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Thickened tailings characterization program for a tailings storage facility design update - case study

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ABSTRACT

This paper presents the results of a thickened tailings (TT) geotechnical and hydrogeological characterization program conducted in the fall of 2013 at the Canadian Malartic Mine (CMM). CMM is a gold mine located in the Abitibi region in the province of Quebec and has been operating since May 2011.

The characterization program included both field and laboratory tests. The field program consisted of cone penetration tests and a drilling program conducted in the tailings storage facility (TSF). The data were interpreted to determine select *in situ* tailings geotechnical properties, assess their liquefaction susceptibility, determine the hydraulic conductivity of the tailings stack and locate the water table in the TSF.

Tailings samples collected at several locations were tested in laboratory. Index tests were performed as well as cyclic simple shear and large strain consolidation tests. TT samples were also taken in the field along the deposition path to evaluate whether there is active segregation of the particles during the deposition at their current solids content.

The results will be compared to the initial parameters and will provide updated geotechnical and hydrogeological properties of the TT being deposited at CMM as part of the update of the TSF design features.

Key Words: large strain consolidation, cyclic simple shear, shrinkage limit, inclusion.

1 INTRODUCTION

The Canadian Malartic Mine (CMM) is located near the town of Malartic, Quebec in the southern part of the Abitibi gold belt. As of 2014, it was the largest open pit gold mine in Canada. The mine started its operation in May 2011, and is currently processing 55,000 metric tons per day (tpd) of ore. In June 2014, a partnership between Yamana Gold Ltd. (50%) and Agnico-Eagle Mines Ltd. (50%) purchased CMM from Osisko Corporation Ltd. CMM is currently developing an extension project extending the life of mine by seven years to the end of 2028. The extension project will increase the amount of waste (tailings and waste rock) to be managed over the life of mine to approximately one billion tons from the 509 million tons originally planned.

The design of the CMM tailings storage facility (TSF) was inspired by the management strategies of several operating mines, in particular the thickened tailings disposal facility at Kidd Creek Metsite (Kidd Creek) in Timmins, Ontario (Kam et al. 2009). Kidd Creek has produced thickened tailings since 1973 in climatic conditions similar to CMM. The CMM TSF was developed over an abandoned tailings facility and used some of the existing dikes as start-up confining structures.

Initial design criteria allowed development of the TSF with TT at 68% solids content (by weight), target establish by client team, and central discharge points. Tailings parameters, including those related to field characteristics and deposition angles were derived from Kidd Creek observation data while others were based on results from laboratory testing made on a single tailings sample obtained from the metallurgical testing. The design approach adopted the observational method of Peck (1969) allowing for adjustments based on field performance and continuous monitoring.

In September 2013, the TSF reached a development stage where sufficient thickness of the CMM tailings was available to allow an *in situ* tailings characterization campaign to be conducted. The main purpose of the tailings characterization was to update the *in situ* TT properties. The operational reality of the CMM and adjustments in the process in the first years of production resulted in tailings behaving differently than anticipated and with different solids content than the design criteria. The observations and updated properties were to be used in the design adjustments based on field performance. This same process of data collection and design update will be performed throughout the life of the TSF, up to its final height (as high as 70 m above ground surface).

This paper presents the main results of the 2013 characterization campaign and compares updated geotechnical tailings and design parameters of the TSF to its initial parameters.

2 CANADIAN MALARTIC MINE TSF CONFIGURATION

Figure 1 shows an aerial view of the CMM TSF as of July 2015. The current TSF footprint is 2.7 km^2 and will accommodate the storage of 183 Mt of tailings as per the initially permitted project.

Figure 1. View of the Canadian Malartic Mine in 2015, looking west.

In September 2013, the TSF active deposition area was organized in seven deposition cells confined by perimeter berms or internal roads. All CMM berms and roads are permeable. The perimeter TSF berms are raised by the upstream method at an overall 10H:1V slope, while the internal roads, sometimes referred to as inclusions, are raised vertically. Two to three raises of 2 m in height are constructed every year using waste rock.

3 2013 TAILINGS CHARACTERIZATION PROGRAM

As mentioned, the 2013 tailings characterization program consisted of field and laboratory tests. The field program included cone penetration tests (CPTs), sampling from drill holes (subsequently converted to observation wells), and surface tailings sample collection. The locations of the CPTs, drill holes and surface samples are presented in Figure 2.

3.1 Cone penetration tests (CPTs)

CPTs with recording of porewater pressure and including dissipation tests were conducted through the tailings stack at various locations to gather information at depth and at different distances from the perimeter and internal berms.

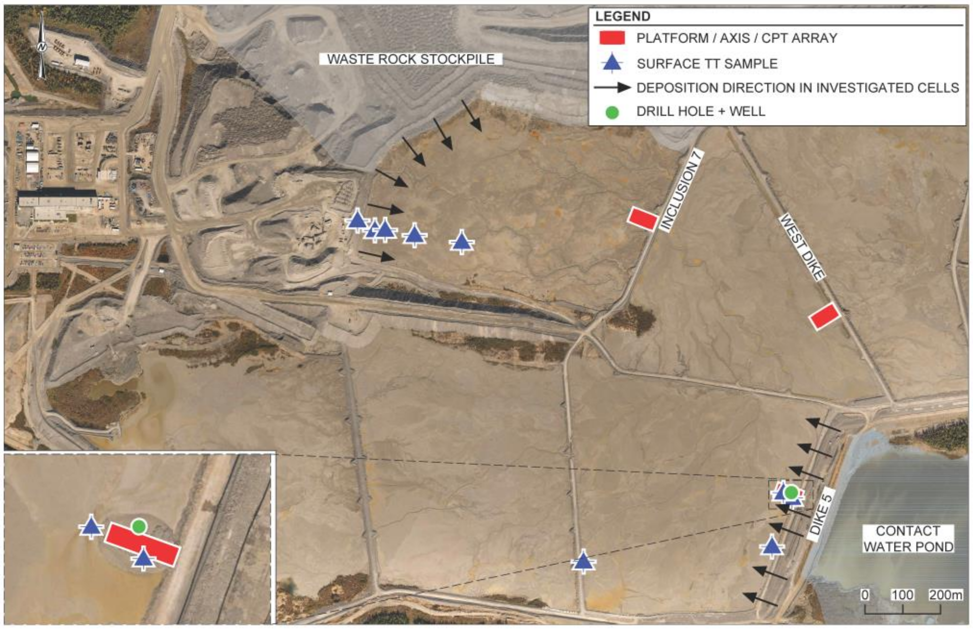

Figure 2. Plan view of the TSF as of September 2013 – CPTs, drill holes and surface sampling locations

Three platforms, shown in red on Figure 3, were built on top of the tailings surface, to provide access to the interior of three different cells. The platforms, built with waste rock, penetrated the tailings to a depth of approximately 2 to 2.5 m. Each axis (platform), aimed at studying a particular condition: the effect of having a former low permeability confinement structure called Dike 5 as a start-up confinement berm; the effect an internal road (inclusion 7) could have on saturation and consolidation; and finally, the effect of an internal road (inclusion) built on top of a former low permeability dike (West dike). Two CPTs were conducted along the platform to obtain profiles along particular axis: one CPT was pushed at approximately 5 m off the main structure (dike, raise or berm) and the second one was pushed 15 m to 25 m further away, towards the center of the cell.

Figure 3 provides a schematic cross section view along the studied axes with the measured cone tip resistance (q_c) and sleeve friction (f_s) profiles for each CPT. The reader should note that for all of the investigated axes, old tailings were present under the CMM tailings. The 2013 tailings characterization and interpretation focused on CMM tailings.

3.2 Boreholes and observation wells

Two boreholes with split spoon sampling were drilled trough the CMM tailings. The boreholes were converted into monitoring wells primarily for measuring of the hydraulic conductivity of the tailings stack and locating the water table within the TSF. One of the boreholes was conducted at the Dike 5 axis location, while the second one was conducted at the north-eastern limit of the TSF (location is outside of the area shown in Figure 2). Samples were collected at different depths to assess the variation in grain size distribution of the tailings. Hydraulic conductivity tests were also conducted in each well.

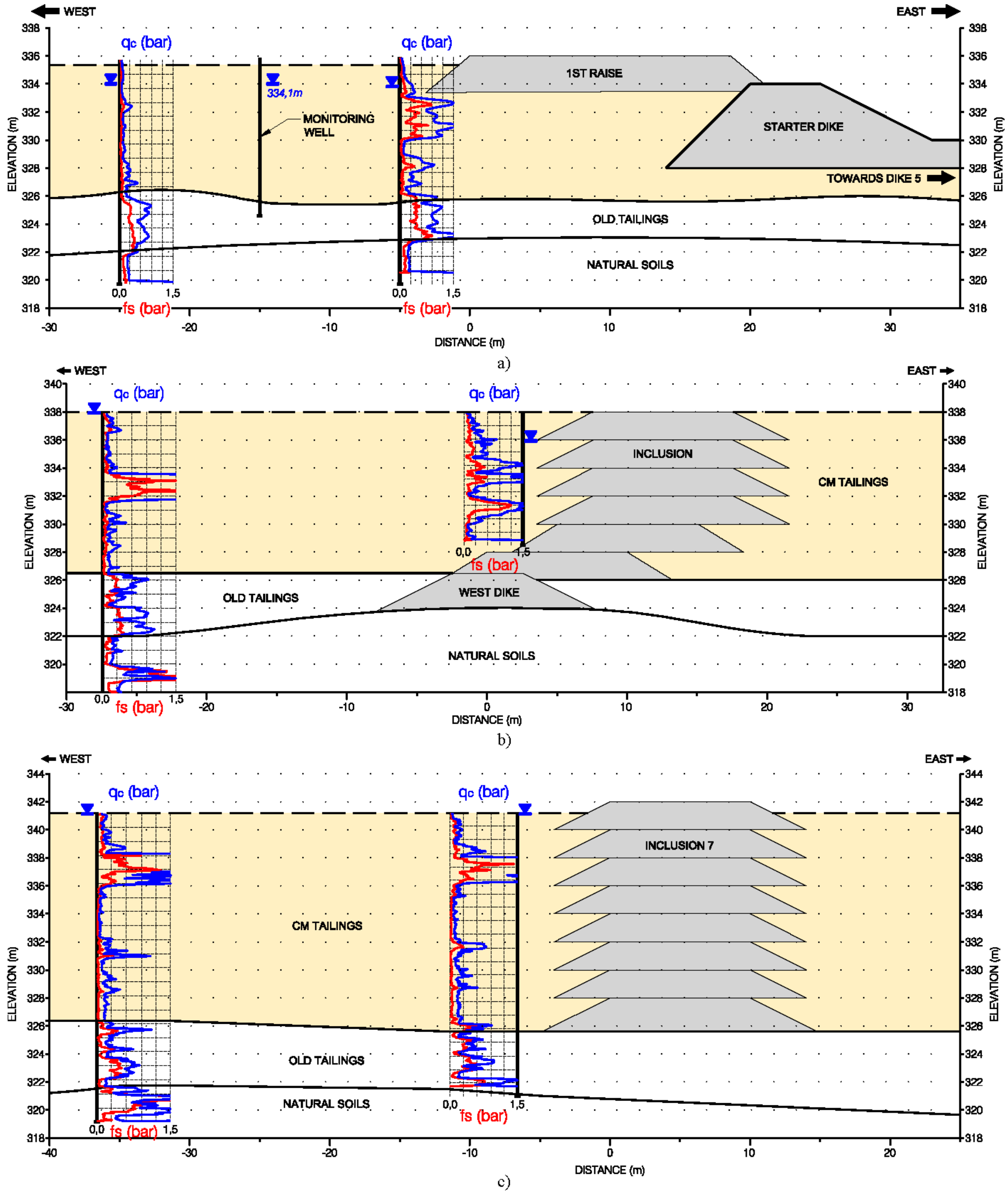

Figure 3. CPT investigation axes a) Dike 5 location b) West dike location and c) inclusion 7 location

3.3 Surface sample collection

Tailings samples were collected *in situ* at the surface of the TSF. Samples were taken along a deposition path in two different cells to evaluate if segregation of the tailings was present. This aspect was of a particular interest as tailings were deposited in the TSF at around 60% solids content (by weight) compared to the initial design solids content of 68%. The two cells were in two different operating conditions: the cell located at the north-west of the TSF was left without tailings deposition for five to six months prior to sampling while the cell in the south-east corner of the TSF was actively filled during the sampling. Nine samples were taken manually at surface as indicated in Figure 2.

3.4 Laboratory program

Common index laboratory tests were systematically conducted on all tailings samples including water content, grain size, Atterberg limits, and specific gravity.

More specific laboratory tests were also conducted on selected tailings samples. These laboratory tests included self-weight consolidation, large strain consolidation (hydraulic conductivity was also measured at different consolidation stages), direct shear and cyclic simple shear, soil water characteristic curve and shrinkage limit.

4 RESULTS AND OBSERVATIONS

Results from the field investigation and laboratory testing were compiled during the winter of 2014. The most important findings and observations are presented in this section.

4.1 Grain size distribution and water content

The CMM tailings consist of silt particles, are non-plastic (ASTM D-4318) and have a specific gravity of 2.74 (ASTM D-854). These properties are similar to those found for hard rock tailings from metal mine in this region of Quebec (Bussière, 2007). Figure 4 shows the particle size distribution (ASTM D-422) of all tested samples. The CMM tailings contain over 70% particles finer than 0.075 mm. The tailings, even at a solids content of 60%, do not seem to generate segregation following the deposition. No significant trend could be observed horizontally (following a deposition path) nor vertically (in the boreholes), except that most surface samples are slightly coarser than the others. Grain size distribution of tailings was then considered fairly uniform for the whole TSF. However, 2013 grain size distribution data suggests some grain size variability, as shown with the curves presented in Figure 4. The uniformity of the tailings mass will need to be reassessed and confirmed in a consistent manner over time. The grain size curve obtained in 2008 with the metallurgic sample show a grain size similar to the range obtained in 2013.

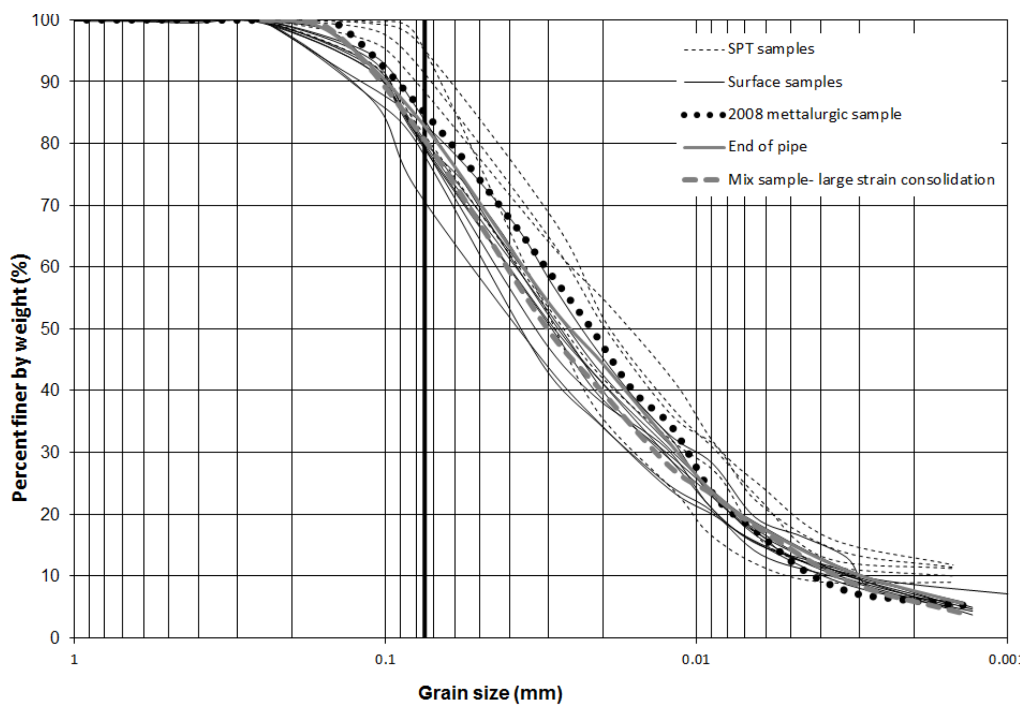

Figure 4. Grain size curves of the 2013 characterization campaign- surface, borehole, end of pipe, mix compound samples

Samples collected at the surface of the TSF showed that the *in situ* water content (ASTM D-4959) of the tailings is relatively uniform with values varying from 26% to 31%. Those values were similar for the cells with recent deposition and those where tailings were at rest for five to six months.

4.2 Water table in the impoundment

The water table measured in the standpipe piezometer near Dike 5 (Figure 3) was located 1.6 m below surface. Along with the standpipe water level measurement, CPTs conducted near Dike 5 seem to show a drawdown from the center of the cell towards Dike 5. A drawdown was also interpreted near internal road, at West Dike, based on CPTs conducted from the platform. At the internal road (inclusion 7), the water table was interpreted to be at surface. In conclusion, based on this limited information, the water table seems to remain very close to surface in all cells investigated.

4.3 Tailings in situ state

CPT results show that the CMM tailings are generally in a loose state as the tip resistance and sleeve friction are relatively low. The tailings consolidation state seems to be locally influenced by the presence of the permeable internal roads (inclusions) or perimeter berms. The CPTs performed 5 m away from those structures indicated the presence of denser tailings than those observed at the CPTs performed 20 m to 30 m away from those structures. A denser state was deduced from higher tip resistance and sleeve friction presented in Figure 3, assuming that the CMM tailings have a fairly uniform grain size distribution which seems to be the case as discussed in Section 4.1.

However, the above observation was made considering CPT profiles at Dike 5 and West dike axes but was not as evident at the location of the inclusion 7 axis. Permeable berms (inclusions) could increase the drainage of the surrounding material (James et al. 2013) and thus increase the consolidation state of this material. However, the presence of discontinuities in the drainage path might be the reason why this effect was not observed perpendicular to inclusion 7.

The impact of the draining inclusions or permeable berms on tailings behaviour is currently difficult to quantify. More instrumentation and analysis will be necessary in the coming years to be able to conclude if a positive (draining) effect is present.

4.4 Consolidation and hydraulic conductivity

Self-weight Consolidation Tests

Self-weight consolidation testing was conducted under single and double drained conditions to determine the settling rate, volume of excess water (supernatant) expected to be released and an estimate of the dry density of the TT at the end of the self-weight consolidation. The test was carried out using a graduated cylinder with a diameter of 630 mm filled with tailings to a height of 300 mm. Prior to testing, the sample was prepared at 60% solids content (by weight). During the test, the location of water-tailings interface was measured, and the increase in the tailings density due to self-weight consolidation calculated.

Self-weight consolidation was completed within three hours of the double drained test with an average dry density increase from 960 kg/m^3 at the initial stage to a final dry density for the consolidated layer of 1340 kg/m^3. The single drained self-weight consolidation was slightly slower than the double drained, as it was completed within approximately five hours. The variation of dry density was from 950 kg/m^3 to 1270 kg/m^3 at the end of the test.

Similar self-weight consolidation tests were conducted on the CMM tailings (Demers-Bonin, M. 2013), with an initial solids content of 68% and laboratory tests presented similar results. The results of the three self-weight consolidation tests are shown in Figure 5.

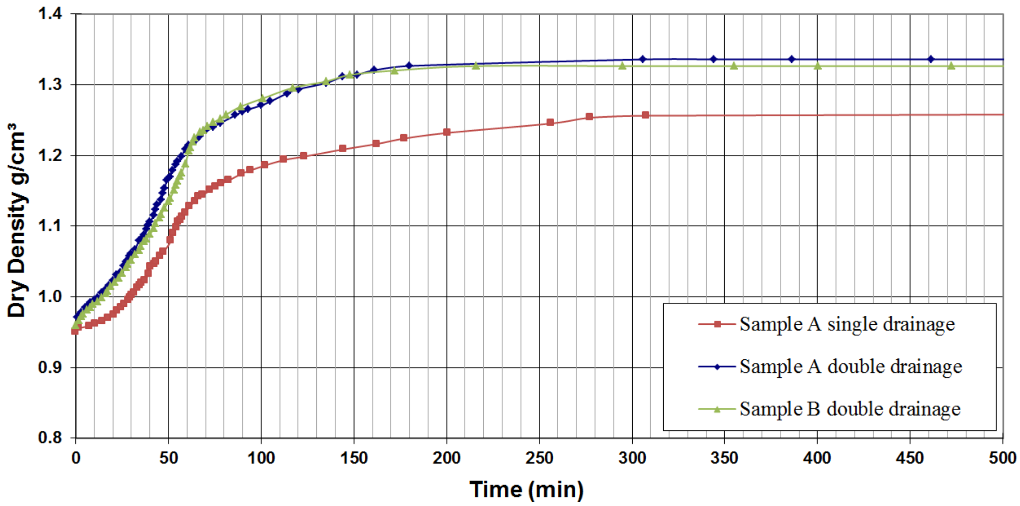

Figure 5. Self-weight consolidation laboratory test results

Large Strain Consolidation Tests

Large strain consolidation tests along with hydraulic conductivity tests were carried out using large strain Trautwein cell consolidometers and described in van Zyl et al. (2014). Prior to load application, the TT were deposited in order to achieve conditions similar to those obtained at the end of the self-weight consolidation, with an initial water content of 36% (73% solids content by weight). The consolidation tests were conducted for a stress range similar to the stresses anticipated in the field until the end of the TSF life.

Hydraulic conductivity of the tailings at various void ratios was directly measured during the large strain consolidation tests. A constant hydraulic gradient was applied to the sample during the hydraulic conductivity tests (i.e. constant head tests). The results of the two tests performed are presented in Table 1.

Table 1. Large strain consolidation laboratory results

Sample	Effective Stress (kPa)	Void ratio	Dry density (kg/m³)	Hydraulic conductivity (m/s)	Compression Index C_c	Consolidation coefficient C_v (m²/s)	Water Content (%)
A (mix of surface samples)	0	1.01	1 370	-	-	-	37.2
	7	0.78	1 540	1.4×10^{-7}	-	8.9×10^{-7}	-
	15	0.76	1 560	1.4×10^{-7}	0.05	1.3×10^{-5}	-
	70	0.71	1 600	1.1×10^{-7}	0.07	2.4×10^{-5}	-
	140	0.69	1 620	1.0×10^{-7}	0.07	5.6×10^{-5}	-
	370	0.66	1 650	1.0×10^{-7}	0.06	1.5×10^{-4}	-
	650	0.63	1 680	8.1×10^{-8}	0.13	1.2×10^{-4}	24.1
B (End of pipe sample)	0	0.95	1 400	-	-	-	35.8
	7	0.74	1 570	6.5×10^{-8}	-	4.2×10^{-7}	-
	15	0.73	1 580	6.9×10^{-8}	0.04	7.7×10^{-6}	-
	70	0.68	1 630	5.6×10^{-8}	0.07	1.1×10^{-5}	-
	140	0.66	1 650	5.2×10^{-8}	0.08	2.7×10^{-5}	-
	300	0.63	1 680	4.8×10^{-8}	0.09	4.2×10^{-5}	-
	650	0.60	1 720	4.0×10^{-8}	0.10	7.1×10^{-5}	23.4

Hydraulic conductivity decreases and consolidation coefficient increases when the confinement pressure increases and the void ratio decreases. Overall, large strain consolidation results indicate an important gain in consolidation with increase of confinement pressure. This conclusion could not however be confirmed with CPT data.

Laboratory measurement values as well as derived compressibility and hydraulic conductivity parameters were used to develop material parameters A, B, C, D and Z defining the following consolidation relationship (see. e.g. Abu-Hejleh and Znidaricic, 1994, 1996).

$e = A(\sigma' + Z)^{-B}$ and $k = Ce^{D}$

In the above relationship, *e* denotes the void ratio, σ'stands for the effective stress and k is the hydraulic conductivity functionally dependant on void ratio. Material parameters determined for tested samples are shown in Table 2.

Table 2. Selected compressibility and hydraulic conductivity parameters

Sample	Compressibility parameters			Hydraulic conductivity parameters	
	A (1/kPa)	B(-)	Z (kPa)	C (m/sec)	D(-)
A	0.854	-0.0550	0.0001	1.411×10^{-7}	2.376
B	0.908	-0.0568	0.0001	3.043×10^{-7}	2.832

The effective stress in the TSF at the time of the investigation was assumed to be very low (about 150 kPa) at the base of the CMM tailings stack. Based on the large strain consolidation test conducted, the associated void ratio varies between 0.91 (1 kPa) to 0.65 (150 kPa), using the constitutive equation presented above. The hydraulic conductivities for the same range of effective stresses vary between 2×10^{-7} m/s to 1×10^{-8} m/s.

The hydraulic conductivities obtained with dissipation tests and *in situ* tests (1×10^{-7} m/s and 1×10^{-9} m/s) seems to provide the same order of magnitude (superior limit) as those obtained in laboratory and inferred from the CPT results, as shown in Figure 6. The same observation was made on tailings, old tailings and natural soils.

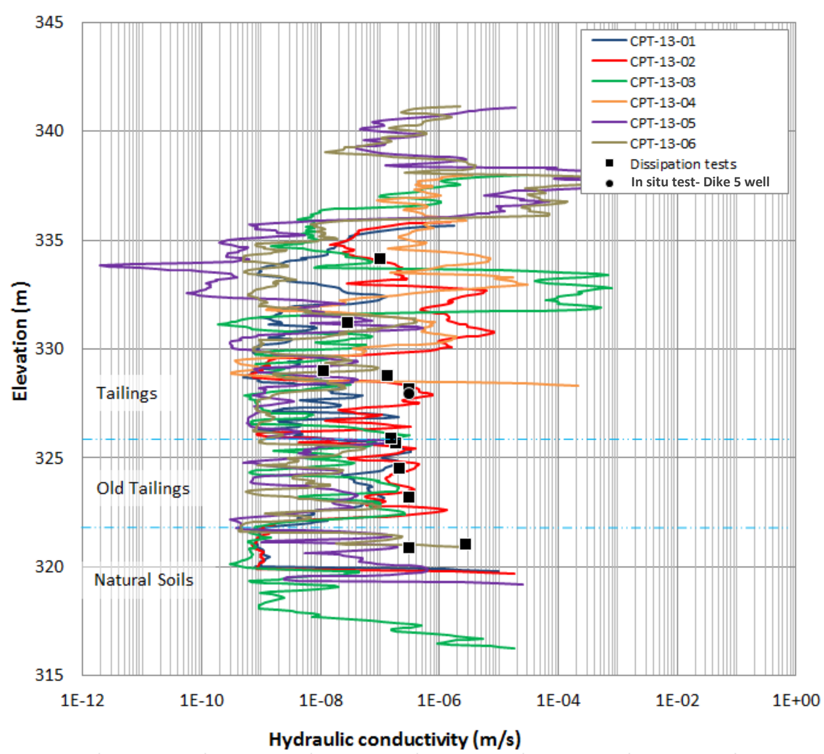

Figure 6. Hydraulic conductivity measured in situ, in laboratory and inferred from CPT results

4.5 Soil-water characteristic curve and shrinkage limit

Drying process was simulated in the laboratory (ASTM D-6836) to determine the soil water characteristic curve using a pressure cell and a pressure plate for the lower suctions (under 1500 kPa). The higher suction points were obtained using saturated salt solutions in desiccators and suction was verified using a chilled mirror hygrometer. The tests in pressure cell and pressure plate were conducted using saturated sample. The sample for the pressure cell was prepared by pushing the steel ring into the tailings previously slurried and allowed to settle. The void ratio of this specimen at the start of the test was 0.81.

The results shown on Figure 7 establish that the air entry value of the tailings is in the vicinity of 65 kPa. The shrinking limit was estimated to be at 22%.

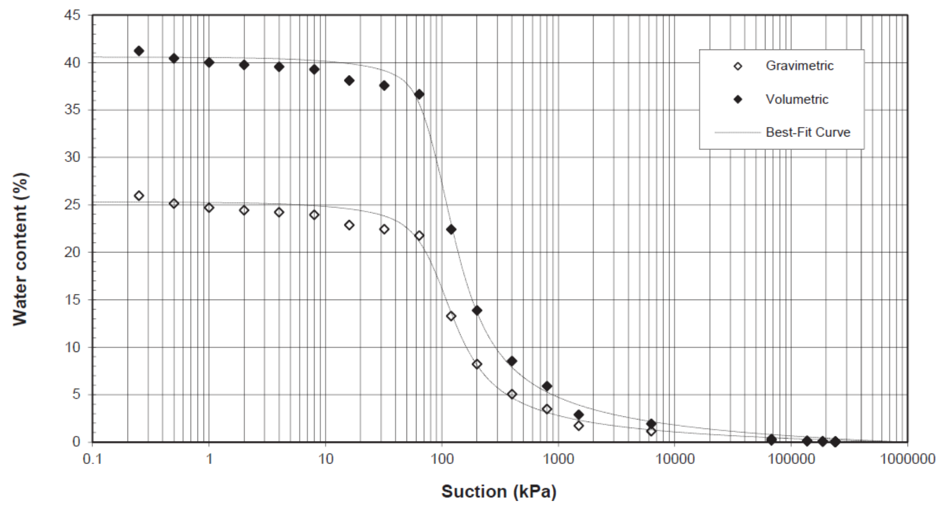

Figure 7. Soil Water Characteristic Curve

4.6 Direct shear

Direct shear tests were conducted in laboratory (ASTM D-3080) and the results are presented in Table 3.

Table 3. Summary of direct shear laboratory test

Void ratio	Normal stress (kPa)	Shear Resistance (kPa)	Void ratio	Normal stress (kPa)	Shear Resistance (kPa)
Sample 1			Sample 2		
0.58	160	135	0.56	160	134
0.55	325	271	0.52	325	274
0.52	485	390	0.53	485	385

These values were used to calculate the friction angle of the CMM tailings. The calculations resulted in a relatively high friction angle of about 39 degrees. According to Bussière's (2007) historical summary of different authors, internal friction angles for hard rock tailings from metal mines are in the range of 30 to 42 degrees. The CMM tailings would be in the high end of this range. However, it is important to mention that the void ratio used in the testing was relatively low (e=0.52 to 0.58) compared to the one obtained in the large strain consolidation test (e=0.61 to 0.68) for similar effective stresses. The results of the direct shear are thus to be used prudently and more characterization will be done in the future.

4.7 Cyclic shear strength and post-cyclic strength

Cyclic simple shear tests were conducted on the CMM tailings using equipment manufactured by GDS instruments (ASTM D-6528). The soil specimens were 70 mm in diameter and 25 mm in height after consolidation. The samples were consolidated, prior to loading at confining pressures of 200 kPa and 400 kPa to simulate the approximate pressures in the CMM tailings at the bottom of the TSF after the deposition up to 1/3 and 2/3 of the final TSF height. The summary of the cyclic simple shear tests is presented in Table 4 below.

The samples were reconstituted in laboratory to be consistent with the tailings deposition method in the field. The reconstitution involved preparing the tailings to a water content of 36% prior to consolidation. This water content represents the approximate water content measured after self-weight consolidation and corresponding to approximately 73% solids content (by weight).

After consolidation, the samples were subjected to a sinusoidal shear stress of constant amplitude with a frequency of 0.1 Hz. The cyclic shear stress was applied to a value of shear strain of 5%. Upon completion of the cyclic loading, each specimen was sheared monotonically at a constant strain rate of 5% per hour to measure the post-cyclic shear strength.

Table 4. Summary of Cyclic Simple Shear Testing

Test ID	e_o	σ'_{vc} (kPa)	e_c	CSR = τ_{cyc}/σ'_{vc}	$N_{cyc-\gamma=3.75\%}$	τ_{p-c}/σ'_{vc}
400 kPa; 0.08 CSR	1.16	400	0.66	0.08	55	0.10
400 kPa; 0.10 CSR	1.25	400	0.71	0.10	13	0.06
400 kPa; 0.12 CSR	1.32	400	0.70	0.12	9	0.08
200 kPa; 0.10 CSR	1.03	200	0.68	0.10	14	0.06

Notes: $\mathbf{e_o}$: Initial void ratio
$\mathbf{e_c}$: Void ratio after consolidation and before shearing
$\boldsymbol{\tau_{cyc}}$: Cyclic shear strain
$\boldsymbol{\tau_{p-c}}$: Post-cyclic shear stress at 20% shear strain.

The cyclic shear resistance of the CMM tailings was defined by the shear stress applied to reach a strain of 3.75%. Figure 8 below represents the number of cycles needed to reach a strain of 3.75% in relation to the cyclic shear resistance ratio (τ_{cyc}/σ'_{vc}). Idriss and Boulanger (2008) suggest that an earthquake magnitude can be represented in laboratory by a certain number of uniform cycles. In the Abitibi region, Earthquakes Canada deaggregation studies proposed to use a magnitude of 6 for a return period of 1:2475 years. Therefore, based on laboratory results, the cyclic resistance ratio (CRR) of the CMM tailings would be around 0.13 in the tested conditions.

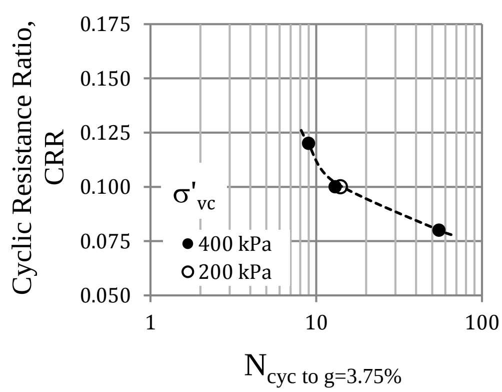

Figure 8. Cyclic resistance of the CM tailings

The normalised post-cyclic strength (τ_{p-c}/σ'_{vc}) was defined as the strength observed at a strain of 20%. In this condition, the normalised post-cyclic strength measured was between 0.06 and 0.10.

4.8 Other observations from field data and tests

Several other observations were made during the field campaign. Some of these are presented below as they are thought to be complementary to the previously presented results.

4.8.1 Desiccation

The degree of desiccation, based on observation, is considered low and the desiccation cracks were considered shallow. At other mine sites, desiccation can be quite rapid and lead to significant strength gain of the tailings stack (Theriault et al. 2003). However, currently at this site, no significant desiccation cracks were observed and the moisture content at surface still remains higher than the shrinkage limit.

4.8.2 Frozen tailings

Frozen tailings (1-2 m in thickness) were encountered in three of the six CPTs. They were intercepted up to approximately 3 to 6 m below the surface. Although the frozen layers of tailings were not observed in the boreholes, based on the ability to advance the CPT through the tailings indicates that the encountered material is likely frozen tailings, rather than a distinct ice layer. The CPT response to frozen tailings was distinguished by higher tip resistance and pore pressure, with lower sleeve friction.. Temperature was also measured by the CPTs showing values close to 0 °C.

It is difficult at the present time to establish the impact of the frozen tailings on performance as the layers do not seem to be either homogeneous or continuous. Based on some observations at other sites in the same region, it is expected the frozen layers will thaw with time.

4.9 Summary comparison between some tailings properties

Table 5 below presents a comparison between some design tailings properties and the ones updated with results from the 2013 field and laboratory campaign.

Table 5. Tailings parameters– Design and 2013 data

Parameters	Design	2013 field and laboratory campaign
% passing 75 um	86%	73 to 95%
Specific gravity	2.71	2.74
Relation between saturation ratio, void ratio, hydraulic conductivity	k=4.9 X 10^{-8} m/s (e=0.73) k=1.3 X 10^{-8} m/s (e=0.58)	$e = 0.908(\sigma'+0.0001)^{-0.0568}$ $k = 3.0 \times 10^{-7} e^{2.8}$ m/s
Tailings dry density	1.5 t/m^3 (estimated)	1.4 to 1.72 t/m^3 ($0.95 \leq e \leq 0.6$) [1]
Consolidation parameters	C_c=0.05 C_v=0.03 cm^2/s	C_c=0.05 to 0.13 C_v= 8.9x10^{-3} to 1.2 cm²/s ($0.63 \leq e \leq 1.01$) [1]
Air entry value	40 kPa (e=0.8)	65 kPa (e= 0.6)

1. Based on large strain consolidation tests results of Sample A

5 CONCLUSION

To better understand current performance of the CMM TSF and establish tailings parameters based on field data, a tailings characterization program was conducted in 2013, two years following the start of operations. It consisted of borehole and CPT investigations conducted in different areas of the TSF. Also, laboratory tests were performed on tailings samples, including self-weight consolidation, large strain consolidation (hydraulic conductivity was also measured at different consolidation stages), cyclic simple shear, soil water characteristic curve, shrinkage limit and direct shear. The results of those tests have been presented and discussed. Overall, the properties obtained as a result of the characterization campaign were generally consistent with parameters employed in the initial phase of TSF design, but more information was acquired to improve numerical models.

At this stage, the *in situ* data collected provide a good understanding of the current TSF behaviour. The tailings deposition started recently (May 2011) in the TSF. Future dam raises will be strongly influenced by the engineering properties of the tailings produced by the mill, the depth of the phreatic surface and the consolidation of the tailings stack. The consolidation of the tailings will govern the strength of the material, and ultimately the stability of the overall impoundment. The tailings field conditions and performance of the TSF must frequently be re-evaluated to adjust the design. Therefore, ongoing instrumentation data collection, field observations, frequent tailings characterization and regular design updates during the TSF evolution are key for its successful operation.

6 ACKNOWLEDGEMENT

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