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The evolution of practice in the field of mine waste and water management in the last 10 years with supporting examples

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Abstract

Professional practice in the field of tailings, water, and rockfill management has undergone important changes in the last 10 years, forcing mining companies and practitioners to adapt very quickly. These changes, while already happening, have been accelerated by a series of important failures and the realization that the ways of the past were no longer acceptable. The most significant remaining changes include the realization by mining companies of the importance of their role and responsibilities as Owners in the safe performance of these facilities, the development of new techniques and methodologies to characterize and model the behaviour of these materials, and the integration of new technologies and management approaches to further de-risk projects. The improvement of tailings dewatering technologies has been at the core of some of these profound changes and has allowed the emergence of new mine waste management philosophies that are expressing themselves in a variety of ways throughout the industry. Clear trends have emerged like the deposition of tailings at higher percentage solids, a desire to simplify water management, a push to increase the robustness of infrastructure and systems, and the development of a higher sense of awareness and of more expertise throughout organizations. They also have profoundly changed the way mining companies are now viewing mine waste and water management projects. The following presents an overview of a series of recurrent issues encountered on real projects and how they have been addressed, in particular, through the integration of dewatering technologies. It touches also on some of the key dilemmas facing mining companies since this field remains one of tough choices in the context of the reality of mining projects, the expectations of stakeholders and partners, the financial capacity of companies, the expected life of projects, land access and land/water usage, etc.

Keywords: *mine waste management, tailings, water management, dewatering, governance*

1 Introduction

Professional practice in the field of tailings management has undergone important changes in the last 10 years, forcing mining companies, practitioners, and suppliers to adapt very quickly. These changes, while already happening for many years, have been accelerated by a series of important failures and the realization that the ways of the past were no longer acceptable. The most significant remaining changes include the realization by mining companies of the importance of their role and responsibilities as Owners in the safe performance of these facilities, the development of new techniques and methodologies to characterize and model the behaviour of these materials, and the integration of new technologies and management approaches to further de-risk projects (Julien 1996).

It is now widely accepted, in the case of tailings storage facilities (TSF), that all life-cycle phases are important: design, construction, operation, and closure (MAC 2019). The idea of having sound and clear governance for the management of these infrastructures is considered a key component of a solid risk management program. Good governance rests on the recognition by the Owner of its responsibilities with the performance or non-performance of these facilities. This recognition implies establishing clear roles and responsibilities, a clear line of accountability to the highest echelons of the organization, proper layers of verification and review (both internal and external), and checks and balances to make sure sites have the proper tools, resources, and budgets to manage their risks properly. Given that companies are all different and have their own way of doing things, the notion of governance remaining flexible and adaptable to each specific case is important. The *Guide to the Management of Tailings Facilities* (MAC 2019) (“The Guide”) has been developed with this built-in flexibility to account for varying company sizes and resources and with the assumption that organizations are on a journey of continuous improvement. The *Global Industry Standard on Tailings Management* (GISTM 2020), developed on somewhat different assumptions, is also leaning toward a more flexible framework comparable to “The Guide*”*.

While the industry has clearly improved its overall approach to tailings management, both at the governance and technical levels, it remains that societal expectations are always increasing. Notwithstanding all the improvements in the overall practice, the pursuit of risk reduction, and even risk elimination, has become a clear focus for the industry. To achieve this, tailings disposal below the ground surface (cemented paste backfilling) is maximized when possible, and a strong push toward significant tailings dewatering is happening at many sites.

The improvement of tailings dewatering technologies has been at the core of some of the changes and has allowed the emergence of new mine waste management philosophies expressing themselves in a variety of ways throughout the industry. Clear trends have emerged such as the deposition of tailings at higher percentage solids with little or no excess or bleed water, a desire to simplify water management, a push to increase the robustness of infrastructure and systems, and the development of a higher sense of awareness and more expertise throughout organizations.

These changes have also profoundly changed the way mining companies are viewing mine waste and water management projects. This paper gives an overview of a series of recurrent issues encountered on real projects and how they have been addressed through the integration of dewatering technologies. It touches also on some of the key dilemmas facing mining companies since this is a field of tough choices given the reality of mining projects, the expectations of stakeholders and partners, the financial capacity of companies, the expected life of projects, land access and land/water usage, etc.

2 The push toward reducing risks

The debate surrounding upstream raises of tailings dams is quite revealing of the profound changes occurring in the mining industry. It is fair to say the mining industry has developed unique experience and expertise to build on contractive and loose tailings. Figure 1 shows some examples of construction with rockfill placed directly on loose tailings. It is interesting to observe the pore pressure response during placement and how it dissipates in Figure 1(a). This ability to build on tailings beaches has been essential to allow upstream (and centerline) constructions. Despite the fact that the large majority of upstream raised constructions have withstood the test of time quite successfully (and under a variety of loading conditions), this method is currently considered by many as an unacceptable practice and should be avoided. As pointed out by Morgenstern (2018), there is nothing wrong with upstream tailings dams, provided that key principles are adhered to in the design, construction, and operation of such dams. Morgenstern further mentioned, for the purpose of preliminary design, liquefiable deposits that can liquefy should be assumed to do so and containment should be provided by a buttress of non-liquefiable unsaturated tailings and/or compacted dilatant material. He also stressed the importance of continually demonstrating by monitoring that the assumed unsaturated conditions persist.

Therefore, with the proper level of engineering and control during construction and operation, upstream raises can be seen as a construction method performing in an acceptable manner under the appropriate conditions. It can even perform in a comparable way to other construction techniques, like downstream raises built on controlled materials, as long it is understood that it carries an additional degree of freedom associated with construction on tailings.

(a) (b)

Figure 1 Construction on tailings with waste rock. (a) As loading proceeds, excess pore pressure in the front dissipates progressively; (b) The loading rate and construction method are keys to reducing risks.

Nevertheless, the upstream construction technique is now commonly seen in a negative way and is even banned in some jurisdictions. Despite the good engineering that could be applied and long experience with this construction technique, it is now clearly an uphill battle for anyone who may decide to take this route for new sites.

Beyond construction on tailings, the mining industry has been required to construct embankments on foundations exhibiting strain weakening/brittleness or general contractive behaviour. Again, as pointed out by Morgenstern (2018), the application of geotechnical principles adequately provides for accommodating these types of foundations. The challenge resides in ensuring that these principles are properly understood and applied in the design.

Figure 2 shows an actual project with the two previous conditions: Type 1 Potential Failure Mode on brittle foundations (note: the stability analysis was controlled by the residual strength parameters of the weak layer) and Type 2 Potential Failure Mode within the tailings acting as the foundation to the upstream raises (note: the stability analysis was controlled by the post-liquefaction parameters of the tailings). Figure 2 (b) provides mitigation measures for both potential failure modes (Julien & Masengo 2021).

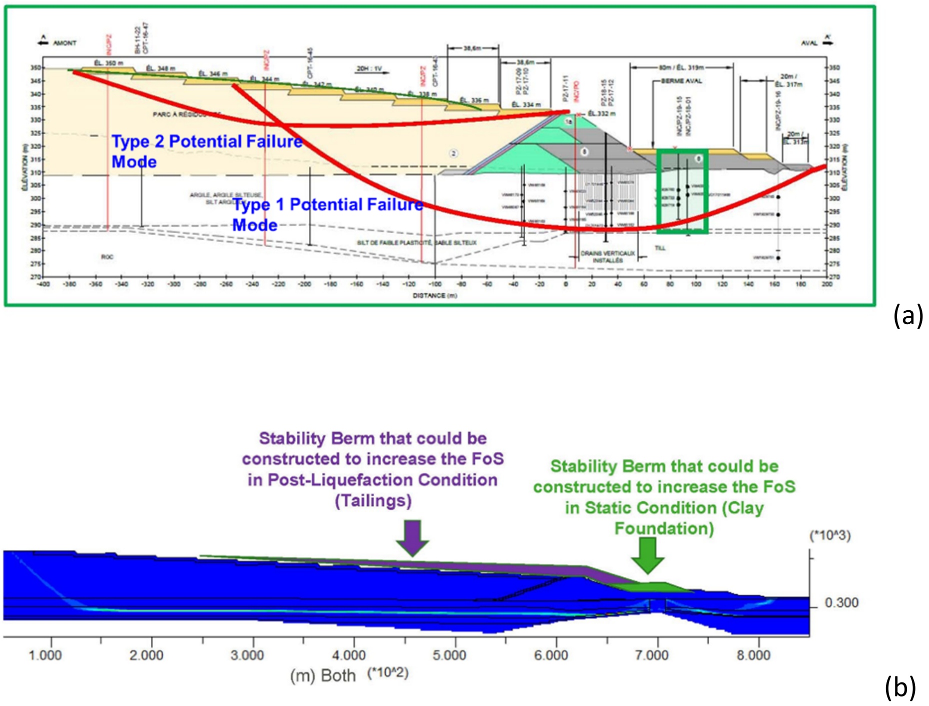


Figure 2 Project with upstream raises with a 10H:1V overall slope. (a) Two dominant failure mechanisms to be addressed; (b) Mitigation measures to address these failure mechanisms.

As for the upstream raises, the technical conversations involving foundations that could show strain weakening/brittleness are becoming increasingly complex and may end up being debates only reserved for experts. They tend to rely on debatable assumptions on material properties and assessments of the stress-strain path. In the end, there are always remaining doubts about the proximity to limit conditions leading to strain weakening or softening that could cause sudden loss of strength. Also, a great deal of effort is spent on debating the importance of statistically marginal measurements on the overall behaviour.

There is therefore a clear trend aiming at closing these open doors by promoting the removal of the problem all together at the source such as by removing questionable foundation materials, constructing shear keys, or considering soil improvement techniques (Julien & Masengo, 2021). Figure 3 shows the construction in 2022 of a large 60 m shear key based on a competent foundation for a new TSF dam at Canadian Malartic Mine. This construction's intent was to eliminate the risk for Type 1 and 2 failures.

Figure 4 shows aerial views of part of the TSF at Canadian Malartic Mine. The TSF was constructed with a series of 2.0 m rockfill raises on tailings with a flat slope. Figure 4(b) shows the buttress to confine the tailings and some test plots for the final cover. Again, the intent here was, at the very least, risk reduction.

Figure 3 **Construction of a massive shear key on competent foundations at Canadian Malartic Mine to remove brittle materials in the foundation.**

(a)

(b)

Figure 4 **Thickened tailings and upstream raises at Canadian Malartic Mine. (a) A series of cells with 2 m raises; (b) Buttress to confine liquefiable tailings and test plots for the final cover.**

Another important aspect being increasingly emphasized (and rightfully so) is the so-called Dam Break Analysis (DBA), which has complex ramifications well beyond its technical aspects. As clearly pointed out in some initiatives like GISTM (2020), there is a need to engage communities and external stakeholders with these questions, particularly in the context of emergency preparedness. While the practice with DBA has greatly evolved in the last few years, the overall state of practice in this space still needs to firm itself more consistently (Julien 2019). Depending on the assumptions used, the outcome of these analyses can vary greatly. Figure 5 provides a simple way to represent the possible response of a flowing material through a breach (CDA 2021). The response will vary widely depending on the water content of the material (*not all failures will result in mud flow*). Given all the uncertainties, the practitioners in this field often give a range of behaviours. The intervals of behaviour can have radically different consequence levels. The worse one will always prevail, given the sensitivity of the topic. Another fundamental problem with the DBA is the frequent disregard of the engineering controls put in place to prevent breach creation. Similarly, to the previous potential failure modes, DBA may lead to difficult and complex conversations, having a huge impact on an operation.

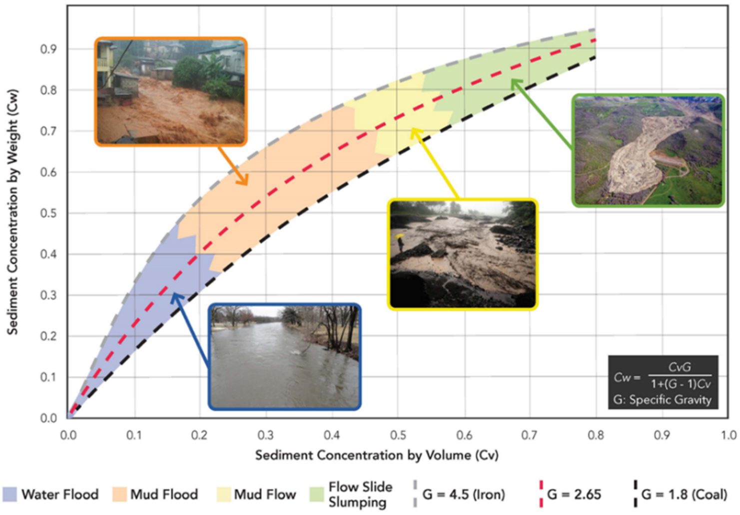


Figure 5 **The behaviour of the liquefied material can vary a lot depending on its characteristics, resulting in a wide range of responses of the flowing material (source CDA 2020).**

As mentioned, the practitioners in this field will tend naturally to take a defensive position irrespective of the engineering controls by assuming the system will fail anyway. Their reaction is quite understandable. While there is merit in being conservative, practitioners need also to realize the resulting difficult conversations, especially when they involve risk to human life, private property, and the environment. Failure Modes and Effects Analysis (FMEA) (CDA 2013, 2019) is becoming quite important in this context to promote conversations on credible failure modes. After a DBA is completed and an agreement has been reached, the organization needs to be ready to tackle the complex messaging and actions that may follow. It is important to mention one should be realistic regarding what can be achieved with warning and alarm systems: these remain tools with lower efficiency in the hierarchy of controls.

The following provides interesting excerpts from an actual DBA report. This example is quite revealing: (…) *used the estimated solids content (70% to 73%) and the laboratory tested yield strength (20 Pa) of the (…) tailings to identify their flow behaviour when mobilized. Both "slurry flow" … and "granular flow" … were proposed as plausible, based on literature sources. Slurry flow was modelled using the Bingham Non-Newtonian Model, which led to long run-out distances of the mobilized tailings. Granular flow was modelled assuming a frictional rheology model as well as a plastic rheology model*. This led to the following results provided in Table 1. The variability of the results is striking and the consequences on a project evident. In this particular instance, it took three years of discussion, material characterization, modeling, and analyses to reach a reasonable agreement on a narrower and more realistic interval of consequences. This agreement was reached between the different groups involved (the designer, the reviewers, and the company) and part of the governance model and did not involve stakeholders outside of the governance framework.

Table 1 **Examples of DBA results obtained for a project. Depending on the choice of flow behaviour for the material after failure, the consequences varied greatly.**

	Granular Flow	Slurry Flow
Volume mobilized	1Mm3	23.6Mm3
Distance	100 m	+20 km
Residences impacted	<2	>30

Therefore, the conversations surrounding the performance of TSFs are becoming increasingly more technical and complex. They always lead to the definition of residual risks which are hard to quantify and are open to debate. In the context of increasing disclosure to rightsholders and different external stakeholders, the resulting conversations may be quite difficult. In applying the notion of hierarchy of control (Australia Government 2008), it is becoming evident the industry has no other choice than to move progressively to higher levels of control, such as risk reduction, and when possible, even risk elimination.

An additional note on risk assessment, an underlying tool for this whole discussion, greatly benefited from the work of some contributors like Silva et al. (2008) who have expressed in simple words the importance of the whole life-cycle in the assessment of a project. In particular, their work has greatly contributed to the nuanced notion of the Factor of Safety when viewed in the context of the effort put into the design (investigation, laboratory testing, and analysis), the rigour applied during construction, and the quality of the monitoring during operation. With their intuitive approach, they have put forth this idea of the Probability of Failure in a simple and palatable way. Their work has been extended to TSFs (Julien et al. 2019, Chovan et al. 2021). These tools have been found to be quite useful to engage in conversations with non-experts and to identify priorities.

3 Tailings dewatering and water management

Tailings dewatering has been used routinely for many decades. Cemented paste backfill has been instrumental in the evolution of mining in the last 30 years and requires tailings thickening to achieve the right recipe (Potvin and Hadjigeorgiou 2020). These techniques have been applied successfully even for high throughput operations. The introduction of surface disposal using thickened tailings has had a more complicated story but nevertheless was followed and was progressively adopted. It is clear that tailings dewatering, particularly to the point where tailings have a percentage solids (mass of solids/total mass) (%solids) that limits and even eliminates the amount of excess or bleed water, has greatly contributed to risk reduction. Figure 6 shows an interesting example where an operation increased its average %solids (end of pipe) from 53% to 65% after a retrofit of the main thickener. It is remarkable to observe the difference in the quantity of excess water to manage and the ensuing overall risk reduction. Contrary to common belief, the actual in-situ characteristics (strength, void ratio, and dry density) of the in-situ tailings are not that different in the end. Clearly, higher %solids tailings will undergo less segregation. However, from the design and stability perspectives, in many cases, these materials will not be that different (at least, it is the author's experience).

The greatest advantages of thickened tailings are the ability to develop tailings beaches more effectively (by reducing the energy at placement) and the significant simplification of water management and associated risk reduction. Having simplified water management allows, among other things, a higher water recirculation rate, better overall environmental management, and the possibility of progressive closure.

It is interesting to point out that while the focus has been for the last 10-15 years on tailings themselves, the issue with water management has been somewhat overshadowed. Water management is key to the industry: it is hard to find a site without water management issues. Beyond that, water remains probably the prime interface with external stakeholders, communities, governments, etc. It is clear for the author that anything that can be done to simplify and improve water management is beneficial. It is not rare to see that some projects that started several decades ago without water treatment plants now may have more than three!

(a) (b)

Figure 6 Thickened tailings in a TSF before and after the retrofit of a thickener to bring end of pipe %solids from 53% to 65%. (a) At 53% solids with a lot of excess water to manage; (b) At 65% solids.

4 The opportunities and challenges with filtered tailings

4.1 Producing an engineered material

For many decades, filtration has been an integral part of the mining industry to obtain either a concentrate with the proper moisture content or to produce a good quality paste backfill for underground applications. With the recent advances in the design of pressure filters to accommodate large throughputs, a transformational opportunity has arisen for the mining industry. The possibility (and *possibility* should be emphasized) is to actually produce an engineered material with tailings when placed in a TSF. This engineered material can be obtained by coupling the placement of filtered tailings with proper compaction. Compaction here is key: without it, filtered tailings may very well remain a contractive material and, in some conditions, potentially liquefiable.

In geotechnical engineering, the tools exist to make sure these compacted filtered tailings can be considered as dilatant and potentially non-liquefiable. Nevertheless, using filtered tailings is not the solution to all applications. Some tailings containing high clay contents can be particularly difficult to filter. Furthermore, filtered tailings can be more problematic geochemically, such as when they are potentially acid generating (PAG). These limitations have been widely recognized, but filtered tailings remains an interesting possibility for a wide range of applications referred to as Best Available/Applicable Technology.

Figure 7 shows an interesting application involving filtered tailings placed in a mined-out open pit in Mexico (Falmagne et al 2023). The interesting technical aspects of this project were to first use an existing mined-out open pit (prime real estate!) in order to minimize the impacted surface footprint, while allowing the safe continuation of the underground mine activities underneath. This project involved the construction of an artificial crown pillar of roller compacted concrete (RCC) with a series of filters and drainage layers and a Super Well to pump water accumulating at depth. The site also involved a lot of instrumentation (vibrating wire piezometers, inclinometers, and extensometers) to monitor the pit wall and the behaviour of the tailings. Figure 6(a) and (b) show the project in 2016 and 2021. Currently, the open pit has reached pretty much its final elevation, and closure preparation is underway.

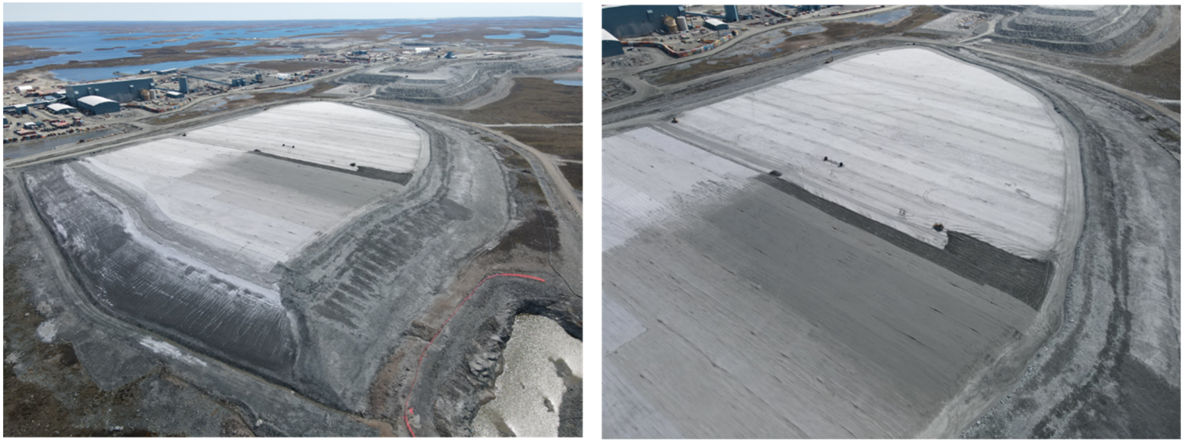
Meliadine Mine in Nunavut (Figures 8 and 9) had opted for filtered tailings when its operation started in 2019. The decision to go filtered was not an easy one: it took about three years to reach a final decision. There were a lot of concerns about the technical feasibility and operating costs in Arctic conditions. Figure 8 shows two aerial views of the site and the TSF. The placement strategy at Meliadine can be summarized by the transport of the material by trucks from an accumulation dome on a peripheral road that goes up as the stack goes up. Final cover placement follows as the facility increases in height.

(a)

(b)

Figure 7 **Filtered tailings in a mined-out open pit over an active mine in Mexico. (a) An artificial crown pillar was constructed to protect the mine; (b) The open pit almost completely filled with tailings (2021).**

The objective of the project is to construct a sustainable landform that will pass the test of time in this continuous permafrost environment. The site is also highly instrumented with vibrating wire piezometers, thermistors, and inclinometers. From the available thermistor results, it can be seen the site is getting progressively integrated into the permafrost. Figure 8 shows the placement of the material involving the truck pulling back, the dozer placing the material to the appropriate lift thickness, and the smooth roller compactor following. The lift thickness is about 0.3 m.



(a)

(b)

Figure 8 **Filtered tailings at Meliadine Mine, Nunavut. (a) Tailings are transported by truck on an access road on the periphery; (b) Dusting needs to be constantly monitored and controlled.**

(a) (b)

Figure 9 Placement of filtered tailings at Meliadine Mine, Nunavut. (a) Trucks pulled back followed by the dozer (spreads and places) and the compactor; (b) Tight control on lifts to achieve proper compaction.

Dust management has been an area of focus for the site. Dust is a nuisance to be expected for such applications. Dust management should be included in operational planning. The site had to innovate and put in place a series of mitigation measures.

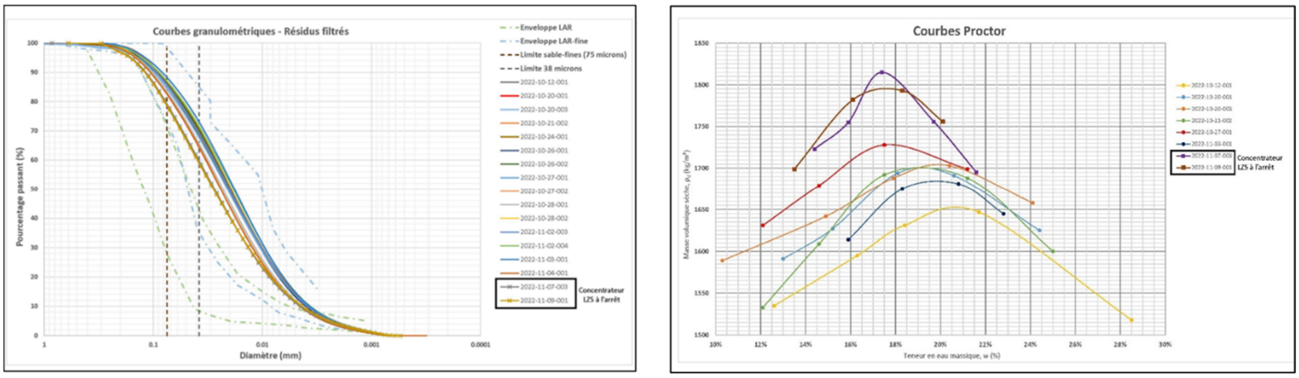
4.2 Adaptation of placement strategy to material variability

An interesting application of filtered tailings is taking place at LaRonde Mine in Quebec (Figure 10). The filtration plant was commissioned in 2022. Its design had to accommodate significant variability with the feed to the filtration plant. LaRonde Mine is processing two streams of ore from two distinct orebodies (LaRonde and LZ5). LaRonde tailings are coarser at about 80% passing 75 microns produced at a rate of up to 7,000 t/day, while LZ5 is much finer at 80% passing 40 microns produced at a rate of about 3,000 t/day. Both streams are mixed in the pump box before being pumped to the filtration plant. In addition, when the paste backfill plant is operated, it uses only LaRonde tailings and, at full capacity, can accept all the LaRonde tailings produced. Therefore, the filtration had to be designed to accommodate a wide range of conditions: LaRonde tailings (from 0 to 7,000 t/day) plus LZ5 tailings (from 0 to 3,000 t/day). The plant so far has performed surprisingly well under this varying feed.

With respect to the filtered tailings produced, a sample of the gradation distribution is given in Figure 11(a) clearly showing how variable the material sent to the TSF is. Regarding the compaction, a series of Standard Proctor has been developed to capture this variability. Figure 11(b) shows a fairly broad range of Standard Proctor values from 1,650 to 1,825 kg/m^3 (and associated moisture content). This situation has led to a series of tests and discussions with the designer on what is *acceptable* compaction for this site and what should be used on a day-to-day basis. It is clear at the end of the day, realistic expectations needed to prevail, and the QA/QC had to accommodate these variable conditions.

Another aspect that makes this project quite unique is the fact that filtered tailings are deposited over an existing cell of the TSF (Cell A4), which is essentially full of contractive tailings. This approach was selected in order to limit the expansion of the footprint of the TSF. In order for the placement to proceed on these tailings, a rockfill platform (referred to as the Bridge Lift) 2 m thick is being constructed. This Bridge Lift serves as a platform for the circulation of the trucks, the placement of the filtered tailings, and a drainage layer to dissipate the excess pore pressure of the underlying tailings. Figure 10 shows the state of advancement of the Bridge Lift during summer 2022 (in the background, the new Cell 5 North and South, dedicated to water management, is visible). The rockfill used for this layer is a PAG rockfill that would have required rehabilitation. The site is well instrumented to monitor pore pressure and settlement and to correct the predictive models as the work progresses. The rate of raise for the filtered tailings has been assumed to 3.0 m/year to allow proper pore pressure dissipation. So far, the work has been progressing well.

Figure 10 LaRonde Mine in Quebec (2022). An existing cell full of tailings is re-used to place filtered tailings on top of a platform (bridge lift) of rockfill (2.0 m). This figure shows a partial bridge lift.



(a) (b)

Figure 11 Filtered tailings at LaRonde Mine in Quebec. (a) Gradation curves vary depending on the tailings feed at the filtration plant; (b) Standard Proctor varies depending on material.

4.3 Developing a business case

Beyond the fact that some materials may be challenging to filtrate, probably the biggest challenge to overcome with this technology remains its higher upfront capital requirement and high operating costs in the context of limited Life of Mine. The experience has shown, in order to build a solid business case, one should include in the comparison of options, the notion of level of uncertainty for these costs, and the potential benefits at closure. It is unfortunately well known that construction costs of tailings dams often tend to be underestimated. This is particularly true when extensive foundation preparation (like grouting) is required. It is the author’s opinion that mechanical equipment tends to be easier to cost with a higher level of certainty than the dams themselves. The cost variability should be factored in which may allow the filtration option to be more competitive. Regarding operating costs, filtered tailings will also tend to be costly. The integration of the closure costs may make this value proposition much more attractive.

A point worth mentioning is the higher level of standard of care applied in the placement of filtered tailings in general and what should be the sweet spot to achieve the design intent while not killing the project. It is therefore important not to lose sight of this aspect versus conventional disposal and to include the willingness to accept change management as part of the optimization process.

5 Conclusion

The changes the mining industry is undergoing with tailings management have accelerated these last few years by the establishment of more solid governance within the organizations and a continuous desire to move toward risk reduction, if not risk elimination. Advances in the field of tailings dewatering have been instrumental in this journey. For the case of TSFs with liquefiable tailings, the decoupling of water management from tailings management with the use of thickened tailings has been found to be a good practice. The construction of robust buttressing to confine liquefiable tailings using non-liquefiable unsaturated tailings and/or compacted dilatant material is seen as a good practice.

On the other hand, for TSFs constructed on foundations that can exhibit strain weakening/brittleness or general contractive behaviour, using standard tools in geotechnical engineering has been quite effective. Amongst the techniques available, the removal of problematic material, the construction of robust shear keys, and soil improvement techniques are seen as good practice.

With the development of filtration techniques, it is now possible to dewater tailings to the point they can be considered engineered materials. Standard geotechnical practice also provides the tools to improve the strength characteristics of these materials to make them essentially non-liquefiable with the introduction of proper compaction and construction QA/QC and by leveraging in-situ investigation techniques. However, tailings filtration remains a tool in the toolbox with its limitations and challenges. Beyond the fact that some materials may be challenging to filtrate, probably the biggest challenge remaining with this technology is its higher upfront capital requirements and high operating costs. It is therefore highly recommended to build a solid business case involving potential benefits at closure. One important aspect to emphasize when constructing such business cases is the higher inherent uncertainty of certain costs. Recent experience (even during inflationary times) has shown that building dams intrinsically carries higher costs of uncertainty, especially when foundation preparation is involved. Another challenge inherent with filtration is to protect against upset conditions and to accept variability with the feed. In addition, this technique may be more susceptible to nuisances like dusting and carries a higher sensitivity to geochemical effects. Still, despite all these possible challenges and limitations, tailings filtration will definitely be transformational for the mining industry in the upcoming decades.

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