, B.

CDA, Canadian Dam Association, Technical Bulletin, 2014. Application of dam safety guidelines to mining dams.

Dezfuli, H., Kelly D., Smith, C., Vedros, K., Galyean, W., 2009. Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis, National Aeronautics and Space Administration, June.

Henschel, M. D., Lehrbass, B., 2011. Operational Validation of the Accuracy of InSAR Measurements over an Enhanced Oil Recovery Field. Fringe 2011. Frascati, Italy: European Space Agency.

Henschel, M., D, Dudley, J., Lehrbass, B., Shinya S., Stockel, B.-M., 2015. Monitoring Slope Movement from Space with Robust Accuracy Assessment. Slope Stability 2015. Cape Town, South Africa: SAAIM.

Independent Expert Engineering Investigation and Review Panel, 2015. Mount Polley.

Independent Forensic Team, 2018. Report on Oroville Dam Spillway Incident. Department of Water Resources, California, US.

Mäkitaavola, K., Stöckel, B.-M., Sjöberg, J., Hobbs, S., Ekman, J., Henschel, M. D., Wickramanayake, A., 2016. Application of insar for monitoring deformations at the Kiirunavaara mine. 3rd International Symposium on Mine Safety Science and Engineering, Montreal, August.

Morgenstern, N. R., 2010. Improving the safety of mine waste impoundments. In: Tailings and Mine Waste ’10, Vail, CO. October 17-20.

Morgenstern, N. R., 2018. Geotechnical Risk, Regulation, and Public Policy, The Sixth Victor de Mello Lecture, University of Alberta Edmonton, Alberta, Canada, 9th Portuguese –Brazilian Geotechnical Congress, Salvador, Bahia, Brazil.

Oboni, C., Oboni F., 2013. Factual and Foreseeable Reliability of Tailings Dams and Nuclear Reactors -a Societal Acceptability Perspective, Tailings and Mine Waste 2013, Banff, AB , November 6 to 9.

Oboni, F., Oboni, C., Zabolotniuk, S., 2013. Can We Stop Misrepresenting Reality to the Public?, CIM 2013, Toronto

Oboni, C, Oboni. F, 2014. Aspects of Risk Tolerability, Manageable vs. Unmanageable Risks in Relation to Governance and Effective Leadership, International Symposium on Business and Management, Nagoya, Aichi-ken, Japan, April.

Oboni, F., Oboni, C., 2016a. Military Grade Risk Application for Mining Defense, Resilience, and Optimization, Risk and Resilience 2016, Vancouver Canada, November 13-16.

Oboni, F., Oboni, C., 2016b. A systemic look at tailings dams failure process, Tailings and Mine Waste 2016, Keystone, Colorado, USA, October 2-5.

Oboni, F., Oboni, C., 2017a. Screening Level Risk Assessment for a Portfolio of Tailings Dams, Fall issue of Canadian Dam Association (CDA, ACB) Bulletin, Vol. 28 No. 4.

Oboni, F., Oboni, C., 2017b. Towards Improving Environmental and Social Disclosure in NI43-101, CIM Technical Session, CIM2017, Montreal Canada, May 2.

Oboni, F., Oboni, C.H., Morin, R., Brunke, S., Dacre, C., 2018. Space Observation and Quantitative Risk Assessment Synergy Delivers Value to Mining, Symposium 2018 sur l’environnement et les mines, Rouyn-Noranda, June.

Oboni, F., Oboni, C. H., Dacre, C., Henschel, M. D., Morin, R., Brunke, S., 2018.Tailings 2.0: Quantitative Risk Assessment & Space Observation create value, One day course at TMW2018, University of Colorado, Keystone, 2018.

Oboni, F., Oboni, C., 2018b. Triaging 50 km of dykes, Geohazards 7, Canmore AB, June 3-6.

Riskope blog 2016 https://www.riskope.com/2016/04/20/solomon-islands-gold-mine-contaminated-water-spill-disaster/

Riskope blog 2018 https://www.riskope.com/2018/09/18/updating-tailings-dam-quantitative-risk-assessment-and-space-observation/

Roche, C., Thygesen, K., Baker, E. (Eds.), 2017. Mine Tailings Storage: Safety Is No Accident. UNEP Rapid Response Assessment. United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal,

www.grida.no ISBN: 978-82-7701-170-7
Silva, F., Lambe, T.W., Marr, W.A., 2008. Probability and Risk of Slopes Failures, JGGE, ASCE , 2008
Taguchi, G. 2014. "Fault Tree Analysis of Slurry and Dewatered Tailings Management – A Frame Work". University of British of Columbia, Vancouver, Canada.
Ulaby, F. T.; Moore, R. K., Fung, A. K., 1986. Microwave Remote Sensing: Active and Passive: Volume 2: Radar Remote Sensing and Surface Scattering and Emission Theory, Artech House, Inc.