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**Real-time monitoring for structural health, public safety,
 and risk management of mine tailings dams**

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 Manuscripts

1 **Real-time monitoring for structural health, public safety, and risk**
2 **management of mine tailings dams**

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9 **Abstract**

10 Public awareness of tailings dam failures is increasing in the wake of incidents in Canada and
11 abroad. The present work establishes the current state of practice in mine tailings dam
12 monitoring and provides a summary of the current technical and operational gaps identified
13 through industry and stakeholder engagement. These gaps may be addressed with currently
14 available technologies supplied by commercial instrumentation manufacturers; however, the
15 assumed costs and lack of regulatory demand may serve as barriers to adoption. An integrated
16 approach and diverse suite of technologies is needed to address issues of dam stability, worker
17 and public safety, and environmental protection.

18 Technological applications and limitations are described and design requirements are proposed
19 for an integrated, real-time monitoring system. Socio-economic impacts and loss reduction
20 benefits are considered and the need for industry and regulator participation is emphasized.

21 *Key words:* **tailings, dam failure, mine safety, monitoring systems, instrumentation, public**
22 **safety**

23 **Introduction**

24 ***Failures of mine tailings dams***

25 Over the last century, the failure of mine tailings dams has emerged as a significant public
26 concern and the source of immense liability risk for the mining industry. The earliest modern
27 record of tailings dam failure may be traced back to 1915 at Agua Dulce in Chile (Chambers and
28 Bowker 2017) where overflow due to strong rains resulted in the collapse of the dam and the
29 release of 180,000 cubic metres of copper tailings to the environment. Later, one of the most
30 tragic failures in history was the disaster in the Stava Valley, Italy in 1985. With 268 lives lost
31 and 133 million Euros in damage (Lucchi 2011), it may be regarded as one of the worst
32 industrial catastrophes in the world.

33 Between 1915 and 2016, over 290 tailings dam failures were reported. These incidents resulted
34 in at least 1,934 fatalities, significant costs to owners, and impacts to the environment and global
35 economy. The average cost of the largest of these catastrophic tailings dam failures is estimated
36 at over \$500 million USD (Bowker and Chambers 2015). During the same period, 22 failures
37 occurred in Canada. Twelve of those incidents were recorded since 1970, indicating that failure
38 has become a more substantiated and pressing issue for shareholders and stakeholders in recent
39 decades (Hui and McKinnell 2015). A recent report in the wake of the 2014 Mount Polley
40 tailings dam failure in Canada recognized that the rate of serious tailings dam failures is
41 increasing (Bowker and Chambers 2015). Moreover, half of the serious tailings dam failures in
42 the last 70 years (33 of 67) occurred in the 20 years between 1990 and 2009.

43 Not surprisingly, the reliability of tailing dams is among the lowest of earthen structures and
44 multiple reviewers have compiled information on the nature and consequences of tailings dam

failures (Azam et al. 2010; Davies et al. 2000; Engels et al. 2012; Kossoff et al. 2014; Rico et al. 2008b; USCOLD 1994; WISE 2012). Significantly, the failure rate of tailings dams is estimated to be 10 to 100 times greater than the failure rate of hydroelectric dams (Azam et al. 2010; Mattox 2015).

Although tailings impoundments and their associated dam structures are among the largest of anthropogenic structures, the approach to their construction and management is unique to the mining industry. Mine tailings dams are typically constructed on a near- continuous basis during the mine life, rather than over a definite construction period. Tailings dams are commonly constructed from readily available geo-materials (including borrow, mine overburden, and mine waste products) rather than the carefully formulated concrete employed in hydroelectric structures. After the initial footprint and waste-retaining structure has been established, the confining embankments can either be raised by several means (Martin 1999): upstream, vertically (centre-line), downstream, or by some combination of these techniques using run-of-the-mill materials. This raising occurs during operations and can provide decades of additional volume capacity, depending on the rate of ore production, available footprint, and tailings characteristics (namely moisture content and consolidation characteristics). Upstream raising is often the lowest-cost option among the three methods of construction, as a smaller amount of building material is required (Soares 2000). However, upstream-raised dams are also the most likely to fail (Davies 2002; Rico et al. 2008a; Rico et al. 2008b) as they usually incorporate lower-strength materials into load-bearing zones of the dam (by design or by unexpected mass movement of the tailings).

Risk management and the need for monitoring

Tailings dams are generally managed without in-house geotechnical expertise in many mining operations - relying instead on specialized consulting engineers (Davies 2000) who may change in name and service throughout the mine operation. The owners themselves may change from time to time, and operating budgets will fluctuate with market conditions. Most mine waste facilities, including tailings impoundments, represent a continuous value sink to mine, unlike hydroelectric dams that continuously generate value for the owners. This in itself may be a source of tension between mine management and tailings impoundment operators, placing constraints on the availability of human resources, equipment and materials, and third-party oversight.

Therefore, the integrity and safety of a mine tailings dam is dependent on conservative design, diligent operation, and continuous, cost-effective monitoring. Geotechnical designs can be improved by increasing resistance factors; however, even dams with conservative characteristics may experience unexpected failure due to the presence of unidentified geologic features, abnormal weather patterns, seismic shock, and the inherently variable quality of a construction project that spans multiple decades and technological paradigm shifts. Diligent, well-trained operators and a reliable monitoring system are therefore critical for failure prevention and loss reduction in the face of known and unknown unknowns. To this end, an adequate system should highlight the problematic behaviours that could lead to tailings dam failure with advanced warning. Experts in the field remind us that:

"For any engineer to judge a dam stable for the long-term simply because it has been apparently stable for a long period of time is, without any other substantiation, a potentially catastrophic error in judgment" (Szymanski and Davies 2004).

This is particularly true for tailings dams during mine production phases, as the structures undergo constant evolution.

Review of failure modes and current monitoring practice

There are several ways in which a tailings dam may fail structurally. It is critical to understand the failure mechanisms (the process or processes leading to failure) and the failure modes (the manner in which the dam ultimately fails) in order to design an effective monitoring practice. Keep in mind, however, that each failure mechanism rarely occurs in isolation; it is often a combination of sequential or simultaneous structural, environmental and operational failures that results in unexpected and catastrophic end states.

Failure modes

The key failure modes identified by the U.S. Committee on Large Dams (USCOLD) were reviewed in the present work. The number of failures attributed to each mode is summarized from 106 incidents in Figure 1 (USCOLD 1994). Slope instability failures, earthquake-induced failures, and failures due to overtopping of the dam crest are identified as the top failure modes while seepage, foundation, structural, and mine subsidence issues preceded fewer incidents. It should be noted at this point, however, that there is likely bias at work in these statistics as slope failures, earthquakes, and overtopping events are more easily identified in retrospect (and thus more readily attributed to the failure) than less conspicuous phenomenon like seepage, foundation instability, and internal structural deficiencies. Furthermore, it is recognized that this data represents the primary failure mode (i.e. that which resulted in a loss of containment) and that other minor modes and underlying mechanisms may have also contributed to ultimate failure. For example, the effect of elevated water held behind the tailings dam can contribute to a

111 significant failure initiated by slope instability, overtopping, and seepage combined (Smith and
112 Connell 1979) and incipient slope failures very rarely occur without some deformation or surface
113 expression.

114 ***Intent, cause and effect***

115 Since the integrity and safety of a tailings dam can be influenced to a substantial degree by the
116 *intentional actions* related to its design, operation and monitoring, each intentional action is a
117 means to limit catastrophic failure. An intentional action, in the philosophical sense, is an action
118 undertaken consciously and deliberately, providing a reasonable response to the question ‘Why?’
119 *Why* was the dam constructed at 3H:1V? *Why* is the rate of rise limited to 0.5 metres per year?
120 *Why* is the horizontal displacement of the face *monitored continuously*? The answers to this line
121 of questioning should form the foundation of transparent and safe dam design and operation. The
122 dam operator must be familiar with the structure’s design intent and the level of monitoring
123 required to assure safety and continuity of operations.

124 As failure investigations become more forensic in nature, our understanding of the
125 interdependencies of the tailings dam system and the complexity of failure mechanisms become
126 more apparent. The considerable number of unknown failure modes in Figure 1 is indicative of a
127 systemic, underdeveloped monitoring culture, a lack of established industry-wide best practices,
128 and inadequate post-failure investigations. Unfortunately, a root cause analysis may indicate
129 complacency or ignorance within the organization and its shareholders resulting in a lack of
130 committed resources.

131 Failures likely stem from degrees of ignorance or unplanned actions during any one of the phases
132 of the structure’s lifecycle. Ideally, a structure will be designed with adequate resistance factors

to limit the initiation of failure, it will be operated in a diligent and proactive manner so to mitigate deviations from the design, and it will be monitored such that corrective measures can be enacted throughout its service life and beyond. Crucially, if the monitoring component is omitted, ignored, or diminished, then there will be an increased likelihood that operations will not adhere to or consider the original design intent. External forcing (wind, rain, snow, and ice) also contributes to unplanned operational conditions, but prudent monitoring of the ‘mineshed’ (including the mine site, its regional geology and meteorology; waste facilities; and the receiving environment) should provide leading indicators for upset potential.

Table 1 summarizes the relationship between the possible failure modes considered in this work and opportunities to reduce the risk of failure. Note that seismically-induced failure is difficult to mitigate over any meaningful timescale and therefore earthquake-exposed sites must rely heavily on the design parameters and emergency response planning. All other known failure modes can be monitored and reasonably predicted given adequate information and an understanding of the expected behavior of the system. Table 2 enumerates several parameters of interest, changes in which are characteristic of behavioral changes in the dam system. The identification of undesirable behaviours is key to assessing the risk of failure.

Conventional and emerging monitoring technologies

There are several measurement principles and techniques that can be applied to monitor tailings dam behavior and known failure mechanisms, as summarized in Table 3. These techniques are typically differentiated into the two categories of geotechnical instrumentation and geodetic surveying. Each of the monitoring techniques will have specific advantages and disadvantages for certain environments and data requirements. When combined, geotechnical instrumentation

155 and geodetic measurements from both discrete locations and broad surveys may form a system
156 capable of self-validation.

157 Most deformation monitoring techniques will only provide measurements from a specific point
158 location or a group of discrete points, as is the case with measurement by extensometer,
159 inclinometer, global positioning systems (GPS), or robotic total stations (RTS). For those
160 techniques, it is critical to appropriately define the density and location of measurement points to
161 allow sufficient sampling and detection of deviations from normal behavior. The application of
162 distributed optic fiber sensors, on the other hand, is one of the few techniques that provides direct
163 measurement for critical interior zones within the dam, and can be installed either in existing
164 dams or during new constructions (Goltz et al 2010; Inaudi *et al.* 2013). In this case it is possible
165 to cover the critical length, area or volume of the dam and not only detect, but also localize
166 damage. While geotechnical instruments are sensitive to the effects of environmental
167 temperature, instrument/electronic drift, and conversion constants of the readout, geodetic
168 techniques are subject to line-of-sight constraints and local anomalies in geology and geography.

169 Among geodetic techniques, the commercialization of several technologies provides new
170 opportunities for monitoring. Ground-based synthetic aperture RADAR (GB-SAR)
171 interferometry provides excellent coverage and measurement density, which can potentially
172 replace the conventional surveying methods for exterior deformations (Alasset et al. 2013).
173 Terrestrial laser scanning is another promising technique with sub-centimeter accuracy and
174 three-dimensional deformation measurements, including displacement vectors and rotations,
175 although it has not been widely applied for tailings dams (Monserrat and Crosetto 2008). Laser
176 scanners are strongly affected by changeable atmospheric conditions. In this case, laser scanners

can be supplemented by GPS and/or RTS to provide confirm the stability of the survey stations (Alba 2006; Schneider 2006).

GPS-based approaches are currently employed for deformation measurement. Satellite-based measurement techniques may provide true three-dimensional measurements and have demonstrated excellent long-term stability. However, pseudolites (pseudo-satellites) may be needed to supplement and improve accuracy if the structure is located in deep valleys where poor line-of-sight reduces the accuracy of GPS measurements considerably (Dai et al. 2001; Rutledge 2005). GPS-based automated deformation monitoring offers the advantages of relatively low-cost and real-time monitoring compared to a system built upon ground-based inclinometer installations and triaxial accelerometer arrays (i.e. Shape Accel Arrays, or SAA). Furthermore, systems employing ground-based inclinometers require that the instrument casing is anchored into stable strata. It remains a challenge in the sub-surface to meet this requirement and the cost can be considerable in the case of automated installations involving SAA as well (Radovanovic 2014; Singh and Fleming 2014).

It has been suggested that detectable displacement rates for structures should be at least three times smaller than the maximum tolerable displacements over the observation time interval at a 95% confidence level (Chrzanowski 1993). At this confidence level, the typical range of required accuracy of displacement measurement is 10-15 mm for tailings dam deformations (Chrzanowski 2011). All of the monitoring technologies summarized in Table 3 meet this accuracy requirement. Importantly, the main limitation when selecting appropriate monitoring techniques is not the instrument precision but the environmental influences and the instability of geodetic control points (Chrzanowski and Szostak-Chrzanowski 2009; Chen 1983; Chen et al. 1990).

Geotechnical monitoring techniques have evolved tremendously over the last two decades. Emerging technologies have the potential to improve measurement accuracy and reliability while decreasing the cost of data acquisition. Compared to traditional wire and tape extensometers, rod extensometers and SAA systems are more reliable, robust, and cost effective. The increased accuracy and continuity of the measurements enables the analyst to better localize deformations and to quantify the impact. However, the reliability and cost of the monitoring techniques varies with the operating conditions and signal noise must be processed efficiently.

Lessons from open-pit wall monitoring techniques

Concerning their size relative to an operation, their criticality, their potential for generating negative impacts, and their geological and environmental dependencies, tailings dams and open pit walls represent similarly significant risks for mines. However, the operating environments (e.g. personnel exposures), materials (e.g. rock vs. multi-phase tailings), construction processes, and failure modes are substantially different.

In open pit environments, the expected deformation varies depending on the slope geometry and aspect, the geology and intersected structures, the rock mass properties and weathering conditions, and the ground and surface water conditions, for example. The failure modes of open-pit walls will include plane failures, wedge failures, step path failures, raveling, and toppling failures (Girard, 2001) which are generally well understood physical phenomenon with tell-tale characteristics and warning signs. However, tailings dams experience different failure mechanisms related to fluid storage, such as overtopping and seepage, as well as time-dependent, construction-related and geotechnical phenomenon such as consolidation and liquefaction. These differences indicate that the monitoring techniques and strategies may differ between these two

cases, though the intent and monitoring philosophy will be similar. It is noted that the monitoring practices developed for open-pit wall safety are generally more advanced than the current state of practice for tailings dams.

With today's instrumentation, it is feasible and practical to monitor each possible pit wall failure mode and several significant failures have been successfully predicted. Notably, Utah's Bingham Canyon Mine continuously monitored the pit slopes with redundant monitoring systems (including RADAR, laser, seismic, and GPS). Alarming displacement rates signaled staff to evacuate the pit nearly twelve hours before the catastrophic rock avalanche occurred in April 10, 2013. Ground movements had been monitored months before, allowing rerouting of key infrastructure and communication with stakeholders.

The positive experiences resulting from open pit-wall monitoring can and should be translated to best practice for the monitoring of tailings dams as well. The uniqueness of individual tailings dams and mining operations will require different monitoring strategies depending on the dam configuration, impounded materials, construction type and stage of development, foundation soils or bedrock type, and levels of risk to operators and the public. Furthermore, the monitoring strategies and technologies for the health monitoring of other civil infrastructure (e.g. bridges and hydroelectric dams) could conceivably be applied to tailings dams as well.

Current monitoring practice

The authors have reviewed the state of practice through personal experience and consultation with over forty industry stakeholders and consultants to identify the most pressing technical and operational gaps in current monitoring practice; however, it is first helpful to review the current state of practice before highlighting its deficiencies.

244 First, most tailings dams will undergo routine visual surface inspection and limited
245 instrumentation monitoring. The reading of instrumentation is typically performed manually and
246 infrequently, limited by safe access conditions, weather, and staff availability. The monitoring is
247 often conducted by junior or under-qualified staff that may lack the experience and judgement
248 necessary to escalate concerns identified during an inspection. This is especially true for smaller
249 operations that may not employ a substantial environmental or structural monitoring team.
250 Furthermore, it can be precarious and hazardous for workers to access instrumentation on the
251 face or near the pond (retained water behind the dam), especially in poor weather conditions. All
252 of these activities are subject to human error and moral hazards including inaccurate reporting,
253 misidentification of instrumentation, and omission of instrumentation from a survey.

254 Second, manual readings and data processing can require substantial person hours that may result
255 in delays of up to a few days before behavioural trends can be identified (Newcomen 2002).
256 During and after an extreme event such as earthquake or heavy rainfall, the collection and
257 processing of manual measurements can cause delay in the assessment of the tailings dam
258 conditions and may directly expose workers to a potential health and safety hazard.

259 Third, some monitoring techniques can only provide information over a very limited period of
260 time to monitor surface deformation. Krautmann (2013) reported that it is critical to maintain
261 instrumentation readings over time to contextualize the observed behaviours.

262 Additional technical and operational gaps identified include:

- 263 • Most tailings dam operators are using outdated point-sensing techniques to monitor only
264 select locations. New techniques for broad area monitoring have not yet been employed.

Measurement over a broad area allows mine operators to monitor dam behaviour and to locate problematic areas that require closer attention.

- Automated early-warning functions in the current monitoring practice are lacking; such systems would allow miners the opportunity to take loss-reduction actions in advance.
- Not all the failure modes have been adequately addressed in monitoring practices, such as the foundation failure at Imperial Metal's Mount Polley mine in British Columbia, Canada.
- Resilient and redundant systems are needed to cover the failure of individual sensors and increase confidence in measurements. Once installed within the dam, the geotechnical instruments typically cannot be recovered or re-calibrated. Therefore, some geotechnical instruments may provide unreliable data or even fail during the life of the tailings dam. Redundancy is even more effective when multiple sensing technologies are used to monitor and cross-validate the same parameter.
- Monitoring instrumentation is useful for collecting a large volume and variety of data; however, it is not well understood how to relate these diverse observations to the overall behavior and stability of the dam.
- Tailing dam safety relies on the integrity of design, operation, and monitoring. Cost-effective design cannot prevent failure without diligent operations and monitoring.
- New guidelines for best practice are needed to elevate the monitoring standard with consideration for the use of advanced monitoring technologies.

The role of technology and systems engineering

286 Despite heightened attention to tailings dam failures in recent decades, the inspection and
287 monitoring practices in Canada and abroad have not kept pace with more advanced sensor
288 technologies, methods, and systems engineering philosophies. If the status quo were to continue
289 into the next decade, it is suggested that more mining waste disasters like Mount Polley are
290 inevitable (Bowker and Chambers 2015). A complete monitoring system for a tailings facility
291 should not only address structural integrity but should also report on the impoundment
292 performance (e.g. leachate and seepage quantity and quality) and the health of surrounding
293 environment (e.g. turbidity and composition of local water courses) as indicators of the system's
294 general health. In addition to the needs of monitoring operating tailings dams, more and more
295 closed and abandoned mines in remote regions also require an updated monitoring approach.

296 In this work, the known failure mechanisms, corresponding monitoring parameters, available
297 technologies, and strategies for addressing the major gaps in the current practice are reviewed.
298 An integrated, real-time monitoring system has been identified by the authors as a key element
299 needed to facilitate sustainable safety management of tailings dams. The potential impacts on
300 operating cost and safety for mine operators and the public are also discussed in this work.

301

302 Among the available geodetic and geotechnical techniques, there is no single approach that can
303 address all failure modes and fully satisfy all monitoring requirements. Therefore, various
304 techniques must be combined in an integrated monitoring system. Point sensing and broad area
305 measurement with both geodetic and geotechnical techniques must be integrated into a system to
306 complement each other while providing redundancy and reliability. The practice of manual and

periodic readings of instrumentation must be updated to allow for automatic and systematic monitoring systems with advanced technologies to close the gaps in the current practice.

An updated monitoring practice will have limited value without appropriate alarm functions (aligned with the organizational and societal risk tolerances) and detailed response plans for preserving life safety and mitigating environmental impacts. For each monitoring environment, different levels of alarm must be defined and linked to a clear and simple action plan (Vanden Berghe 2011). Through diligent monitoring, areas of concern may be noted and quickly repaired or abandoned, thereby preventing failure or mitigating loss. In addition to monitoring the stability of the dam, the performance of seepage-reducing liners and drainage or bypass systems should be continuously evaluated.

Dr. Adam Chrzanowski and his research team at the University of New Brunswick (UNB) have championed the need for an integrated dam monitoring system since the 1980s and tremendous pioneering work was done for the development of such a system (Chrzanowski 1990, Chrzanowski 1993, Chrzanowski 2009, Chrzanowski 2011, Duffy et al. 2001). Many of their comments are applicable to the current state of practice, notably:

“Poorly designed monitoring schemes, inadequate instrumentation, lack of calibration facilities, and insufficient accuracy of measurements, are, with few exceptions, common problems of the dam safety program in Canada” (Chrzanowski 1990).

The lack of a real-time monitoring system specifically designed to cover all the failure modes for tailings dams also makes it difficult for regulators to prescribe requirements for monitoring that are both adequate and reasonable.

System design requirements

In order to predict possible failures of the dam system, all undesirable behaviours must be identified and appropriate monitoring parameters and tolerances must be established. Table 2 listed several of the monitoring parameters related to each individual failure mode considered in this work. Each parameter should be assigned acceptable tolerances for displacements, velocity, or acceleration and related to the overall dam. Monitored parameters and tolerances are linked using functional relationships to describe acceptable and unacceptable behaviours. For example, if the rate of crest settlement exceeds an acceptable threshold and the horizontal displacement trigger value is reached, this could indicate that a weak zone has been mobilized within the dam's foundation and the likelihood of failure is elevated. Similarly, if pore water salinity increases in the toe of the embankment but freeboard increases despite recent rainfall, then seepage through the core or foundation may need to be addressed. A human- and activity-centred system would also provide recommendations to the operations team on remedial actions required based on instrument feedback.

The dam designer and the monitoring system designer should identify which of the possible failure mechanisms potentially expose the operator to catastrophe and rank them according to their probability of occurrence and severity of consequences. Prioritization of monitoring actions and the allocation of monitoring technologies, such as those described in the preceding sections, should be based on this exercise.

A continuously operating, real-time monitoring system for a tailings dam requires multi-level systems engineering and solutions from the fields of geosciences, mechanics, electronics, geodetics, analytics, and forecasting. Human factors must also be considered in designing the alarm functions and user interfaces. Figure 2 is a schematic representation of an idealized monitoring system workflow. The system design follows from an initial structural design and

352 risk tolerance assignments. The selection of instruments is based on their expected performance
353 and their reliability is continuously monitored. Signal processing algorithms are employed in
354 order to identify undesirable behaviours in the system. If intolerable behaviours are identified,
355 corrective actions are recommended to the operator. In this case, communication to internal
356 stakeholders (workers and owners) is critical. The timing of communication to external
357 stakeholders may depend on the level of risk. If the intervention is successful, communication of
358 the results should be communicated internally and, if warranted, externally to promote
359 confidence in the system. If the intervention is unsuccessful, failure results and an emergency
360 response plan is enacted. If the situation cannot be remedied and failure does occur, emergency
361 management must be activated and communication with internal and external stakeholders will
362 be critical.

363 Beyond the significant work done by UNB, only a few research and development have focused
364 on tailings dam monitoring practices (Yu et al. 2011; Li et al. 2011; Hu et al. 2011; Sun et al.
365 2012). There is still a need for research into the optimal integration of various monitoring
366 techniques, the optimal fusion of available signal processing technologies, and the improvement
367 of measurement reliability and cost-efficiency.

368 A flow chart with the key considerations for the proposed monitoring system is presented in
369 Figure 3. Key monitoring parameters, as identified in this work, need not all be monitored
370 simultaneously or at every stage of the dam's service life (though this would be the ideal
371 situation given unlimited resources and data processing capacity). The allocation of resources to
372 parametric monitoring should be done on a risk-basis. For example, pond water levels may be
373 maintained rigorously with multiple redundant pumps and vigilant operators; however, the dam's
374 rate of rise may be high enough to warrant constant monitoring of excess pore pressures within

the dam and vertical displacements along a continuous portion of the dam crest. The selection of monitoring techniques depends on the specific needs and operating conditions of each mine. Robust data acquisition and data transfer techniques are available and vary between different suppliers of sensors. The data analysis can be performed either by statistical (regression analysis) or deterministic methods (ENEL 1980; Chrzanowski and Chen 1990). The statistical method evaluates the correlations between observed deformations and probable observed loads (external and internal forces producing the deformation). The deterministic method utilizes information on the known loads, properties of the materials, and constitutive laws governing the stress-strain relationship. Furthermore, geometrical analyses of deformation and both statistical and deterministic methods have been previously combined in a dam monitoring system (Chrzanowski and Chen 1990). However, the aspects of data analysis and relationships to earth-dam performance require further work.

Socio-economic considerations

Loss reduction

Spills of process-affected water and mine residues due to the failure of tailings dams have resulted in significant impacts to the environment and mining activities. The significant economic consequences of failures include business interruption or down time of mining and processing operations, environmental damage and clean-up, and socio-economic and political issues associated with transboundary migration of effluent in rivers (Kossoff et al. 2014; Lucas 2001). The loss due to business interruption includes direct expenses, deferred cash flow, loss of asset value, and drop of share price (Davies 2000). Reputation and goodwill are likely to suffer as well. Readily available and comprehensive data on the economic impacts of tailings dam

failures are limited and incomplete. Most compilations usually focus on impacts on the environment, infrastructure and people (WISE 2012). Imperial Metals reported a loss in the first three months of 2015 of \$33.4 million and revenues of \$1.5 million. The decrease is primarily due to the absence of revenue from Mount Polley due to the suspension of mine operations. Cash flow was negative, and dropped \$26.4 million from the same three-month period in 2014 (Hoekstra 2015). The average cost of catastrophic tailings dam failures is estimated to be \$543 million; the total cost of approximately \$6 billion is estimated for 11 catastrophic failures predicted globally from 2010 to 2019 (Bowker 2015). However, the estimated cost of the recent Samarco dam failure in Brazil on November 5, 2015 is estimated as high as \$60 billion, which includes legal claims and fines, claims for reparation, compensation and moral damages.

With a real-time automated monitoring system, the risk of tailings dam failures can be diminished by reducing both the frequency and severity of failures through proactive maintenance and early warning systems. The initial cost to equip an operation with such a system could be high; however, payback over time is expected through reductions in labour demand, risk financing obligations (e.g. insurance premia), claims exposure, and regulatory penalties. Given cost savings combined with increased shareholder confidence, goodwill, and societal tolerance of mining operations, the initial capital investment required would be negligible for most operations. Based on automation upgrades alone (an update from manual readings to an automatic data acquisition system for both piezometer and inclinometer readings), it is estimated that the payback period is just over one year (Choquet 2016). The estimate is based on a cost calculation that considers daily labour and equipment costs associated with required manual monitoring frequency.

Regulatory influence

420 The regulation of dams in Canada is a provincial and territorial responsibility. Canada does not
421 have a federal regulatory agency or over-arching program that guides the development of
422 requirements for the safe management of dams; however, the Dam Safety Guidelines developed
423 by the Canadian Dam Association (CDA) provide primary references for owners, operators and
424 regulators for the design, monitoring and maintenance of all dams including tailings dams (CDA
425 2017). Monitoring and reporting on the status of the dam should include monthly and annual
426 reports, an annual geotechnical inspection, periodic dam safety reviews, and monitoring of
427 piezometers, water levels and outflows.

428 The recent analysis, *Post-Mount Polley: Tailings Dam Safety in British Columbia* (Chambers,
429 2016), underscores the need for the province to immediately bring in firmer legislation and says
430 it is time that B.C. lived up to commitments to make the mining industry safer. The B.C.
431 government reacted with mining-code revisions, including new design standards for tailings
432 storage facilities, which it says will ensure such a disaster never happens again; however,
433 monitoring has not been prioritized in improving current practice.

434 **Conclusions**

435 With the significant costs associated with failures of tailings dams and increasing public
436 awareness, it is time to affect change in tailings dam monitoring. The proposed integrated
437 monitoring system for water and waste management of tailings will provide real-time
438 information with alarm functions. The current practice of periodic instrument monitoring and
439 inspection should be replaced by semi-automated and continuous monitoring systems to increase
440 confidence in the performance of these structures.

The advanced monitoring system for tailings ponds will contribute to optimizing operations and maintenance by providing automatic and consistent real-time monitoring data and remote access in order to ensure worker and public safety. The system also reduces environmental risk and operational cost by avoiding losses with early alarm functions to prevent dam failure or at least mitigate consequences and loss of human lives. The system will provide support to new regulation to meet current and future standards for tailings dam management as well. We conclude that in addition to the obvious advantages of reduced environmental risk, the benefits of a good monitoring system lie in operational cost advantages and loss reduction.

The National Research Council of Canada is working with instrumentation suppliers and engineering firms to develop and promote the use of technology to reduce environmental risks and operational costs resulting from tailings dam failures in Canada and abroad. Still, further research is needed on the optimal integration of various monitoring techniques and on the optimal fusion of data analysis packages. The continued support of mine owners and industry regulators is critical to the successful deployment of such monitoring systems.

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References

- Alasset, P.J., English, J., Allan, B., Hakobyan, M., Adlakha, & P., Power, D., 'Slope stability and critical dam operations monitoring using ground based radar', *CDA 2013 Annual Conference*, Montreal, QC, Oct. 5-10, 2013.
- Alba, M., Fregonese, L., Prandi, F., Scaioni, M. & Valgoi, P., 2006. 'Structural monitoring of a large dam by terrestrial laser scanning', *Proceedings of International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Dresden, Germany, Vol.XXXVI: Part 5, (CD-ROM), September 25–27, 2006
- Azam, S. and Li, Q. 2010. 'Tailings Dam Failures: A Review of the Last One Hundred Years', *Geotechnical News*, December, pp. 50-53.
- Bowker, L.N. & Chambers, D.M., Report from Earthworks Action, 'The risk, public liability, & economics of tailings storage facility failures', Available from: <http://www.earthworksaction.com>. [21 July 2015].
- Canadian Dam Association (CDA), 'Regulation of Dams in Canada', Available from: http://www.imis100ca1.ca/cda/Main/Dams_in_Canada/Regulation/CDA/Dams_In_Canada_Pages/Regulation.aspx?hkey=2bee099d-%C2%AD%E2%80%90901234-%C2%AD%E2%80%90904be2-%C2%AD%E2%80%90908d92-%C2%AD%E2%80%9090a3527e0cd8fe
- Chambers, D.M. 'Post-Mount Polley: Tailings Dam Safety in British Columbia.' Available from: http://miningwatch.ca/sites/default/files/post-mountpolleytailingsdamsafety_0.pdf [17 July 2017].

Chambers, D.M. & Bowker, L.N., 'Tailings Dam Failures 1915-2016', Available from: <http://www.csp2.org/tsf-failures-1915-2016> [January 2017] .

Chen, Yong-qi. 1983. 'Analysis of deformation surveys — A generalized method.' Department of Surveying Engineering Technical Report No. 94, University of New Brunswick, Fredericton, N.B.

Chen, Yong-qi, A. Chrzanowski, & Secord, J. 1990. 'A strategy for the analysis of the stability of reference points in deformation surveys', *paper presented to CISM Journal ACSGC, Winter 1990*.

Choquet, P., Taylor, R.M., & Byerley, C. 2016. 'Payback of Automated Geotechnical Instrumentation Monitoring for Open Pit Mines as Compared to Manual Data Collection', *paper presented to CIM Conference 2016, Vancouver*

Chrzanowski, A. 1990. 'Integrated Monitoring and Analysis of Dam Deformations: Problems and Solutions', *Dam Safety*.

Chrzanowski, A., & Chen Yong-qi. 1990. 'Combining geometrical analysis with physical interpretation of deformation monitoring.' *Proceedings of the XIX International FIG Congress, Helsinki, Finland, 10-19 June, Paper No. 612.3*.

Chrzanowski, A., 1993. 'Modern Surveying Techniques for Mining and Civil Engineering, Comprehensive Rock Engineering', Chapter 33, Pergamon Press, Oxford, New York, 3:773-808.

Chrzanowski, A. & Szostak-Chrzanowski, A. 2009. 'Deformation Monitoring Surveys – Old Problems and New Solutions, Reports on Geodesy, Research Contributions in the Field of

Engineering Surveying within the period 2007-2008', *Warsaw University of Technology*, No. 2 (87), 2009, pp. 85-104.

Chrzanowski, A., Szostak-Chrzanowski, A. & Steeves R., 'Reliability and efficiency of dam deformation monitoring schemes', *CDA 2011 Annual Conference Congrès annuel 2011 de l'ACB*, Fredericton, NB, Canada, October 15 -20, 2011

Dai, L., Wang J., Rizos, C., & Han S. 2001. 'Applications of Pseudolites in Deformation Monitoring Systems', *10th FIG International Symposium on Deformation Measurements*, Orange, California, pp. 11–22.

Davies, M., Martin, T., & Lighthall, P. 2000. 'Mine Tailings Dams: When Things Go Wrong.' *Tailings Dams 2000. Association of State Dam Safety Officials, U.S. Committee on Large Dams*, Las Vegas, Nevada, pp 261–273.

Duffy, M., Hill, C, Whitaker, C., Chrzanowski, A., Lutes, J., & Bastin, G., 2001. 'An automated and integrated monitoring program for Diamond Valley Lake in California', *Proceedings of the 10th Int. Symp. on Deformation Measurements (Metropolitan Water District of S. California)*, Orange, CA, March 19-22, 2001,

ENEL, 1980. 'Behaviour of ENEL's Large Dams' *Entennazionale per l'Energia Elettrica*, Rome, Italy.

Girard, J.M., 2001. 'Assessing and monitoring open pit highwalls', *Proceedings of the 32nd Annual Institute on Mining Health, Safety and Research*, Salt Lake City, Utah, August 5-7, 2001.

- Goltz, M., Aufleger, M., & Perzlmaier, S., 'Research on the effects of deformation and stress in embankment dams on DEOT monitoring results', *CDA 2010 Annual Conference*, Niagara Falls, ON., Oct 2-7, 2010.
- Hoekstra, G. 2015. 'Imperial Metals losing money as Mount Polley still closed'. *Vancouver Sun*, May 18.
- Hu, J., & Liu, X. 2011. 'Design and implementation of tailings dam security monitoring system.' *Procedia Engineering*, Vol. 26: pp 1914 – 1921.
- Hui, S., McKinnell, J. 2015. 'A need of advanced monitoring system for tailings ponds', *CDA Conference & Exhibition*, Oct. 3-8, 2015, Mississauga, Ontario
- Inaudi, D., Cottone, I., Figini, A. 2013. 'Monitoring dams and levees with distributed fiber optic sensing', *Proceedings of the 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Hong Kong.
- Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G. & Hudson-Edwards, K.A. 2014. *Applied Geochemistry*, Vol. 51: pp 229–245.
- Krautmann, C., Abbaszadeh, S., Gutierrez, J. 2013. 'Field Deformations Compared to a Numerical Model for a Staged Centerline Raise – Cerro Corona Tailing Storage Facility, Peru', *Proceedings of Tailings and Mine Waste 2013*, November 4.
- Li, Q., Wang, Y., & Li, G., 2011. 'Tailings dam breach disaster on-line monitoring method and system realization', *Procedia Engineering* 26 (2011) 1674 – 1681.
- Lucas, C., 2001. 'The Baia Mare and Baia Borsa accidents: cases of severe transboundary water pollution.' *Environ. Policy Law*, Vol. 31: pp 106–111.

- Lucchi, G.: L'attività mineraria in Val di Stava, in: Stava-Tesero la ricostruzione e la memoria, 1985–2010, Litotipografia Alcione, pp. 23–50, 2011 (in Italian).
- Martin, T.E., & Davies, M.P., 2000. 'Trends in the stewardship of tailings dams', *Proceedings of Tailings and Mine Waste '00*, Fort Collins, January, Balkema Publishers, pp 393–407.
- Martin, T.E., & McRoberts, E.C., 1999. 'Some considerations in the stability analysis of upstream tailings dams.' *Proceedings of Tailings & Mine Waste '99*, pp. 287–302.
- Mattox, A., Higman, B., McKittrick, E. & Coil, D., 2015. 'Understanding Dam Failure'. Available from: <http://www.groundtruthtrekking.org/Issues/OtherIssues/understanding-dam-failure.html>. [2 September 2015.]
- Monserrat, O. & Crosetto, M. 2008. 'Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching', *Journal of Photogrammetry and Remote Sensing*, Vol. 63, Issue 1, pp. 142–154.
- Newcomen, H.W., Murray, C. & Shwydiuk, L. 2002. 'Monitoring Pit Wall Deformations in Real Time at Highland Valley Copper', 2002.
- Radovanovic, R., Ebeling, A. & Lo, D. 2014. 'Augmenting inclinometer-based information capture with high-precision GPS positioning: Towards fully automated top-down deformation monitoring', *CDA 2014 Workshop E: State of the Art Technologies for Monitoring Dams and Mining Dams*
- Government of British Columbia, 2015. Independent Expert Engineering Investigation and Review Panel Report on Mount Polley Tailings Storage Facility Breach. Available from:

<https://www.mountpolleyreviewpanel.ca/mount-polley-review-panel-delivers-final-report>.

[2 September 2015].

Rico, M., Benito, G., & Diez-Herrero, A., 2008a. 'Floods from tailings dam failures', *J. Hazard. Mater.*, Vol. 154: pp 79–87.

Rico, M., Benito, G., Salgueiro, A.R., Diez -Herrero, A. & Pereira, H.G., 2008b. 'Reported tailings dam failures: a review of the European incidents in the worldwide context.' *J. Hazard. Mater.*, Vol. 152: pp 846–852.

Rutledge, D.R. & Meyerholtz, S.Z. 2005. 'Using the Global Positioning System (GPS) to monitor the performance of dams.' *Geotechnical News*, 23(4), pp. 25–28.

Schneider, D., 2006. 'Terrestrial Laser Scanning for Area Based Deformation Analysis of Towers and Water Dams' *Proceedings of 3rd IAG/12th FIG Symposium*, Baden, Austria, May 22-24, 2006, pp.10.

Singh, N., & Fleming, C. 2014. 'Challenges in long-term and automated inclinometer measurements at highland valley copper's high tailings dams', *CDA 2014 Workshop E: State of the Art Technologies for Monitoring Dams and Mining Dams*

Smith, E.S. & Connell D.H., 1979. "The Role of Water in the Failure of Tailings Dams" Available from: https://www.imwa.info/docs/imds_1979/IMDS1979_Smith_627.pdf. [23 March 2017].

Soares, L., Arnez, F.I. & Hennies, W.T., 2000. 'Major causes of accidents in tailing dam due to geological and geotechnical factors.' *Proceedings of the Mine Planning and Equipment Selection – International Symposium*, pp. 371–376.

- Sun, E., Zhang, X. & Li, Z. 2012. 'The internet of things (IOT) and cloud computing (CC) based tailings dam monitoring and pre-alarm system in mines.' *Safety Science*, Vol. 50: pp 811–815.
- Szymanski, M.B., & Davies, M.P. 2004. 'Tailings Dams - Design Criteria and Safety Evaluations at Closure' *BC Reclamation Symposium 2004*.
- United States Committee on Large Dams (USCOLD), 1994. 'Tailings Dam Incidents. A Report Prepared by the USCOLD Committee on Tailings Dams', Available from: <http://ussdams.org/pubs.html>. [2 September 2015].
- Vanden Berghe, J.-F., Ballard, J.-C., Wintgens, J.-F. & List, B. 2011. 'Geotechnical Risks Related to Tailings Dam Operations', *Proceedings Tailings and Mine Waste 2011*, Vancouver, BC, November 6-9.
- WISE World Information Service on Energy Uranium Project, 2012. 'Chronology of Major Tailings Dam Failures.' Available from: <http://www.antenna.nl/wise/uranium/mdaf.html>. [2 September 2015].
- Yu, G., Song, C., Zou, J., Wu, Y., Pan, Y., Li, L., Li, R., Wang, P. & Wang, Y. 2011. 'Applications of online monitoring technology for tailings dam on digital mine.' *Trans. Nonferrous Met. Soc. China*, Vol. 21: pp s604-s609.

Figure Captions

Figure 1. Failure modes of tailings dams and frequency distribution

Figure 2. An idealized structural health and safety monitoring (SHSM) workflow from system design to communication with internal and external stakeholders.

Figure 3. Essential monitoring system considerations

Table Captions

Table 1. Failure modes and opportunities to reduce risk

Table 2. Failure modes and corresponding monitoring parameters

Table 3. Comparison of select monitoring techniques for addressing tailings dam structural health and safety management

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Figures

Figure 1. Failure modes of tailings dams and frequency distribution

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Figure 3. Essential monitoring system considerations

Tables

Table 1. Failure modes and opportunities to reduce risk

Failure Mode	Design	Operation	Monitoring
Slope instability	✓	✓	✓
Earthquake	✓		
Overtopping		✓	✓
Seepage	✓		✓
Foundation	✓		✓
Structural	✓	✓	✓
Mine subsidence	✓	✓	✓
Unknown			?

Table 2. Failure modes and corresponding monitoring parameters

Failure Modes	Monitored Parameters / Behaviours
Slope instability	Displacement, rotation, settlement, pore pressure change, tension cracks
Earthquake	Ground acceleration, pore pressure change, settlement
Overtopping	Freeboard change, pore pressure change, seepage flux
Seepage	Seepage quantity and quality, settlement/sloughing
Foundation	Displacement, rotation, tension cracks

Structural	Displacement, tension cracks, seepage (core failure)
Mine subsidence	Ground acceleration, settlement
Erosion	Effluent quantity and quality change, surface elevation changes

Table 3. Comparison of select monitoring techniques for addressing tailings dam structural health and safety management

Monitoring Technology	Monitored Parameters	Monitoring Scope and Results
Piezometer	hydraulic head / pore-water pressure	Interior, point, high reliability; low cost
Extensometer	1D displacement	Interior/exterior, point, high reliability; low cost, achievable accuracy: 0.05mm / 10m
Slope-indicator inclinometer	/ 1D/2D displacement / slope	Interior/exterior, point, high reliability; low cost, achievable accuracy: 3mm/ 10m
Tiltmeter	2D displacement	Interior/exterior, point, high reliability; low cost
Settlement cell	1D displacement (vertical)	Interior/exterior, point, high reliability; low cost
Time-domain reflectometer ¹ (TDR)	deformation in a linear array	Interior/exterior, feature, no measurement of absolute displacements
Time-domain reflectometer ² (TDR)	soil moisture content / pore water salinity	Interior, point, sensitive to soil type and mineralogy; depends on strong calibration
Surveying (optical)	3D displacement	Exterior, point/feature, e.g. level profile surveys; labour intensive
Robotic/automated stations (RTS/ATS)	total 3D displacement	Exterior, point/feature, high accuracy, lower labour costs, sub-cm accuracy for distances < 1 km
Secondary surveillance RADAR (SSR)	3D displacement	Exterior, feature

Light Detection and Ranging (LIDAR)	3D displacement	Exterior, feature, high accuracy, point cloud data; high data processing cost
Distributed optical fibre strain sensors	1D displacement (strain), acoustics	Interior/exterior, feature, high initial cost for permanent monitoring; achievable accuracy: 10^{-5} mm/m.
Distributed optical fibre temperature sensors	1D temperature	Interior/exterior, leak and seepage detection/localization.
Global positioning system (GPS) / Global Navigation Satellite system (GNSS)	3D displacement	Exterior, point/feature, real time kinematics (RTK) can be used to enhance GPS/GNSS measurements
Shape Accel Arrays (SAA)	3D displacement	Interior/exterior, feature, 3D deformation of a linear array
Multi-beam sonar	3D displacement	Exterior, feature
Interferometric synthetic aperture RADAR (InSAR)	3D displacement	Exterior, feature, ground-based or satellite-borne, sub-centimetre accuracy
Satellite data analysis	2D/3D displacement	Exterior, feature, measurement interval limited by satellite return time and atmospheric conditions
Aerial imaging analysis	2D/3D displacement	Exterior, feature, stereographic need for vertical displacement

1 - TDR application in coaxial cables for changes in impedance

2 - TDR application for measurement of soil permittivity