Tailings impoundment stabilization to mitigate mudrush risk

Amy Adams[1,a], Daniel Friedman[2,b], Ken Brouwer[2,c], Scott Davidson[3,d]

[1]*Knight Piésold Ltd., North Bay, Canada*
[2]*Knight Piésold Ltd., Vancouver, Canada*
[3]*New Gold Inc., Kamloops, Canada*

[a]aadams@knightpiesold.com
[b]dfriedman@knightpiesold.com
[c]kbrouwer@knightpiesold.com
[d]scott.davidson@newgold.com

ABSTRACT

Historical tailings impoundments may contain saturated semi-fluid materials at depth, long after tailings deposition has ceased and after surface reclamation has been completed. These saturated materials can liquefy and flow if the impoundment is breached. A historical tailings pile can represent a risk to an underground mine development if there is potential for the mine development to generate a propagating zone of cracking and/or surface subsidence that ultimately interacts with the historical tailings impoundment. The risk of a sudden mudrush breach can be mitigated by reducing the potential for the tailings to flow. This paper presents a case study for the New Afton Mine located in British Columbia, Canada. A rheological model was developed to characterize the yield stress and flowability of a historic tailings deposit. In-situ and laboratory testing was completed to understand the variability between sandy tailings, deposited as above or below water beaches, and finer tailings 'slimes', deposited further from the deposition points. Simple index properties such as moisture content and clay-sized fraction were used to characterize the tailings rheology. A field-scale trial program was implemented to demonstrate that the tailings could be quickly and effectively densified and dewatered using wick drains, consolidation loading, and dewatering wells.

1. INTRODUCTION

Tailings are variable in nature and the disposal techniques vary significantly depending on the mining methods/rates, the ore characteristics, the site conditions and also the environmental, social and economic considerations that prevailed during the permitting, construction and operational stages of the mine. Tailings impoundments often continue to represent an ongoing liability, long after mine operations cease and the surface facilities have been closed and reclaimed. Dams for decommissioned or inactive tailings impoundments need ongoing care and maintenance for as long as these dams are required to securely retain ponded water and/or potentially liquefiable tailings solids within the impoundment.

The dams will no longer need to function as dams, and the tailings pile can be considered to be a stable landform, only after:

- the impoundment surface is suitably dewatered, shaped and capped so that it can no longer function to retain a surface water pond
- the tailings mass at depth is suitably consolidated and/or drained such that there are no longer any 'flowable' materials that could generate a mudflow capable of leaving the site boundary, and
- the facility can be considered to have a risk profile similar to the surrounding environment (MEM, 2008)

The surfaces of many tailings impoundments have been reclaimed by shaping, capping, and revegetation, but there are fewer examples where the tailings pile can be shown to be suitably stabilized with no potentially flowable materials at depth. There are opportunities to use best available technologies to reduce the risk associated with operating and closed tailings facilities. The stabilization of the entire tailings deposit is possible when filtered tailings are produced and compacted during placement to form a suitably dense dilatant soil material that would not be prone to liquefaction, even if the tailings landform became re-saturated at any time in the future. Similarly, dense drained tailings deposits have been successfully developed when controlled thin layer sub-aerial tailings deposition in suitably arid climates is coupled with underdrainage to develop dense non-liquefiable tailings deposits that meet both of the above criteria (Knight & Haile, 1983; Haile & East, 1986; Ulrich et al, 2000).

However, many historical tailings impoundments were progressively developed using relatively simple hydraulic slurry placement within a flooded or partially flooded facility. These 'conventional' hydraulically emplaced tailings deposits form a relatively loose and somewhat segregated mass of interlayered sandy and silty materials, with the finest grained silty and clay-sized (slimes) particles typically deposited farthest from the discharge points. These hydraulically emplaced tailings deposits are typically comprised of materials that are contractive and prone to liquefaction, particularly in the upper 20 to 40 meters of the deposit where they are less consolidated than at greater depths. The 2015 Samarco tailings failure (Morgenstern et al, 2016) provides an example where loose saturated tailings liquefied and created a catastrophic mudflow that rapidly migrated downstream, inundating a village and causing 19 deaths. The geotechnical characteristics of the tailings sand and slimes deposits are very different. Operational factors, such as changing ore characteristics, grind size, or changing the tailings facility filling rate or discharge locations (spigots vs. single point discharge), can also significantly influence the geotechnical properties of the sands and slimes within the heterogeneous tailings pile that is developed during mine operations.

The geotechnical characteristics of a tailings impoundment can also become a critical factor in the success of a project when underground mining activities extend laterally and mine-induced deformations result in cracking or surface subsidence features that may interact with the tailings impoundment. Water and/or fluidized tailings materials can represent significant risks to an underground mine development due to the potential for a catastrophic mudrush. A mudrush event occurred at the Mufulira mine in 1970, in which 89 underground miners lost their lives when ponded water and liquefied tailings created a highly fluid slurry that rapidly flowed into the underground workings through mine-induced cracks. Post disaster forensic investigations led to the development of remedial drainage measures within the remaining surface tailings pile in order to stabilize the materials and allow safe underground mining operations to be resumed (Sandy et al, 1976). Mufulira was a relatively shallow mine compared to the New Afton block cave, but serves as a relevant case history nonetheless.

This paper presents the case study of the investigations and testing relating to the design and progressive implementation of remedial stabilization measures for the historical tailings facility at the New Afton Mine. The methods that have been investigated and are proposed for full scale implementation are considered best available technologies. It was necessary to evaluate both the geotechnical conditions (soil characteristics) of the tailings mass, as well as the potential rheological behaviour (fluid flow characteristics) of any loose saturated zones that could be susceptible to liquefaction and migration into the cave zone or underground workings. Therefore, this study relies on integration of the principles of advanced soil mechanics with fluid mechanics and rheology, particularly as it relates to contractive liquefiable tailings materials that are characterized by considering slurry viscosity and flow behaviour.

2. PROJECT OVERVIEW

The New Afton Mine is a copper gold mine located approximately 10 km west of Kamloops in British Columbia, Canada (Figure 1), that was historically developed from 1978 to 1997 using open pit mining methods. Conventional flotation processes produced a tailings slurry that was hydraulically discharged at approximately 35% solids content via multiple spigots into a nearby facility. The historical mine site was closed and the surface facilities were partially reclaimed. In 2005 New Gold Inc. acquired a portion of the overall property and continues to develop an underground block caving mine operation to exploit deeper mineralized zones. Slurry tailings from the current mill are disposed in the active New Afton Tailings Storage Facility, as illustrated on Figure 1.

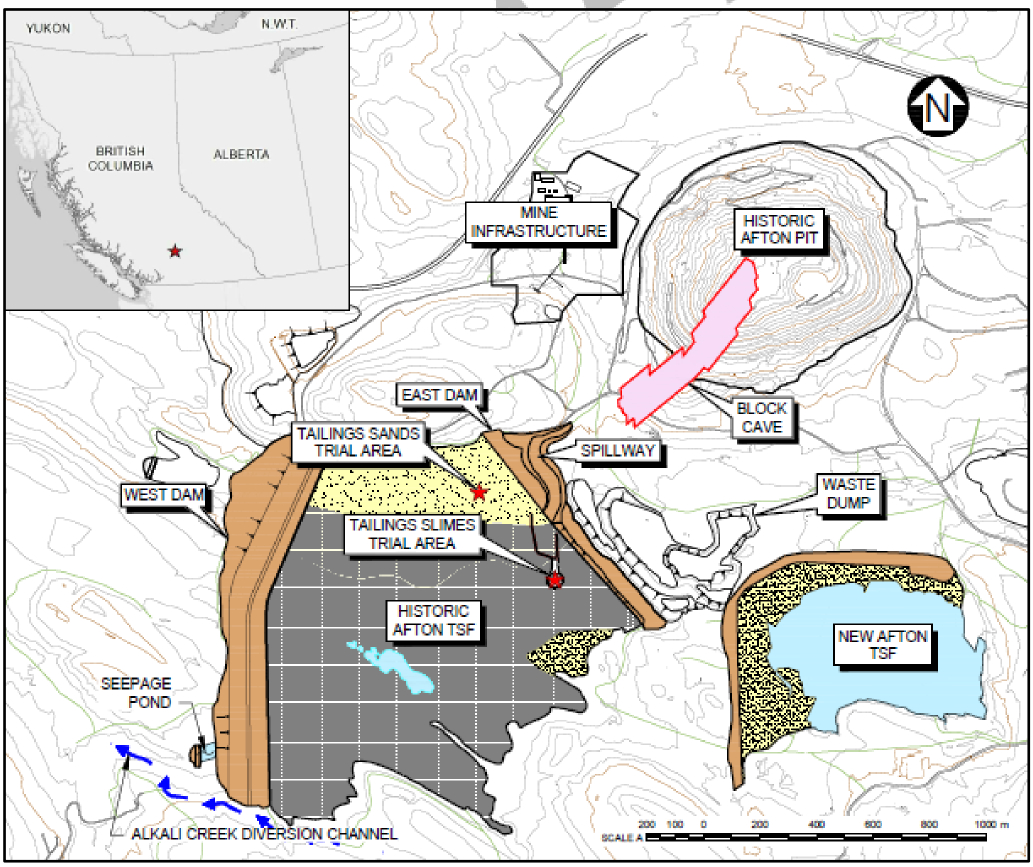

Figure 1 Project Location and Site Layout

The historical Afton tailings storage facility (Historical TSF) includes two zoned earthfill/rockfill dams that were constructed in stages during the previous mine operations. The West Dam is approximately 75 m high and has a crest width greater than 100 m. The underground mine has the potential to induce deformations and cause cracking and surface subsidence that may impact the East Dam. The East Dam was constructed to a height of approximately 65 m (Elevation 706 masl). The current East Dam crest is greater than 100 m wide and was intended to be raised an additional 26 m to the ultimate impoundment elevation of 732 masl (Figure 2). It was constructed as a compacted rockfill dam with an upstream core zone of compacted glacial till. An extensive waste rock dump that is higher than the dam itself is situated immediately downstream and buttresses the eastern extent of the facility. Water management features include an upstream diversion channel to safely route surface runoff from up-gradient catchments around the West Dam, as well as an emergency spillway constructed along the left abutment of the East Dam. The TSF spillway was sized to safely route runoff from extreme storm events into the historical open pit east of the TSF. The Historical TSF does not have a water pond on the surface and is in a negative water balance condition; it is expected to stay dry in the long-term.

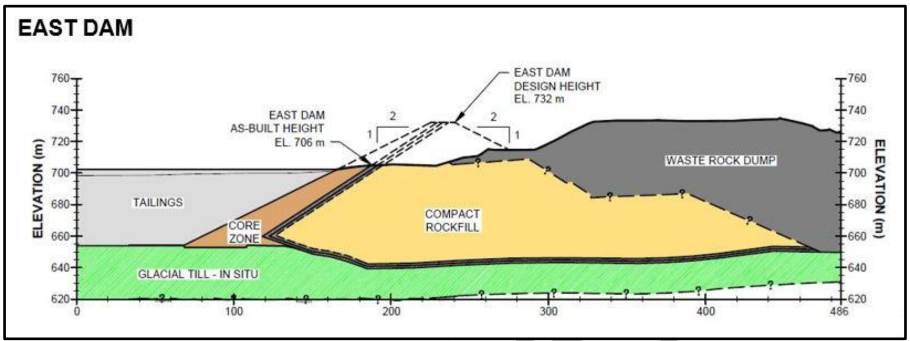

Figure 2 East Dam Section for Historical Tailings Impoundment

3. TSF BREACH CONSIDERATIONS

A surface breach of a tailings retaining structure could result in the release of the entire supernatant pond volume and full or partial discharge of the impounded tailings (Fontaine & Martin 2015). Two discharge mechanisms are typically observed during a TSF dam breach including: (1) an initial flood wave of supernatant water mixed with tailings and embankment materials that may travel 10’s to 100’s of kilometres downstream, and (2) slumping or flow of liquefied tailings that may result in a smaller inundation footprint to the downstream environment. The outflow volume of the breach can be estimated based on the volume of the supernatant pond and the characteristics of the deposited tailings including their density and saturation. Fontaine & Martin (2015) demonstrated that reducing the size of the supernatant pond yields a linear reduction in the size of the breach outflow volume, whereas increasing the dry density of the tailings yields an exponential decrease in the volume of the breach outflow.

A detailed dam breach and inundation assessment for the historical Afton TSF was completed in 2015 (Akkerman & Martin, 2015). The East Dam was classified as a HIGH consequence structure due to the breach outflow into the historical Afton open pit. Two failure conditions were considered during the dam breach assessment: (a) *Sunny Day* failure, or failure during normal operating conditions that would be caused by a dam collapse due to any circumstance; and (b) *Rainy Day* failure, or flood-induced failure that would be caused due to dam overtopping. It is difficult to imagine any of these failure modes as plausible for the East Dam, given the arid local climate, the large capacity of the spillway, the apparent robustness of the embankment design and extensive crest width, the negative water balance resulting in a typically very small or non-existent pond, and the large storage capacity between the tailings surface and the dam crest. Full or partial blockage of the spillway would be required to cause overtopping of the facility during a Probable Maximum Flood event. It is unlikely that this would develop under the continued monitoring and maintenance resulting from the ongoing mining activities at the site. It is important to recognize that the surface pond was removed by pumping to the New Afton TSF in early-2015 and the remaining surface water subsequently evaporated throughout the summer of 2015.

Nevertheless, a dam breach scenario cannot be completely discounted given the semi-fluid nature of the stored tailings and the potential for a pond to form after an extreme storm. Removal of the supernatant water pond in 2015 and construction of the Alkali Creek diversion channel have substantially reduced the potential for an initial flood wave to develop during the unlikely event of a dam breach event. This can be further reduced by selective surface grading to eliminate the potential for ponding during a storm event. Furthermore, densification of the tailings will reduce the volume of interstitial water, increase the solids content and preclude liquefaction, which will in turn eliminate the potential for the outflow of liquefied tailings during a breach event, reducing the consequences to localized slumping. Combined with the very low probability of a dam breach occurring given the robust design and climatic setting, credible failure modes are eliminated once the tailings are suitably stabilized and capped to prevent water ponding during extreme precipitation events.

The New Afton underground mining method commenced in 2012 and will result in surface cracking and subsidence that is conservatively postulated to potentially interact with the overlying historical Afton TSF as the mine development becomes progressively larger and deeper (Figure 3). Worker safety is a primary and fundamental requirement for ongoing mining operations. Sophisticated monitoring systems are coupled with extensive numerical modelling to track deformations and to enable accurate prediction of the influence of future mine developments on surface facilities. The proximity of the historical TSF to the underground mine has been identified as a potential risk factor and represents a potential mudrush hazard, unless appropriate tailings stabilization techniques are implemented as mitigation measures.

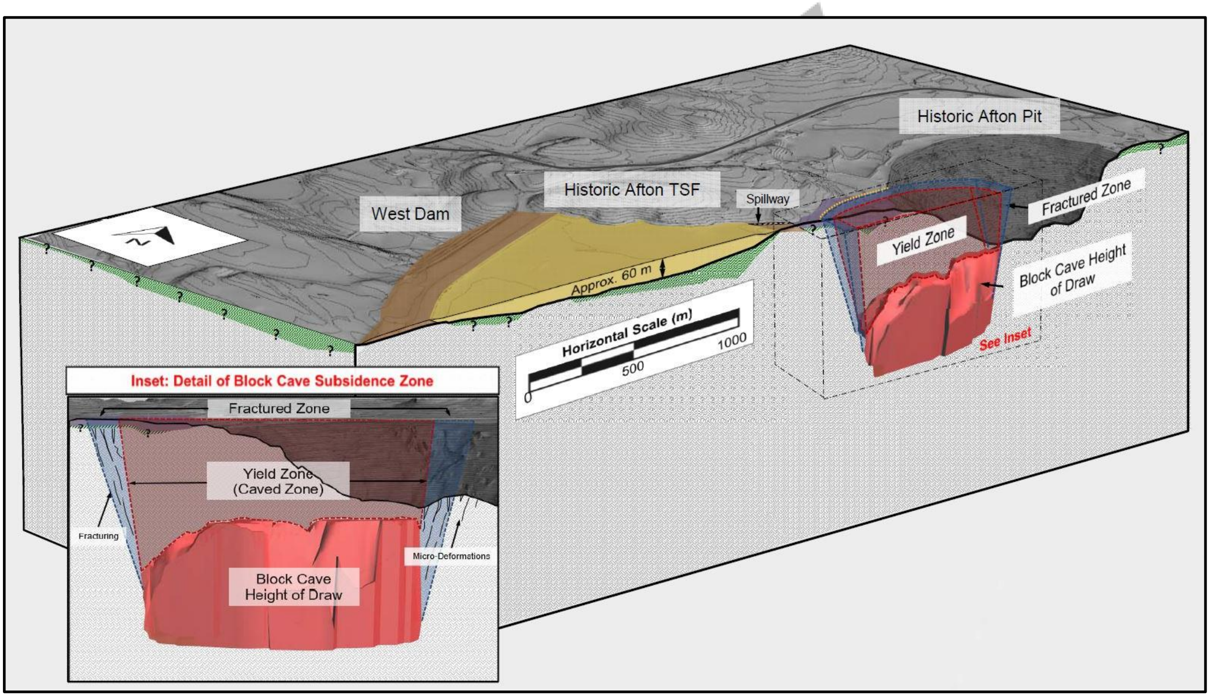

Figure 3 Potential Interaction between Underground Mine and Historical Afton TSF

Detailed in situ geotechnical investigations were completed using seismic cone penetration testing, specialized sampling methods and instrumentation arrays. Hydrogeological testing incorporated pump testing and detailed pore pressure monitoring. Laboratory testing methods incorporated conventional soil mechanics test methods, as well as specialized rheological test work to characterize the full continuum of tailings properties within the facility – ranging from a fluid slurry state to stable soils.

4. TAILINGS CHARACTERIZATION

4.1 Site Investigations

The physical state of the tailings within the historical TSF at the New Afton site prior to the field trials was characterized by three phased site investigations carried out between April and October, 2014. The site investigations included the completion of sonic drillholes, the advancement of land-based and amphibious cone penetration testing (CPT), the excavation of test pits, the installation of vibrating wire piezometers and the installation of observation, pumping and monitoring wells. Undisturbed samples of the fluid like tailings materials were collected with moderate success using a Parky Piston Sampler with passive suction.

Laboratory testing evaluated the following geotechnical properties: moisture content, particle size including clay sized fraction, plasticity (Atterberg Limits), and soil density. Slurry consolidometer testing was completed on select samples to evaluate the compressibility and permeability of the tailings. X-ray diffraction completed on select tailings slimes samples confirmed the presence of up to 40% clay minerals including clinochlore and illite / muscovite.

The tailings in the historical TSF are segregated with tailings sands (silty sand, less than 70% fines) in the north and silty tailings slimes (low to high plasticity clays) in the southern portion of the facility as illustrated on Figure 1. High in situ moisture contents (5 to 45% for the Tailings Sands and 30 to 90% for the Tailings Slimes) suggest that some for the tailings could behave more like a fluid than a soil when disturbed/liquefied.

4.2 Tailings Rheology

Rheological testing was completed on composite mixtures of the tailings to visually and quantitatively measure the variation in yield stress with moisture content and with clay sized fraction. The following rheological testing was conducted:

- **Vane Yield Test:** This test consists of applying torque to a vane inserted into the sample using a 2-inch vertical tube viscometer. Relatively high rotation speeds are applied in order to measure the yield stress in a fully mobilized state.
- **Boger Slump Test:** This 3-inch cylinder slump test is a fast and simple method that can be used to estimate the yield stress of thickened slurries and pastes. The measured slump is related to the yield stress using analytical methods.
- **Crack Simulation Test:** This test was developed specifically for this program to illustrate the potential for tailings samples at various water contents and yield stresses to flow into a crack, such as those that could hypothetically develop below the historical tailing impoundment during future mine operations. This test apparatus consisted of a flat surface with an adjustable gap that was slowly opened.

The results of the rheological testing are illustrated to represent the soil to slurry continuum on Figure 4. As the yield stress increases the tailings transition from a slurry to a paste and then a soil. The photographs show the results of Boger Slump testing and Crack Simulation testing to illustrate the behaviour of the tailings as the moisture content increases. Four ‘flowability zones’ were developed based on observations and measurements made during the rheological testing.

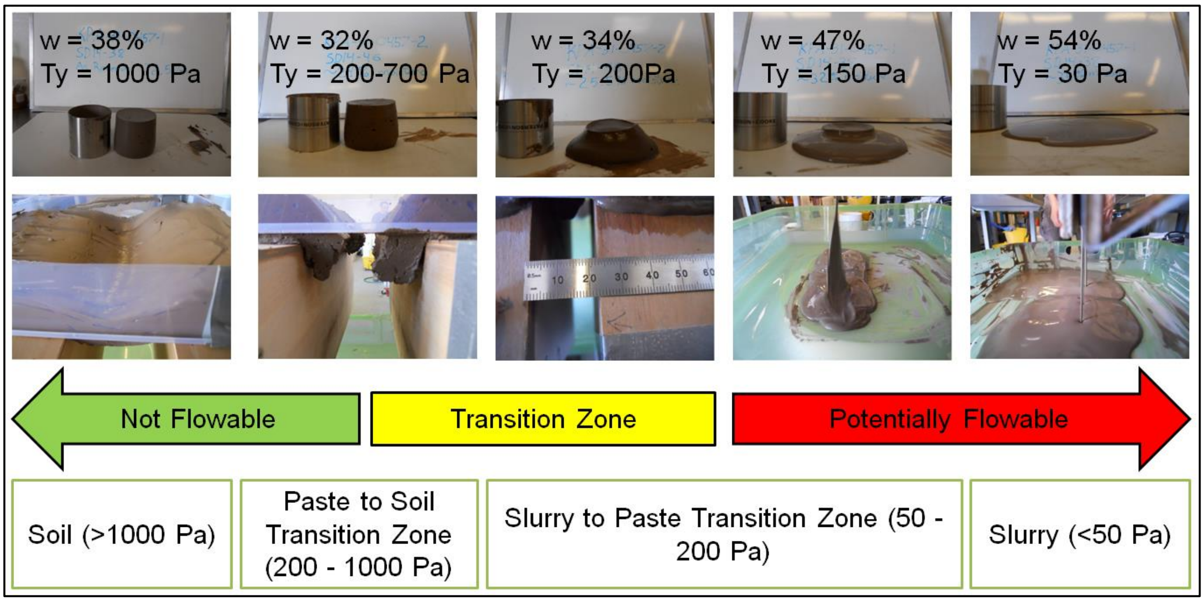

Figure 4 Tailings Rheology: Soil to Slurry Continuum

Vane yield stress tests were carried out on the fluidized samples to develop a rheological model (Figure 5). This model was used to estimate the tailings yield stress knowing the approximate clay-sized fraction and the in situ moisture content. These parameters were obtained through drilling, the collection of undisturbed samples (passive suction piston sampling), and laboratory index testing.

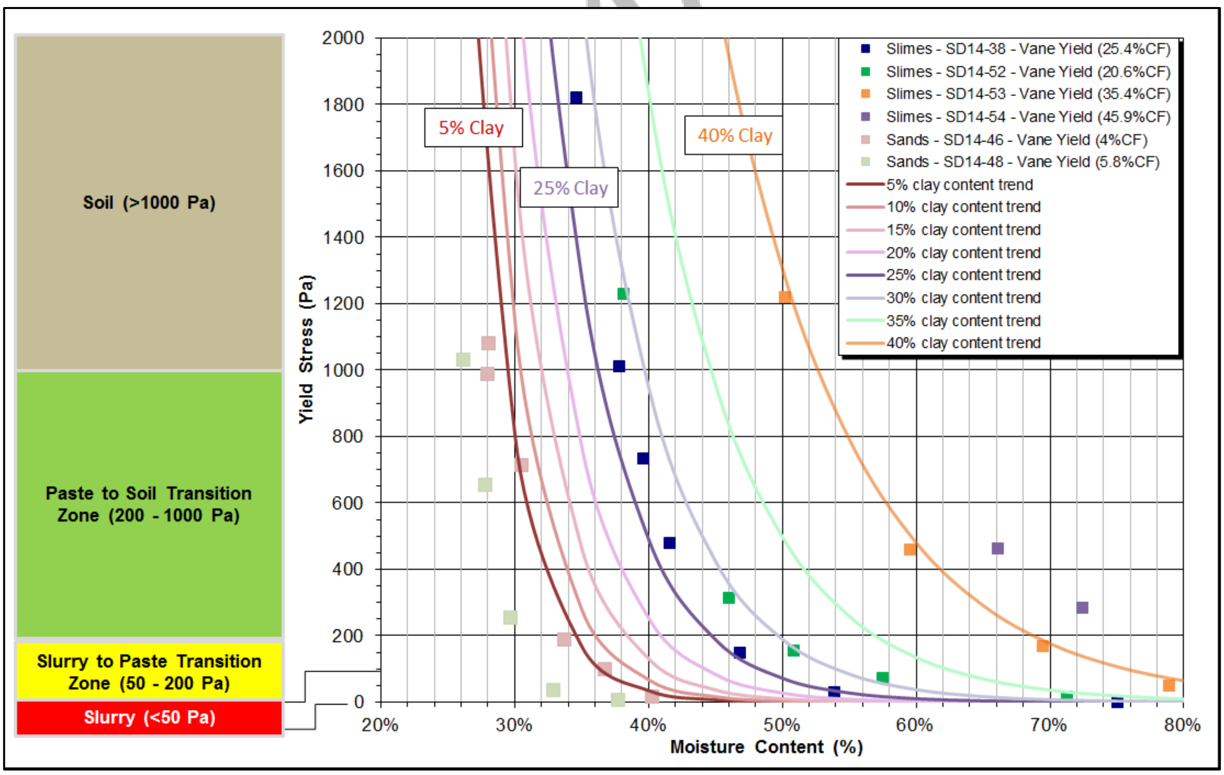

Figure 5 Tailings Rheology Measurements and Model

A “hockey stick” relationship between yield stress and moisture content is observed in Figure 5. The blade (bottom) of the hockey stick represents the slurry or paste-like behaviour where the tailings flow and are best described using rheological parameters. Large changes in moisture content are required to cause small changes in yield stress. The handle (upper part) of the hockey stick represents tailings materials demonstrating soil-like behaviour, with small changes in moisture content corresponding to large changes in yield stress. The heel (hinge) of the hockey stick represents the transition between a fluid and a semi-solid. The transition is abrupt for the sandy tailings (see 5% clay, red line) and gentler for the tailings slimes (see 40% clay, orange line).

4.3 Summary

The tailings behaviour and transition from slurry to paste and then to soil can be described by the in situ moisture content and clay sized fraction. These properties can be measured in the laboratory on undisturbed samples that can be obtained through a site investigation program. The test work shows a consistent increase in the yield stress and reduction in the tailings flowability with decreasing moisture content of the tailings. The sandy tailings experience a sharp transition and rapidly increasing yield stresses once unsaturated conditions develop. The tailings slimes experience a more gradual increase in yield stress with decreasing moisture content. This behaviour is observed because coarser tailings rely on particle to particle contact, or the “sand castle” effect to develop strength, while finer tailings are influenced by electro-chemical forces between the fine particles. The sandy tailings are therefore more sensitive to increasing moisture content beyond the point where the shear stresses are transferred to the carrier fluid from the coarse particles, similar to how a sand castle will quickly collapse once enough water is added to the mixture. A lower fines content also results in reduced carrier fluid density and yield stress, which compounds this effect.

A target yield stress of 500 Pa was selected for the design of stabilization field trials based on the testing results. This yield stress is judged to be within the paste to soil transition zone where small changes in moisture content cause large changes in yield stress. A mathematical model was developed to estimate the crack aperture required to sustain the flow of tailings at a given yield stress. It is estimated that continuous, open cracks with aperture of greater than approximately 5 to 6 cm (at a 70-degree or steeper angle) would be required before tailings with a yield stress of 500 Pa will begin to flow towards the underground workings. Any cracks that do develop are expected to vary in aperture, asperity, and tortuosity. Based on site observations and bedrock crack prediction modelling, a 5 to 6 cm wide crack width was judged to be a conservative upper bound estimate.

5. TRIAL PROGRAM

5.1 Trial Program Description

Reducing or eliminating the risk of mudrush of liquefied tailings from the Historical TSF into the underground mine workings requires removal of the carrier fluid (water). The first and simplest objective is to remove the surface water pond, and the second objective is related to dewatering the historical tailings in order to increase the yield stress and reduce the flowability of the heterogeneous deposit. A target yield stress of 500 Pa was selected based on the rheological testing and bedrock crack modelling.

Two tailings stabilization methods were selected for evaluation during the field trials. Dewatering with pumping wells was selected to reduce the moisture content and reduce the piezometric surface in the coarser tailings (tailings sands). Compressive loading combined with wick drains was selected to consolidate, densify, and reduce the moisture content of the finer tailings (tailings slimes). The objective of the trial program was to evaluate the effectiveness of the selected stabilization methods and to collect field scale data to support the full scale design. The trial program was followed by a site investigation (Phase 4) to collect additional data for analysis of the trial program results.

Explosive compaction was also considered as a potentially applicable ground improvement technology. This technology was not directly evaluated during the field trials, but was determined to be potentially applicable based on precedent at other sites. It could be implemented as a contingency measure for targeted zones within the stabilized tailings mass if needed.

5.1.1 Tailings Sands

An area approximately 100 m long and 50 m wide was selected for study in the Tailings Sands. Two 60 m deep pumping wells were screened for the full interval within the Tailings Sands. Three existing wells ranging in depth from 27 to 52 m were used as observation wells. Wick drains were installed in a 5 m triangular pattern to 33 m depth. Ten (10) drive point Vibrating Wire Piezometers (VWP's) were installed along three cross sections to monitor pore pressures and drawdown. The wick drains and piezometers were installed by Hayward Baker, a specialist ground improvement contractor. Survey monuments were installed on the surface of the tailings and monitored multiple times daily.

The water level fluctuation was measured during three pumping tests as follows:

- **Step pump tests:** One per well at rates of 0.3 and 6.2 L/s (4.5 to 98 gpm) to further develop the well, estimate borehole efficiency, and provide input for flowrates for subsequent tests.
- **24-hour pump tests:** One per well, at rates of 1.9 to 4.4 L/s (30 to 70 gpm). Wick drains were installed following the 24 hour pumping tests. A second 24 pumping test with the same parameters (4.4 L/s or 70 gpm) was completed on one well to evaluate the effect of the wick drains on the hydraulic properties of the 'tailings aquifer'.
- **7-day pump test:** Both wells at a combined rate of 6.6 L/s (100 gpm).

Data from the pump tests was collected using automated loggers installed at each well, manual water level observations and automated measurements of the VWP's. Water was discharged approximately 400 m down-gradient of the test site to prevent re-circulation.

5.1.2 Tailings Slimes

The conical fill load with access ramp (Test Pad) shown on Figure 6was constructed over the Tailings slimes; the tailings were approximately 25 m thick in the trial area area. A 1 m thick, 60 m diameter base underlain with Mirafi HP570 geotextile was first placed on the tailings surface to provide safe access for wick drain installation. Vertical wick drains were installed in a 2 m triangular grid pattern to a depth of approximately 25 m. The wick drains were included to help increase the rate of tailings densification, moisture reduction, and strength gain by increasing the hydraulic conductivity of the tailings mass. A total of 14 drive-point VWP's were installed at five locations including two locations at the centre and three locations along the circumference of the Test Pad.

A - Installation of Wick Drains **B - Fill Placement**

Figure 6 Test Pad Construction

Thirty-Five (35) radial and two internal survey monuments were installed to monitor settlements and deformation. Two central survey monuments incorporated a 0.5 m diameter aluminium culvert with a drill steel and 6 mm (1/4") thick steel plate placed on the HP570 geotextile overlying the Tailings Slimes surface. Additional sections of culvert or drill steel were added using couplers as the fill was placed.

The 50 m diameter conical Test Pad was developed using staged construction in 1 to 2 m lifts over a two month period. The VWP's were monitored carefully and the construction loading sequence was adjusted to allow for sufficient pore pressure dissipation in the foundation tailings in order to prevent bearing capacity failure due to rapid fill loading. The ultimate as-constructed thickness of the trial pad was approximately 10 to 11 m after accounting for settlement during construction.

5.1.3 Phase 4 Site Investigation

The Phase 4 site investigation program was conducted following completion of the trial program to evaluate the degree of soil improvement that resulted due to placement of the test fill. Following a monitoring period, the top of the Test Pad was levelled off to approximately 6 m height to provide a surface to complete the site investigations. Eight Hollow Stem Auger drillholes and nine SCPT's were completed, and undisturbed (Shelby Tube) samples were collected. Index testing was completed on select specimens from the Shelby tube samples to determine the moisture content, grain size, plasticity, and specific gravity at various depth intervals.

Auger drilling methods (without drilling fluids) were used to avoid influencing the moisture content of the tailings materials during drilling and sampling and to provide confidence that the moisture content values from the Shelby tube samples were representative of in situ conditions. A mechanically actuated stationary piston sampler was used to maximize sample recovery and minimize disturbance in the difficult to sample tailings slimes. The use of a mechanically actuated sampler as opposed to one which is hydraulically actuated also eliminated the potential to influence in situ moisture content as no water is added down the hole to actuate the sampler.

One CPT and one drillhole were completed at the same location as a previous CPT and Sonic drillhole to confirm the quality of the data collected using both sonic and auger drilling methods. The results showed comparable moisture content and particle size distributions suggesting that the sonic drilling method did not substantially affect the samples.

5.2 Trial Program Results

5.2.1 Tailings Sand

The pumping tests demonstrated that conventional pumping wells screened through the tailings sands can effectively remove water from the aquifer. The sandy tailings aquifer responded quickly to the applied hydraulic stress and the two pumping wells were able to sustain a combined flow rate in excess of 6.3 L/s (100 gpm) during the long term (7 day) pilot test. Wick drains increased the aquifer storativity (i.e. the total amount of water available for pumping) by approximately one order of magnitude.

The discharge water was clear, illustrating that the well screens, filter packs and applied development techniques were effective in excluding the fines from the wells. A very small vertical displacement of the tailings surface was observed in the survey results during the long term (7 day) pumping test that may indicate some volume reduction due to consolidation. The wells responded rapidly to pump shut off, with approximately 82% recovery after 8 hours and 96% after 3 days. The hydraulic conductivity was determined (Hantush & Jacob, 1955) to range from 4×10^{-5} to 6×10^{-6} m/s with an estimated storativity ranging from 0.001 to 0.003.

The trials confirmed that pumping is a viable method to dewater the tailings sands, thereby increasing the yield stress and reducing the flowability. It is expected that the degree of saturation can be sufficiently reduced in the tailings sands to achieve the target yield strength needed to mitigate the mudrush risk for the underground mine. Wick drains may also be installed in the portion of the stabilization zone where the tailings sand is interlayered with finer silts and clays (tailings slimes) to increase the vertical hydraulic conductivity of the aquifer and enhance dewatering. This will help drain groundwater perched above low permeability horizons and reduce the potential for groundwater compartmentalization.

5.2.2 Tailings Slimes

The tailings below the centre of the test pad on the slimes area compressed approximately 2.2 m vertically as a result of the applied fill loading. The tailings along the edge of the Test Pad settled approximately 0.25 to 0.50 m vertically. Small deformations and sub-parallel surface cracking (i.e. settlement tension cracking) were noted in the tailings beyond the edge of the test pad. No signs of major displacements, either vertical or lateral, or slope instabilities in the test pile were observed. The pore water pressures increased during fill placement and dissipated rapidly suggesting that consolidation of the tailings was occurring with minimal horizontal displacement. All piezometers remained intact and functional at the end of the construction program, and were still functioning one year later.

Construction of the test pad resulted in an increase in the CPT tip resistance (q_t), a decrease in the moisture content, and an increase in the estimated yield stress (Figure 7) for the majority of the underlying tailings slimes.

The tailings slimes below the Test Pad are relatively uniform based on the CPT results from different locations. The yield stress was estimated using the rheology model shown in Figure 5. Based on the observed results, more consolidation time and higher loads will be required to achieve the target yield stress of 500 Pa throughout the tailings column, although the target yield stress was achieved in the trial for the majority of the tailings below a depth of 14 m.

The data collected during the field trials was used to estimate a field scale horizontal coefficient of consolidation (CH) of 0.07 m^2/day and a virgin compression index (strain based, CR) of 0.21 for the slimes tailings underling the Trial Pad.

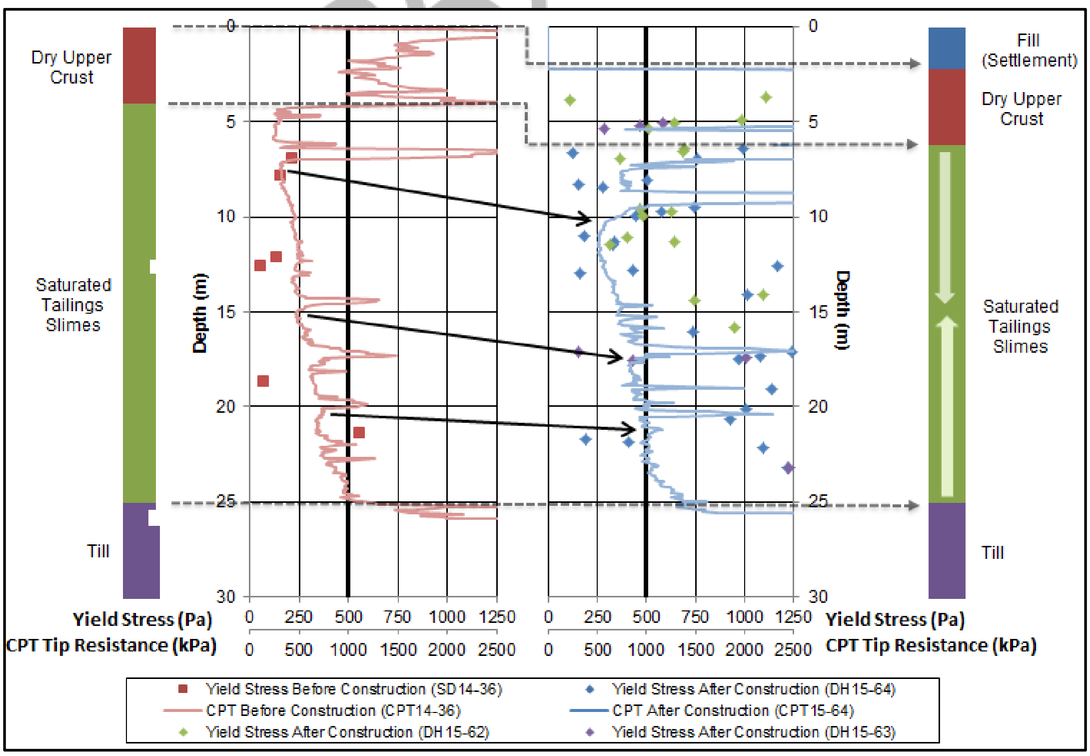

Figure 7 CPT Tip Resistance and Yield Stress - Before and After Consolidation Loading

6. SUMMARY AND CONCLUSIONS

The historical tailings facility at the New Afton Mine is currently inactive and was last operated using hydraulic emplacement of slurry tailings from 1978 to 1997. It contains approximately 37 million tonnes of saturated tailings solids, which were naturally segregated during multiple spigot tailings deposition at approximately 35% solids to form sandy tailings beaches along the north side of the impoundment and finer grained slimes tailings deposits along the south. The impoundment is constrained by the 75 m high West Dam and the 65 m high East dam.

A stabilization program is planned to improve the in situ characteristics of the historical tailings deposit in order to achieve two fundamental objectives:

- the development of a stable landform comprised of densified and/or dewatered tailings that are no longer capable of generating a mudflow that can migrate off site.
- to stabilize the tailings mass so that it does not represent a potential mudrush risk to the underground mining operations.

Complete removal of the surface pond is the simplest and most significant mitigation measure as the absence of a water pond eliminates many of the credible failure modes that would typically be considered for a dam breach assessment. Surface shaping of the impoundment, along with appropriate storm water routing can also be implemented to preclude the potential for pond development in the future. Once the release of a surface water pond is precluded, the only remaining failure mechanism would be liquefaction and flow of saturated tailings solids. If these saturated tailings materials can be dewatered and densified to the extent required to render them non-flowable, then the tailings impoundment can be considered to be a stable landform with no credible failure modes.

Ground stabilization techniques that would reduce the moisture content, increase the in situ density and thus reduce the fluidity of remoulded tailings solids to such an extent that they would no longer readily flow in the event of any catastrophic breach of the impoundment, were also considered. Conventional soil mechanics analyses were coupled with rheological assessments for the heterogeneous tailings materials contained within the historical tailings impoundment to define appropriate procedures for stabilizing the pile to a stable landform and to mitigate the risk of tailings mudrush through any hypothetical cracks that could interconnect into the progressively expanding underground mine. Field scale trial programs were used to demonstrate that the following two ground stabilization methods could be utilized to dewater, densify, and increase the yield stress of the historical tailings pile:

- Dewater Sandy Tailings to reduce moisture content, reduce liquefaction potential and/or increase the yield stress of remoulded tailings. Pumping wells were supplemented with vertical wick drains to enhance the dewatering of the tailings sands. Monitoring equipment including VWP's and survey monuments were used to evaluate the results of field scale pumping tests to estimate the hydraulic conductivity and storativity of the tailings sands. The trial pumping tests indicated that dewatering using multiple pumping wells is viable.
- Consolidate Slimes Tailings to increase density, reduce moisture content and increase the yield stress so that remoulded materials will be non-flowable. VWP's and survey monuments were used to monitor the construction of an 11 m high conical surcharge load over the tailings slimes constructed in stages over 2 months. Approximately 2.2 m of consolidation settlement was observed at the centre of the test pad. Follow-up site investigations showed a decrease in the in situ moisture content with a corresponding increase in yield stress due to the consolidation that resulted from the trial loading.

Geotechnical index testing, including grain size, moisture content, and Atterberg plasticity, were combined with interpreted CPT soundings to map the location of the tailings sands, transition zones and tailings slimes at the historical TSF adjacent to the New Afton mine. A site-specific rheological model was developed based on the results of vane yield rheological tests completed at different moisture contents and on samples with varying clay-sized particle fractions. This rheological model will be used to estimate the tailings yield stress using simple index properties that can quickly and easily be measured via a direct sampling drilling program. In this manner the transition of a loose contractive particulate material that would potentially behave as a fluid (with certain rheological characteristics) would be transformed using the selected ground improvement technologies, into a non-flowable solid that is best described using traditional soil mechanics parameters.

The combination of pumped dewatering wells for the more permeable sandy tailings zones, and surcharge loading to promote consolidation dewatering and densification has been shown to be a viable ground improvement strategy for the historical tailings pile adjacent to the New Afton mine. These ground improvement methods can be enhanced by including a suitable spacing of vertical wick drains to enhance fluid migration during the dewatering processes. Explosive compaction is also considered to be a potentially viable ground improvement technology and would be implemented as a surgically targeted contingency measure. The stabilized tailings mass will no longer be susceptible to uncontrolled rapid flow out of a hypothetical dam breach and would not represent a potential mudrush hazard to the underground mining operations. These stabilization measures are considered to represent best available technologies and will promote drainage, consolidation, and in situ soil stabilization of the historical tailings pile. These technologies may also represent practical options to consider during the design of new tailings impoundments, and for the expansion and closure of pre-existing TSF's.

7. REFERENCES

Akkerman, A. & Martin, V. (2015). *Assessing Credible Modes of Failure: Afton TSF Dam Breach Study.* Proceedings of Tailings and Mine Waste Conference. Vancouver, British Columbia. October.

Fontaine, D. & Martin, V. (2015). *Tailings Mobilization Estimates for Dam Breach Studies.* Proceedings of Tailings and Mine Waste 2015 Conference. Vancouver, British Columbia. October.

Haile, J.P. & East, D. R. (1986). *Recent Developments in the Design of Drained Tailings Impoundments.* Proceedings of the Geotechnical and Geohydrological Aspects of Waste Management Conference. Fort Collins, Colorado.

Hantush, M.S. & Jacob, C.E. (1955). Non-steady Green's functions for an infinite strip of leaky aquifer. Transactions of the American Geophysical Union. Vol 36, No. 1. P. 101-112.

Independent Expert Engineering Investigation and Review Panel (IEEIRP), 2015. *Report on Mount Polley Tailings Storage Facility Breach.* January 30. British Columbia.

Knight, R.B. & Haile, J.P. (1983). *Sub-aerial Tailings Deposition.* 7th Pan-American Conference on Soil Mechanics and Foundation Engineering. Vancouver, British Columbia.

Ministry of Energy, Mines and Petroleum Resources, Mining and Minerals Division (MEM), 2008. *Health, Safety and Reclamation Code for Mines in British Columbia*. Victoria, British Columbia.

Morgenstern, N., Vick, S., Viotti, C., Watts, B. (2016). *Report on the Immediate Causes of the Failure of the Fundão Dam.* Fundão Tailings Dam Review Panel. August 25.

Sandy, J.D., Piésold, D.D., Fleischer, V.D., and Forbes, P.J. (1976). *Failure and subsequent stabilization of No. 3 Dump at Mufulira Mine, Zambia.* Proceedings of the Institute of Mining and Metallurgy and the Institution of Mining Engineers, October.

Ulrich, B., East, D.R., and Gorman, J. (2000). *Subaerial Tailing Deposition – Design, Construction, and Operation for Facility Closure and Reclamation.* Proceedings of Tailings and Mine Waste 2000 Conference. Fort Collins, United States. January.