

# Characterizing and Stabilizing a Historical Tailings Facility: The Rheology to Soil Mechanics Continuum

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**ABSTRACT:** Historical tailings facilities often contains materials that have a consistency that ranges from fluid to solid, depending on a number of factors such as particle size, depth, drainage, and depositional history. Historical impoundments may contain saturated semi-fluid materials at depth, long after tailings deposition has ceased and after surface reclamation has been completed.

This paper presents a 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 located in British Columbia, Canada. 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 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 in combination with fluid mechanics and rheology, particularly in relation to slurry viscosity and flow behaviour of contractive potentially liquefiable tailings materials.

A rheological model was developed to characterize the yield stress and flowability of the historical tailings deposit. In-situ and laboratory testing was completed to understand the variability of the tailings in the facility. Simple index properties including moisture content and clay-sized particle 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 stabilized by densification and dewatering 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 can continue to represent an ongoing liability, long after mine operations cease and the surface facilities have been closed and reclaimed. 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.

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 geotechnical characteristics of a tailings impoundment can 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. The 2015 Samarco tailings failure (Morgenstern et al. 2016) provides a more recent example of the liquefaction and subsequent mudflow in loose, saturated tailings. A catastrophic mudflow rapidly migrated downstream, inundating a village and causing 19 deaths.

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 to develop a geotechnically stable landform. The opportunities to use best available technologies to stabilize tailings are discussed in our companion paper “Novel Application of Proven Best Available Technologies to Stabilize a Historical Tailings Impoundment” (Adams et al, 2017a). 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 at surface in the case of a dam breach and at depth into the cave zone or underground workings. This study relies on integration of the principles of soil mechanics along with fluid mechanics and rheology to describe contractive liquefiable tailings materials that may become fluid in nature and flow.

## 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). The New Afton Mine occupies the site of the former Afton Mine 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 TSF, as illustrated on Figure 1.

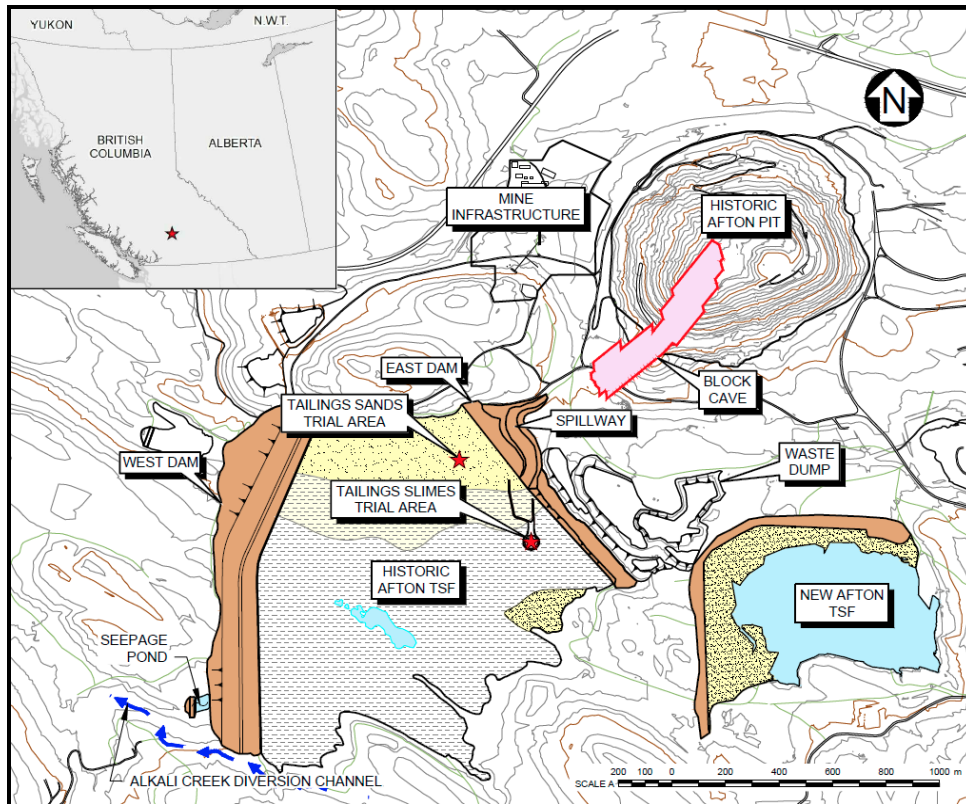


Figure 1. Project Location and Site Layout

Water is routed around the Historic Afton TSF (Historic TSF) via a diversion channel. The small water pond, shown on Figure 1, has been removed and the Historic TSF is in a negative water balance condition; it is expected to stay dry in the long-term. Thus a key objective for removal and elimination of any free water pond on the tailings surface has been readily accomplished.

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 Historic TSF as the mine development becomes progressively larger and deeper (Figure 2). Worker safety is a primary and fundamental requirement for ongoing mining operations. The proximity of the Historic TSF to the underground mine has been recognized as a potential risk factor relating to a potential mudrush hazard, unless appropriate tailings stabilization techniques are implemented as mitigation measures.

Given that surface ponding has been eliminated, the presence of free water as carrier fluid is no longer a potential factor in a mudflow risk assessment. Thus, the residual mudflow risk is only related to the flowability of any portion of the tailings solids contained within the Historic TSF. Densification, dewatering, and reduction of the potential for liquefaction were thus identified as critical objectives to stabilize the saturated tailings. 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 included conventional soil mechanics test methods, as well as specialized rheological test work to characterize the full continuum of tailings properties within the facility – which ranged from loose, saturated flowable materials to dense, non-flowable soils

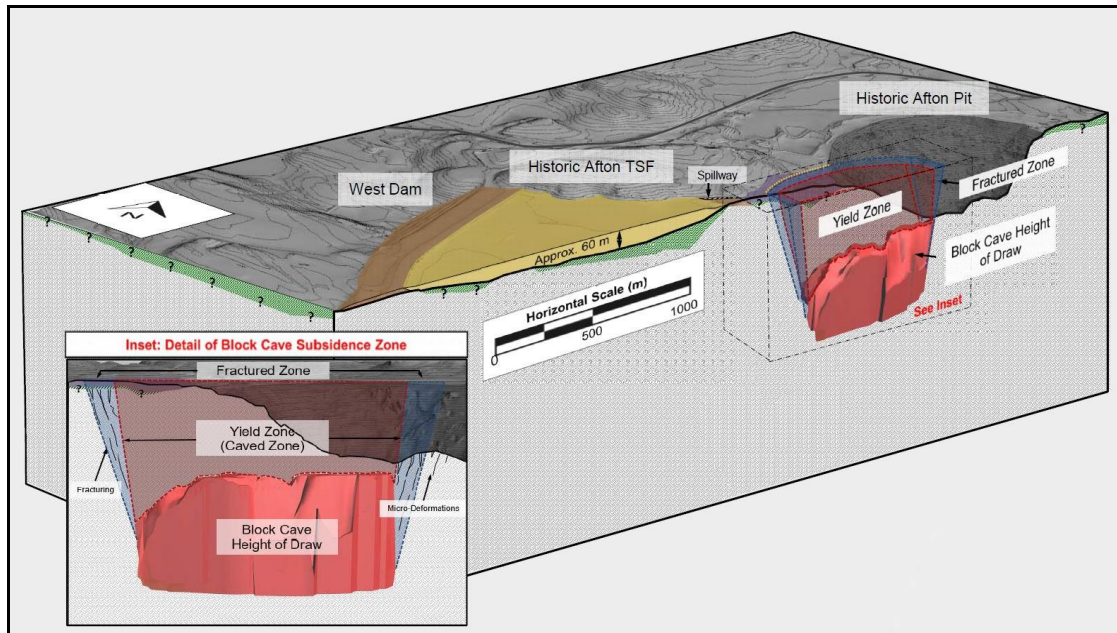


Figure 2. Potential Interaction between Underground Mine and Historical Afton TSF

These investigations were used to evaluate ground improvement technologies, including the use of dewatering wells, wick drains, and compressive loading, to densify and dewater the historical tailings over the full height of the tailings column. The use of ground improvement technologies are discussed in our companion paper entitled “Novel Application of Proven Best Available Technologies to Stabilize a Historical Tailings Impoundment” (Adams et al, 2017a). A field scale trial was undertaken to evaluate the effectiveness of the selected ground improvement technologies with the results indicating successful tailings stabilization at surface and at depth. The following sections describe the tailings characterization and field program developed to evaluate the selected ground improvement technologies.

### 3 TAILINGS CHARACTERIZATION

The Historic TSF contains approximately 37 million tonnes of saturated tailings solids which were naturally segregated during multiple spigot tailings deposition at approximately 35% solids. Sandy Tailings beaches formed along the north side of the impoundment and finer grained silty Tailings Slimes tailings deposits formed towards the south as shown on Figure 1 and Figure 3. High in-situ moisture contents (5 to 45% for the Tailings Sands and 30 to 90% for the Tailings Slimes) suggest that some of the tailings could behave more like a fluid than a soil when disturbed/liquefied.

#### 3.1 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 investigation locations are shown on Figure 3 and included:

- 21 sonic drillholes
- 45 land-based Seismic Cone Penetration Test (SCPT) and 7 amphibious CPT probings
- 10 test pits
- Installation of 1 observation well, 1 pumping well and 3 monitoring wells, including hydraulic response testing in the sandy and silty tailings at 2 locations
- Installation of 25 Vibrating Wire Piezometers at 8 locations

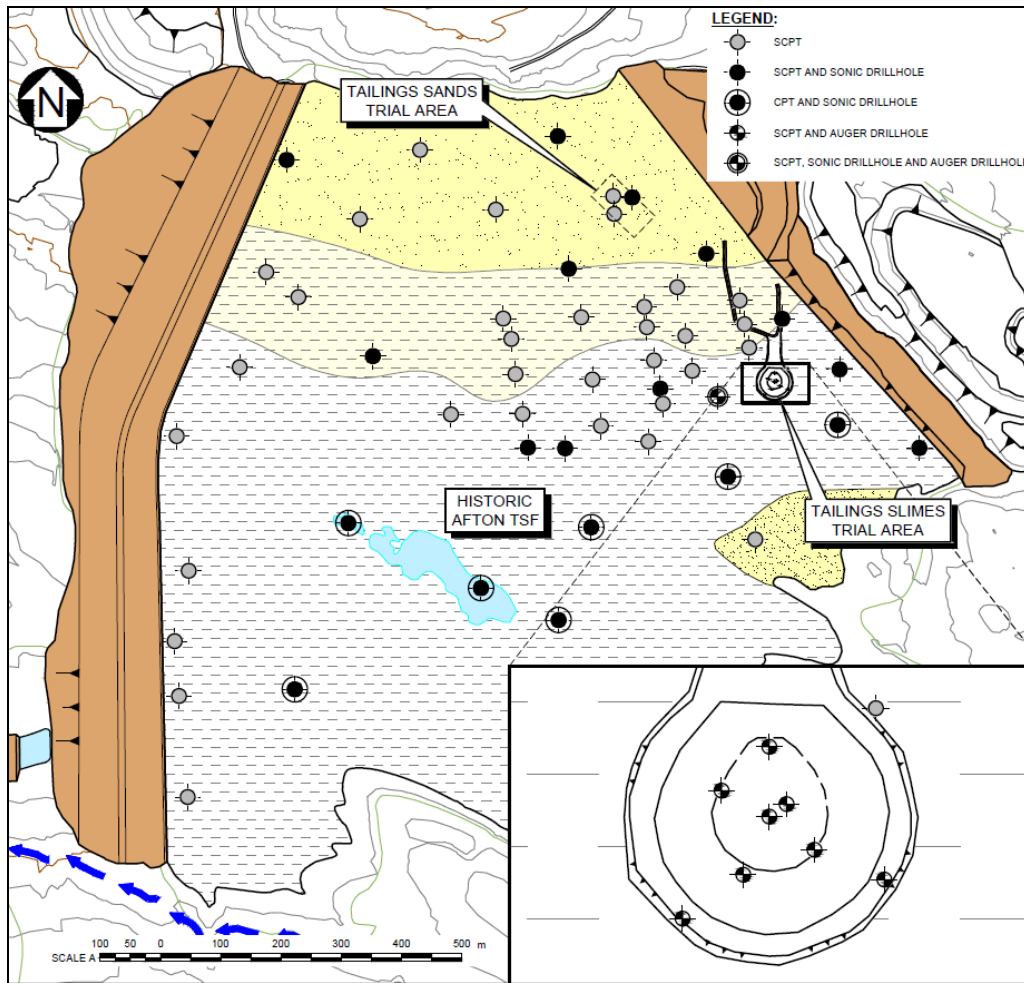


Figure 3. Site Investigation Locations

A total of 99 tailings samples (29 undisturbed) and 8 overburden samples were collected during the Phase 1 through 3 site investigations. The collection of undisturbed samples was challenging due to the high moisture content and fluid like nature of some of the tailings materials. Moderate success was achieved using a Parky Piston Sampler with passive suction.

### 3.2 Geotechnical Testing

Laboratory testing was conducted to characterize the moisture content, particle size distribution (including hydrometer to measure the clay-sized fraction), plasticity, and density of the tailings. Slurry consolidometer testing was completed on select samples to evaluate the compressibility and permeability, and X-ray diffraction was completed to evaluate the mineralogy.

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 of the tailings could behave more like a fluid than a soil when disturbed/liquefied. The tailings contain up to 40% clay minerals including clinocllore and illite / muscovite.

### 3.3 Rheological Testing

Laboratory rheological testing was completed on composite mixtures of tailings samples 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 consists of applying torque to a vane inserted into the sample using a 2-inch vertical tube viscometer. The peak torque is recorded as the yield stress required to mobilize the sample.
- **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 qualitative 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 TSF during future mine operations. This test apparatus consisted of a flat surface with an adjustable gap (crack) 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.

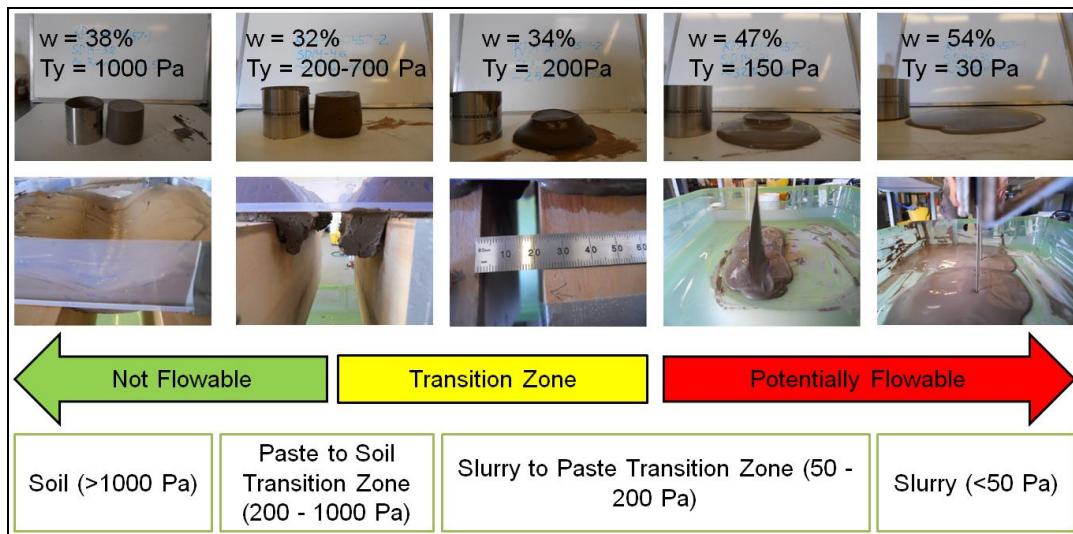


Figure 4. Tailings Rheology: Soil to Slurry Continuum

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.

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).

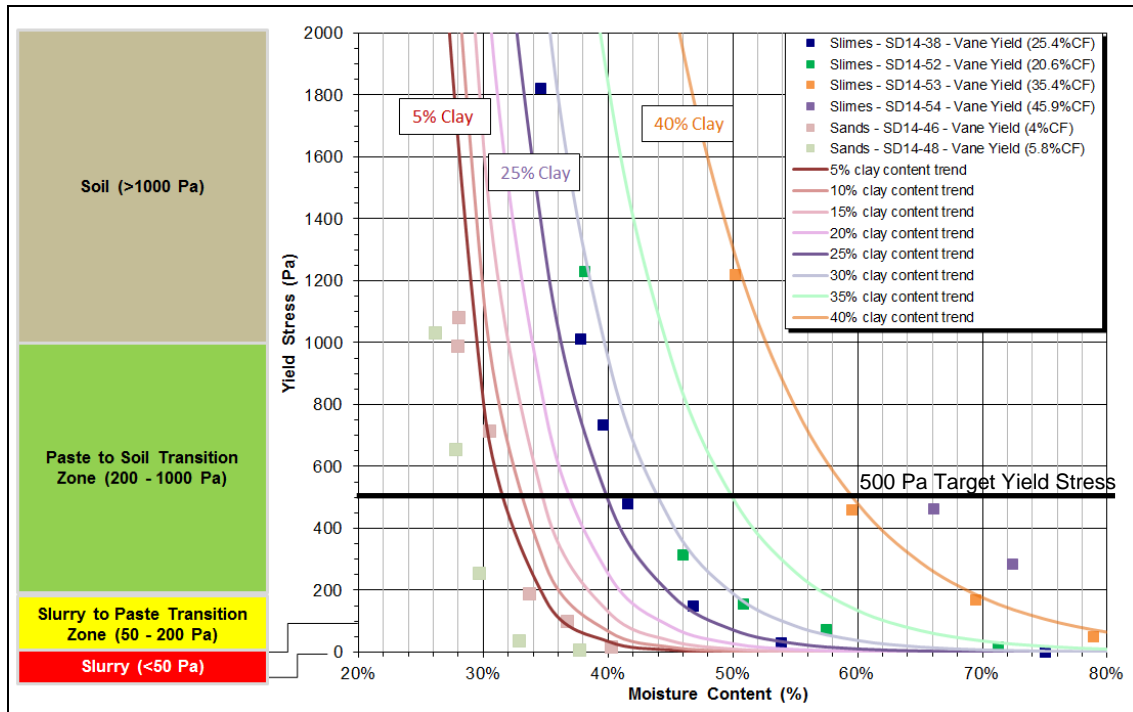


Figure 5. Tailings Rheology Measurements and Model

### 3.4 Estimating Flow Through a Crack

A simplistic mathematical model was developed to describe the potential flow of tailings through a hypothetical crack intersecting the TSF (Figure 6) and to support the development of a target yield stress. The model assumes an idealized singular crack is formed by two parallel plates separated by a gap,  $t$ . The width,  $w$ , and length,  $L$ , of the crack are much greater than the gap,  $t$ , making sidewall and inlet effects negligible. The crack slopes downwards at an angle  $\theta$  from the horizontal, giving a vertical intrusion depth equal to  $L\sin\theta$ . The flow of an assumed infinite volume of homogeneous tailings with yield stress  $\tau_y$  through the crack is modelled as a force balance between the driving forces of the tailings stored in the impoundment applying a pressure  $P$ , and the shear resisting forces of the tailings along the upper and lower crack walls. The tailings will always be in contact with the lower crack wall under the force of gravity, with the possible exception of a vertical crack, but may not be in contact with the upper wall depending on the angle of repose and flow rate.

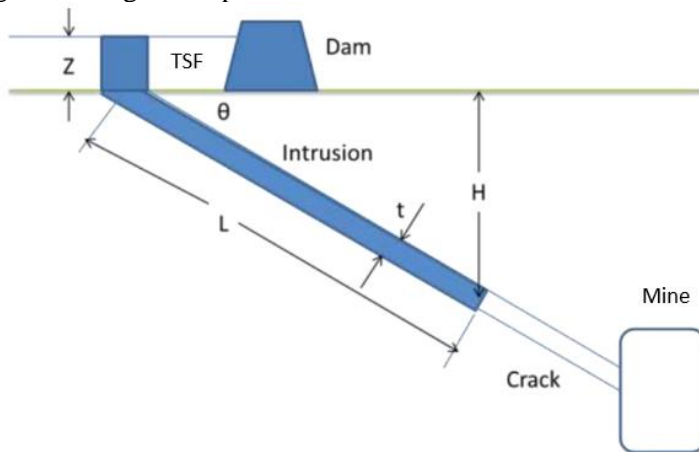


Figure 6. Tailings Flow Through Hypothetical Crack

If there is no surface pressure on the crack, the paste can not move through the crack if the gap is too small,

$$t \leq \frac{2t_y}{\rho g \sin \theta}$$

If the crack is pressurized, with the static pressure of the tailings above the crack idealized as a fluid pressure, and the tailings within the crack and the impoundment are assumed to be homogeneous (i.e. have the same yield stress), the gap size at which flow will initiate is described as follows:

$$t = \frac{2t_y}{\rho g \sin \theta} \left\{ \frac{1 + \frac{H}{Z} \sin^2 \theta}{1 + \frac{H}{Z}} \right\}$$

For unpressurized tailings with density ranging from 1.7 to 2.0 t/m<sup>3</sup>, the crack width required to initiate flow varies from 2 to 2.5 cm at 200 Pa to 10.5 to 12.5 cm at 1000 Pa if a conservative 70 degree angle is assumed between the underground mine and the eastern extent of the Historic TSF (Figure 2). Under these conditions, tailings with a yield stress of approximately 500 Pa will begin to flow towards the underground workings once the crack aperture exceeds approximately 5 to 6 cm angled at 70 degrees or steeper. Variations in the surface pressure were found to have limited effect (one to two cm) on the crack width required to initiate flow.

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. A target yield stress of 500 Pa, representative of the paste to soil transition, was thus selected for the design of stabilization field trials.

### 3.5 Summary of Geotechnical and Rheological Characteristics

The tailings behaviour and transition from slurry to paste and then to soil is strongly influenced by the in-situ moisture content and clay-sized fraction. These properties can be measured in the laboratory on undisturbed samples 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 and negative pore pressures (or the “sand castle” effect) to develop strength, while finer tailings with clay minerals 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 crack flow modelling. 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.

## 4 FIELD TRIAL PROGRAM

### 4.1 Trial Program Description

Reducing or eliminating the risk of liquefied tailings flowing from a hypothetical TSF breach or a mudrush of liquefied tailings flowing from the Historical TSF into the underground mine workings requires removal of the carrier fluid (water). Given that the surface pond has already been removed, the objective is to dewater the historical tailings in order to increase the yield stress and reduce the flowability of the heterogeneous deposit.

Two ground improvement technologies were selected for a field trial program (Adams et al, 2017b):

- 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 stabilization program. The trial program incorporated confirmatory site investigations (Phase 4) to collect additional data for analysis of the trial program results. The following sections briefly describe the field trials and results.

#### 4.1.1 *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 VWP's were installed along three cross sections to monitor pore pressures and drawdown. The wick drains and VWP's 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 6 hour, 24 hour, and 7-day pumping tests with pumping rates varying from 0.3 L/s (4.5 gpm) to 6.6 L/s (100 gpm). The pumping tests demonstrated that conventional pumping wells screened through the Tailings Sands can effectively remove water from the aquifer. Comparison of pump test results completed prior to and following wick drain installation demonstrated that wick drains increased the aquifer storativity (i.e. the total amount of water available for pumping) by approximately one order of magnitude. A very small vertical displacement of the tailings surface was observed in the survey results during the long term (7 day) pumping test that likely indicates some volume reduction due to consolidation.

The trial 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 of 500 Pa needed to mitigate the risk of liquefaction of the tailings. This in turn mitigates the risk of the tailings flowing from the TSF during a hypothetical dam breach scenario as well as eliminating 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 promote drainage of groundwater perched above low permeability horizons and reduce the potential for groundwater compartmentalization.

#### 4.1.2 *Tailings Slimes*

A 50 m diameter conical consolidation fill load with access ramp (Test Pad, Figure 7) was constructed over the approximately 25 m thick Tailings Slimes using staged construction over a two month period. The fill was underlain with Mirafi HP570 geotextile 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 depth 25 ft to help increase the rate of tailings densification, moisture reduction, and strength gain. VWP's were installed at five locations, including two locations at the centre and three locations along the circumference of the Test Pad, to monitor pore pressures during construction. Survey monuments were installed on and around the test pad to monitor settlements. The Test Pad was developed using staged construction in 1 to 2 m lifts over a two month period. The ultimate as-constructed thickness of the Test Pad was approximately 10 to 11 m after accounting for settlement during construction.

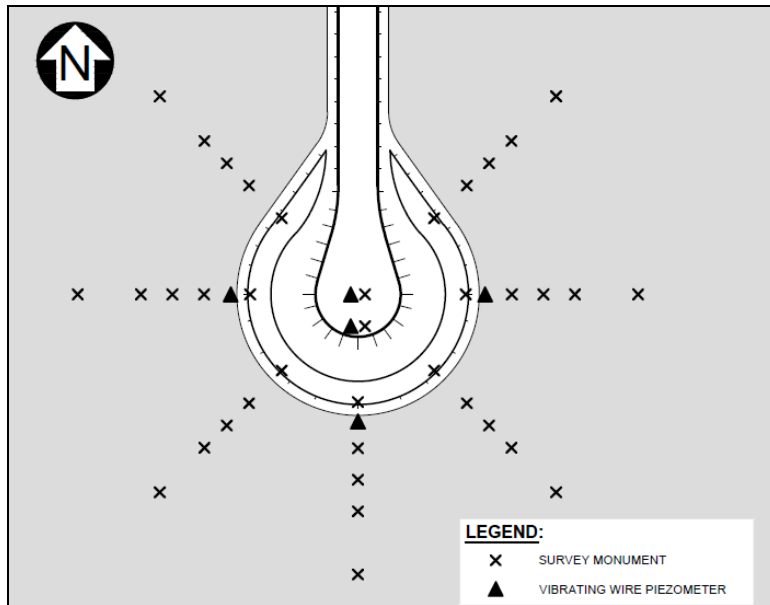


Figure 7. Schematic plan view of Test Pad Constructed over Tailings Slimes

The measured settlement and pore pressures below the test pad are provided in Figure 8. The tailings compressed approximately 2.2 m vertically at the centre of the test pad and between 0.25 and 0.5 m vertically at the edge of the test pad as a result of the applied 11 m of fill loading. The pore water pressures increased during fill placement and dissipated rapidly suggesting that consolidation of the tailings was occurring with minimal horizontal displacement (Figure 7). No signs of major displacements, either vertical or lateral, or slope instabilities were observed. All VWP's remained intact and functional at the end of the construction program, and were still functioning one year later.

The Phase 4 site investigation program was conducted following completion of primary consolidation to evaluate the degree of soil improvement that resulted due to placement of the test fill. 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.

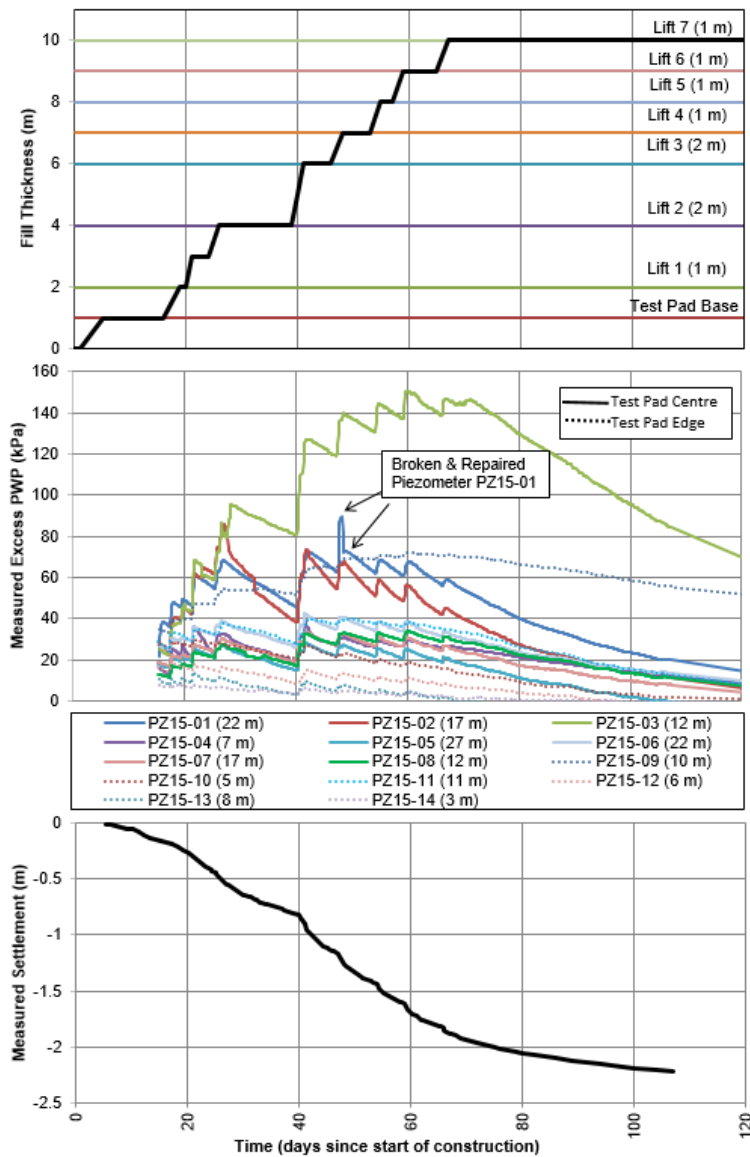


Figure 8. Construction Schedule, Measured Excess Pore Pressures and Measured Vertical Settlement at the Centre of the Test Pad

One CPT and one auger 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 both auger and sonic drilling methods provided similar sample quality.

Construction of the Test Pad resulted in an increase in the CPT tip resistance ( $q_t$ ), a decrease in the moisture content as the Tailings Slimes were densified, and an increase in the estimated yield stress (Figure 9) for the majority of the underlying tailings slimes. The yield stress was estimated using the rheology model shown in Figure 5. Based on the observed results, more consolidation time and/or 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 and overlying any potential cracks.

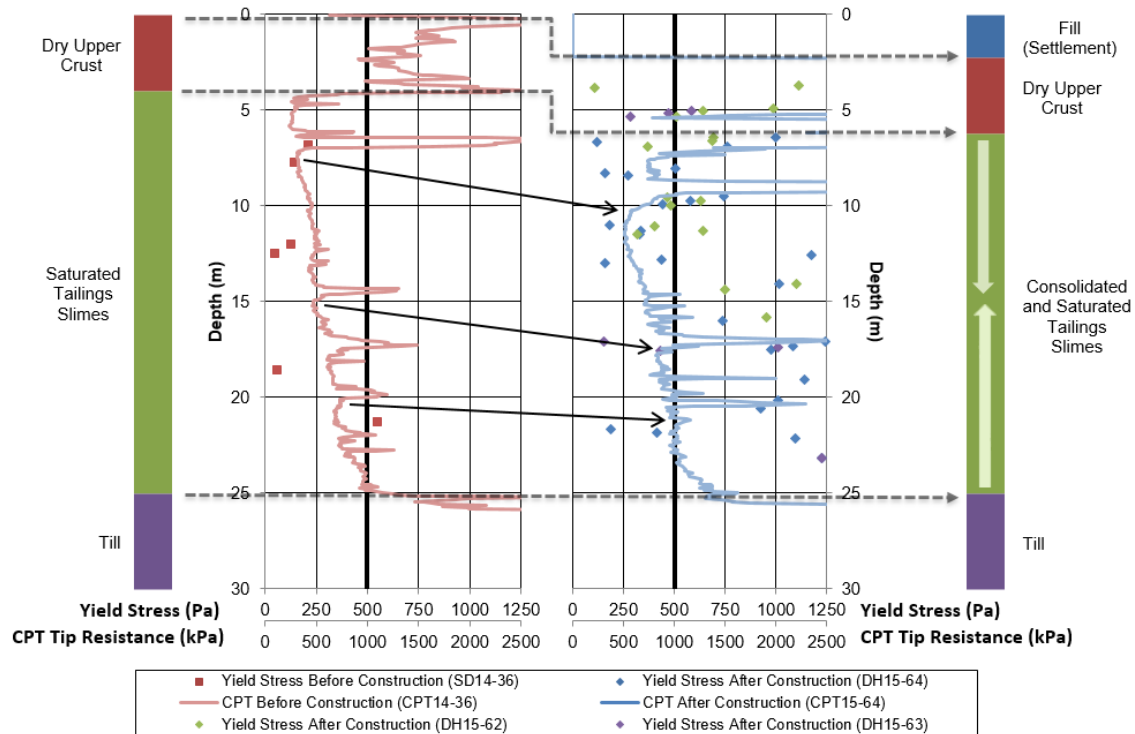


Figure 9. CPT Tip Resistance and Yield Stress - Before and After Consolidation Loading

## 5 SUMMARY AND CONCLUSIONS

The New Afton Mine occupies the site of the former Afton Mine. The Historic TSF is currently inactive and was last operated by the Afton Mine 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. The tailings deposition formed sandy tailings beaches along the north side of the impoundment and finer grained slimes tailings deposits along the south. The Historical TSF represents a potential risk to the nearby underground mine development, which will cause surface cracking and subsidence that could potentially interact with the Historical TSF. A catastrophic mudrush could develop if fluid, or semi-fluid materials, contained within the Historical TSF are able to migrate via connected pathways into the underground workings.

Conventional soil mechanics analyses were coupled with rheological assessments to define and evaluate appropriate ground improvement technologies to transform the tailings to a stable landform and to mitigate the risk of tailings mudrush through any hypothetical cracks that could interconnect into the progressively expanding underground block cave mine. The tailings were characterized through geotechnical and rheological testing. 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.

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:

- **Sandy Tailings:** Dewatering via pumping wells to reduce moisture content, and increase the yield stress of remoulded tailings. Pumping wells can be supplemented with vertical wick drains to enhance the dewatering of the Tailings Sands.
- **Tailings Slimes:** Consolidation loading with wick drains to increase density, reduce moisture content and increase the yield stress so that remoulded materials will be less susceptible to liquefaction and thus non-flowable.

These stabilization measures are considered to represent best available technologies and will promote drainage, consolidation, and in-situ soil stabilization of the Historical TSF. 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.

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