A research project on the use of waste rock inclusions to improve the performance of tailings impoundments

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ABSTRACT
A crucial challenge of mining industry is to minimize the environmental impact of tailings. The co-disposition of tailings and waste rock was proposed, with the waste rock forming rigid and permeable inclusions within the tailings mass, to improve the overall performance of the impoundment. The RIME UQAT-Polytechnique, Canadian Malartic Mine, Golder Associés and other industrial partners are conducting a comprehensive, research project to quantify the effects of inclusions in tailings impoundments and to develop guidelines for their general use. The project is focused on the tailings impoundment of the Canadian Malartic Mine, which contains waste rock inclusions. The research project includes field monitoring and instrumentation, in situ testing, conventional and specialized laboratory testing, physical modelling and numerical simulations. This paper presents an overview of the research project and some preliminary findings.

RÉSUMÉ
Un défi important pour l'industrie minière est de minimiser l'impact environnemental des parcs à résidus. La co-disposition des résidus et des stériles a été proposé avec les stériles utilisés comme inclusions rigides et perméables dans les résidus afin d'améliorer le comportement général des parcs à résidus. L'IRME UQAT-Polytechnique, la mine Canadian Malartic, Golder Associés et d'autres partenaires industriels mènent un projet de recherche pour évaluer l'effet des inclusions sur le comportement d'un parc à résidus et élaborer des lignes directrices pour l'utilisation général des inclusions. Le projet se concentre sur les inclusions de roches stériles du parc à résidus de la mine Canadian Malartic. Le projet de recherche comprend un suivi sur le terrain, une instrumentation du site, les essais in situ et de laboratoire conventionnels et spécialisés, une modélisation physique et des simulations numériques. Cet article résume le projet de recherche et montre quelques résultats préliminaires.

1 INTRODUCTION

The environmental performance and the geotechnical stability of tailings impoundments are major concerns of the mining industry. Despite increased focus on these structures, their rate of failure remains unacceptably high and catastrophic failures such as the Mount Polley Tailings Storage Facility (Canada 2015) and the Fundão tailings dam (Brazil 2016) continue to occur about once a year (ICOLD 2001; Davies 2002; Azam and Li 2010). In some instances, the risks and consequences associated with tailings management can be reduced by using alternative disposal techniques such as thickened tailings, in-pit disposal or underground backfilling. Nevertheless, for the foreseeable future, most tailings will continue to be disposed of as slurry in tailings impoundments where the consequences and risks are the greatest. Furthermore, the effects of climate change are expected to increase these risks.

Aubertin et al. (2002) theorized that waste rock, being relatively strong, rigid and permeable relative to tailings, could be used to improve the hydro-geotechnical behavior of tailings impoundments by incorporating waste rock into the tailings as continuous rows (or isolated heaps) during tailings deposition. These inclusions of waste rock would reinforce the tailings mass and provide drainage to the adjacent tailings leading to improved behavior and stability of the impoundment.

The Canadian Malartic Mine is an open pit gold mine located in the Abitibi region of Quebec, about 20 km west of the City of Val d'Or. Tailings are transported as slurry and deposited into an incrementally-raised tailings impoundment on the site. This tailings impoundment is the first ever constructed with waste rock inclusions.

In 2015, the Research Institute on Mines and Environment UQAT-Polytechnique (RIME), Canadian Malartic Mine and other industrial partners teamed with Golder Associés and Arianne Phosphate on an NSERC-sponsored, 4-year Collaborative Research and Development project for the optimization of waste rock inclusions to improve the short and long-term performance of tailings impoundments. The focus of this research project is the tailings impoundment at the Canadian Malartic Mine. The research consists of an integrated program of field monitoring and observation, in situ testing, conventional and specialized laboratory testing, physical modelling and numerical simulations. The paper presents a summary of the research project as well as some preliminary results. Details are provided in the other papers referenced here.

2 WASTE ROCK INCLUSIONS

The construction of a tailings impoundment with waste rock inclusions (WRI) consists of (Aubertin et al. 2002; James and Aubertin 2012):

- Placement of waste rock along predetermined routes within the impoundment prior to tailings deposition and possibly a thin layer on the bottom of the impoundment and on the upstream sides of the starter dykes as shown in Figure 1a.
- Deposition of tailings from the crests of the retention dykes and tops of the inclusions as shown in Figure 1b.
- Raising of the inclusions with each raise of the retention dykes as shown in Figure 3c.
- Closure could be started on the surface of the impoundment before the end of operations as shown on Figure 1d where the cover, if needed, is shown in green.

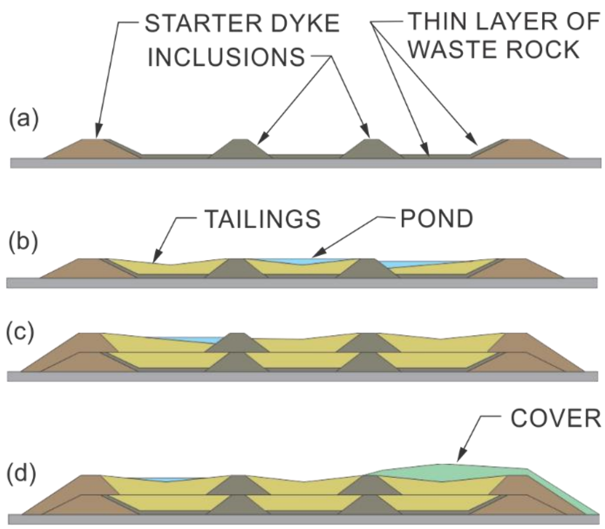

Figure 1. Schematic construction sequence for a tailings impoundment with waste rock inclusions.

A plan and a cross-section of a tailings impoundment with waste rock inclusions are shown schematically in Figure 2.

The advantages of WRI include (James 2009; James and Aubertin 2012):

- Compartmentalization of the tailings (Figure 2).
- Accelerated consolidation and strength gain of the tailings near the inclusions.
- Physical reinforcement of the impoundment.
- Additional options for management and closure of the impoundment.
- Containment and submergence of potentially AMD or CND generating waste rock.
- Reduced volume of waste rock in waste rock piles or, for some underground mines, no waste rock pile.
- Improved control and increased flexibility for tailings deposition.
- Improved drainage and better control of the phreatic surface.
- Reduced volume of tailings released in the event of a rupture of the retention dyke.

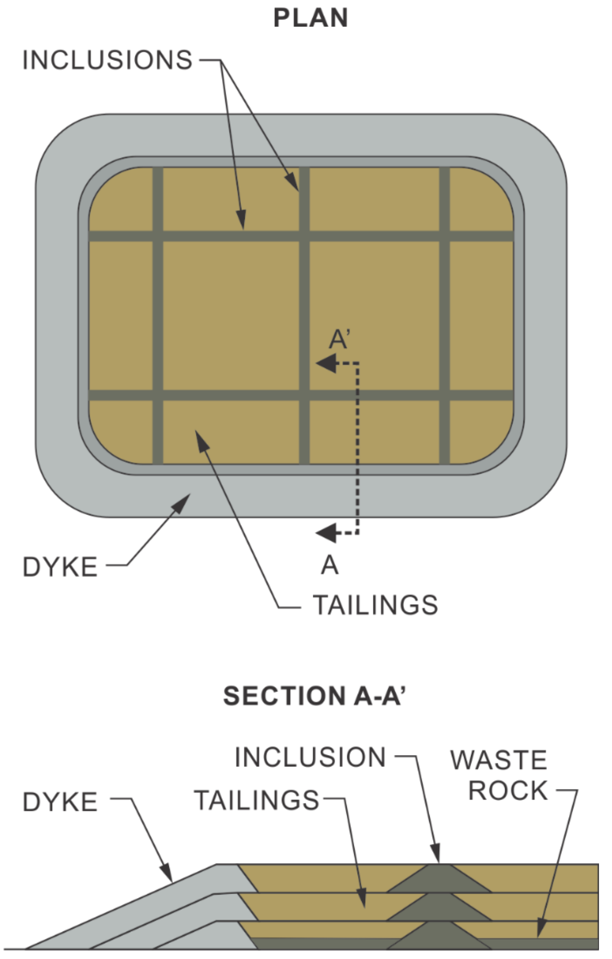

Figure 2. Schematic representation of a tailings impoundment with waste rock inclusions.

2.1 Previous investigations

The use of waste rock inclusions in tailings impoundments has been studied using conventional and specialized laboratory testing, physical models and numerical simulations (e.g. James 2009; Pepin et al. 2012; Ferdosi et al. 2015b).

The first aspect of WRI studied was their effect on the stability of a conceptual tailings impoundment. James (2009) conducted numerical simulations of the static and seismic behavior of a 21-m-high upstream-raised tailings dyke, retaining 20 m of normally consolidated tailings with a beach width of 100 m. The results indicated that the presence of WRI resulted in a minor improvement in the static stability and a very important improvement in the seismic stability, primarily due to the reinforcing effect. In both cases, with and without WRI, the retained tailings liquefied due to the applied earthquake loading. Figure 3 presents the horizontal displacements versus time (during earthquake shaking) of the crest of the tailings dyke with and without WRI subjected to various intensities of seismic loading (moment magnitudes of 6.5, 7 and 7.5 at epicentral distances of 30 km). Without WRI the measured displacements were considerable and the magnitude 7.5 event caused failure. With WRI the displacements were much less and there was no indication of failure.

Also, it was also found that WRI could control the post-shaking dissipation of excess pore water pressures generated within the tailings during shaking. This can help prevent destabilization of the downstream slope of the retention dyke, which can be caused by seepage forces induced by dissipation through the downstream slope. The presence of WRI in the vicinity of the downstream slope, provided preferential vertical drainage paths for dissipation that did not affect stability.

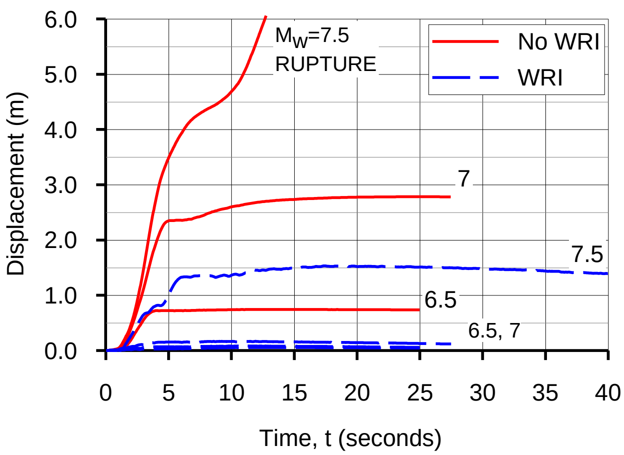

Figure 3. Crest displacements of a conceptual tailings dyke with and without WRI (from James 2009).

Pépin et al. (2012) used a rigid box on a seismic table to physically model the effects of dynamic loading on tailings with rigid, draining and non-draining inclusions. The results indicated that the presence of a rigid inclusion reduced the rate of excess pore water pressure development during shaking. The presence of a draining inclusion facilitated the dissipation of excess pore water pressures after shaking.

Bolduc (2012) and Jaouhar (2012) conducted parametric numerical simulations of tailings with and without waste rock inclusions. Among other findings, the results showed that the zone influence of WRI, with respect to consolidation, can extend a horizontal distance equal to two times the height of the tailings.

Narvaez (2013) used laboratory bending tests and elastic theory to study the tensile strength and apparent cohesion of tailings as a function of the degree of saturation (or moisture content). Tailings from the Canadian Malartic Mine were found to have tensile strengths as great as 138 kPa at about 40% saturation.

Poncelet (2012) developed an experimental protocol for the preparation of tailings specimens for laboratory testing that simulates hydraulic deposition as in an impoundment, without requiring the use of back pressure that can affect the results. Preliminary quasi-static and cyclic testing of Canadian Malartic tailings was conducted.

Contreras (2013) conducted extensive quasi-static and cyclic testing of Canadian Malartic tailings using the specimen preparation method of Poncelet (2012). The results indicate that when normally consolidated and subject to undrained compressive loading, the tailings are not susceptible to static liquefaction. The cyclic response was variable with some specimens undergoing liquefaction and others undergoing cyclic mobility.

Essayad (2015) developed an experimental protocol for the consolidation testing of tailings in a 10-cm-diameter, instrumented column under saturated and unsaturated conditions. One of the major findings was the effect of the suction (degree of saturation) on the coefficient of consolidation.

Ferdosi et al. (2015a, 2015b, 2016) used parametric numerical simulations to evaluate the effect of WRI location, size and spacing on the seismic performance of tailings impoundments. They showed that the width, number and spacing on the inclusions, had significant effects on the deformation and stability of the tailings impoundments, particularly of the retention dyke.

Many phenomena that affect the behavior of an impoundment with WRI cannot be adequately studied in the laboratory, e.g. anisotropy, heterogeneity, tailings movement within a WRI, weather and the effect of scale. Accordingly, a comprehensive research project focusing on the effects of waste rock inclusions in a tailings impoundment was undertaken.

3 THE TAILINGS IMPOUNDMENT OF THE CANADIAN MALARTIC MINE

The Canadian Malartic Mine is located in Malartic (Quebec) about 20 km west of the City of Val d'Or. The mine began commercial production in 2011. Current production is about 55,000 tonnes of ore and 125,000 tonnes of waste rock per day. The annual production of gold is approximately 580,000 ounces. The major features of the mine are shown on Figure 4.

Tailings are produced at the rate of about 55,000 dry tonnes per day. They are transported by pipeline as slurry with a solids content of 60 to 65% to the tailings impoundment and deposited hydraulically from the crests of the retention dykes and the tops of the inclusions.

The tailings impoundment is formed by filter-protected waste rock dykes constructed in 2-m-high raises. The global downstream slope of the dykes is 10:1 (horizontal to vertical). The surface area of the impoundment is 470 hectares and the planned maximum height is 40 m.

The impoundment contains WRI (as shown on Figure 4) that divide the basin into eight cells. The WRI are raised in tandem with dyke raising. The tops of the inclusions are 10 to 12 m wide. Figure 5 is a photograph of a waste rock inclusion at the mine.

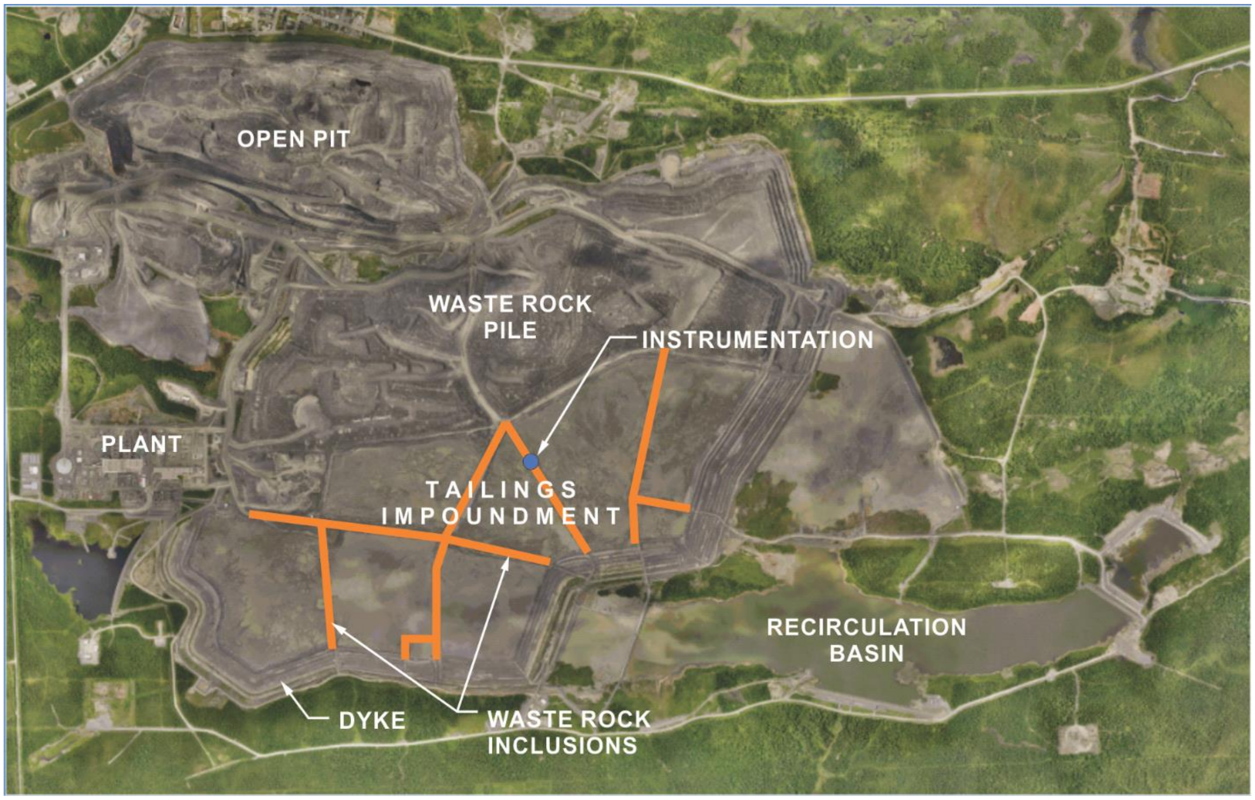

Figure 4. Aerial photograph of the Canadian Malartic Mine with waste rock inclusions shown in orange (from 2015 aerial photograph of site by Canadian Malartic Mine).

Figure 5. A waste rock inclusion in the tailings impoundment of the Canadian Malartic Mine (2016).

4 ONGOING RESEARCH PROJECT

The current research project is an NSERC-sponsored collaborative research and development project that commenced in 2015 and involves several industrial partners, including Canadian Malartic Mine, Golder Associés, Agnico Eagle Mines, IAMGOLD, Glencore/Raglan Mine and Arianne Phosphate.

The primary objectives of this research project are to characterize and quantify the behavior and the performance of the tailings impoundment in the presence of WRI and to develop a method for the design of inclusions (location, number, size, and spacing) in a tailings impoundment. The complimentary objectives include:

- Evaluation of the properties and behavior of the tailings and waste rock under the various conditions expected during the life cycle of the tailings impoundment, including stress, degree of saturation, density as well as static and seismic loads.
- Develop an understanding of the interaction between waste rock inclusions and the adjacent tailings with respect to intrusion of the tailings into the waste rock, migration of tailings through the inclusions, the short and long-term drainage capacity of the inclusions and stress transfer from the tailings to the inclusions.
- Monitor, document and analyze the behavior of waste rock inclusions and the adjacent tailings under field conditions, particularly during tailings deposition in the vicinity.
- Validate, calibrate and modify, if necessary, existing analytical solutions and empirical correlations used in the research conducted thus far based on physical modeling, field measurements and observations.

- Develop a method and guidelines for the design of waste rock inclusions based on the material properties and site conditions.

The research program is composed of five main tasks aimed at achieving the above objectives in an integrated manner:

Task 1	Material characterization and behavior
Task 2	Interaction between the tailings and the waste rock near at an inclusion
Task 3	Field monitoring and observation
Task 4	Numerical simulations
Task 5	Optimization strategy and guidelines

These tasks and the progress made on each are described briefly in the following sections. Some preliminary results are also presented.

The findings and results of the many prior and current investigations of the site by Golder Associés are being incorporated into the research project when suitable. These include boreholes, cone penetration tests, laboratory test results and data from instrumentation and monitoring of the site.

4.1 Task 1 - Material characterization and behavior

The geotechnical characteristics and behavior of tailings are controlled by their mechanical properties (e.g. grain size distribution, particle shape and strength), the method of deposition, and the variation of stresses, density and degree of saturation with time. Tailings from this mine were the subject of prior investigations. However, due to possible changes in their characteristics with variations in the mineral composition or the milling process, additional characterization and behavioral testing was conducted for this research project.

Bulk samples of the tailings slurry (from the thickening plant) were provided by the mine in 2016. The tailings were transported to the Mining Environment and Hydrogeology Laboratory of the RIME in Montreal (Quebec). The tailings were rinsed to replace the process water with clean water and then air and oven dried.

Characterization of the waste rock is underway.

4.1.1 Index testing

Conventional geotechnical index testing was conducted on the tailings and is summarized in Table 1. The relative density of the grains is 2.69. A minimum void ratio of 0.45 was obtained from modified Proctor compaction. A maximum void ratio of 1.53 was obtained from “dry pouring.” Isotropic triaxial consolidation to 2 kPa provided a void ratio of 1.0, which is considered the maximum with respect to field conditions.

The granulometry of the tailings was measured during several prior investigations. In the investigations with samples provided prior to 2013 (e.g. Bolduc 2012; Poncelet 2012, Contreras 2013) the tailings generally consist of fines (<75 μm) with less than 5% fine-grained sand (0.25 mm). However, in investigations with samples provided in 2013 or afterwards (e.g. Essayad 2015; Grimard et al. 2017) the tailings generally consist of fines with as much as 21% fine-grained sand. In all cases the tailings were found to be nonplastic. The tailings are classified as nonplastic silts with trace to little fine-grained sand; ML using the Unified Soil Classification System.

Table 1. Summary of characterization tests on the tailings

Parameter	Value	Method
Relative Density, D_r	2.69	ASTM D854-14
Maximum void ratio, e_{max}	1.53	ASTM D4254-16
Minimum void ratio, e_{min}	0.45	ASTM D1557-12
Void ratio, $e_{(p'=2kPa)}$	1.00	Isotropic triaxial consolidation to 2 kPa

The consolidation of the tailings was evaluated using oedometers, 20-cm-diameter instrumented columns and triaxial cells. Some results are presented in Grimard et al. (2017). The consolidation curve is what would be expected from a normally consolidated fine-grained soil. The average compression index, C_c, of the tailings is 0.08. The unloading-reloading segments are indicative of minor rebound.

When several consolidation curves are plotted together, there is some separation between the curves, as the result of different initial void ratios, but are essentially parallel. This is typical of hydraulically deposited soil.

The water retention curve of the tailings was determined for evaluation of the unsaturated behavior of the tailings. The curves will be presented in future articles and are similar to those of silts.

The properties of the tailings are in very good agreement with the ranges reported by Bussière (2007) for hard rock tailings.

4.1.2 Characterization of the tailings using cone penetration testing

Cone penetration testing is an effective means of evaluating the properties and characteristics of soft soils. However, existing published correlations are for normally or over-consolidated naturally occurring soils and may not be applicable to tailings, particularly to tailings that are not yet consolidated under existing total stresses.

A Master’s student is using an intermediate-scale physical model equipped with an instrumented cone (Ghali et al. 2015) to simulate cone penetration testing of consolidated tailings. The results (tip resistance and side friction) are being compared to properties from the other laboratory testing and the results of CPT campaigns on the site by Golder Associés. Numerical simulations of CPT testing will be used validate and verify tailings properties and characteristics derived from the physical modeling.

4.1.3 Shear strength and potential for static liquefaction of the tailings

One of the objectives of this task is to develop a method to estimate the potential for static liquefaction of the tailings when normally consolidated, when not yet consolidated under existing total stresses due to additional loads (e.g. dyke raising) and during loss of confinement (e.g. dyke rupture).

Triaxial test results indicate that when normally consolidated the tailings have an effective angle of internal friction, ϕ', of 38.1° (c=0). In the range of confining stresses applied, 50 to 600 kPa, the tailings were contractive until phase transformation at a stress ratio (p'/q) of 0.53. The tailings then were dilative until the critical state condition was reached a stress ratio of 0.61. This behavior is known as "limited liquefaction" (Castro 1969) and is unlikely to be problematic with respect to impoundment stability. Triaxial testing continues with the evaluation of the behavior of unconsolidated tailings to compressive loads and of consolidated tailings to loss of confinement. More information on the triaxial testing is provided in Grimard and James (2017).

The shear wave velocity, V_s, of the tailings was measured during oedometric and triaxial consolidation using the P-RAT system developed at the Université de Sherbrooke (Karray et al. 2015). The shear wave velocity of the tailings was found to vary primarily with mean effective stress, p', and secondarily with void ratio, e. Shear wave velocities varied from 95 m/s at 20 kPa to 270 m/s at 600 kPa. A description and the results of consolidation testing with V_s measurements are provided in Grimard et al. (2017)

4.1.4 Dynamic behavior of the tailings

The dynamic behavior, including the potential for dynamic liquefaction, of the tailings was studied by a Master's student using an innovative triaxial-simple shear device at the Université de Sherbrooke. The shear strain and excess pore water development of the tailings were quite similar to those of clean sand. The resistance to liquefaction of the tailings, when normally consolidated, is slightly greater than that of clean sand. The cyclic resistance ratio (CRR) of the tailings decreases with increasing confining stress. The testing program and results are presented in Archambault-Alwin (2017a; 2017b).

An investigation of the dynamic behavior of the tailings under unsaturated conditions and when not yet consolidated under existing total stresses (unconsolidated) is planned for Autumn or 2017.

4.2 Task 2 - Interaction of tailings and waste rock near an inclusion

The interaction between a waste rock inclusion and the adjacent tailings is an important aspect of this research project. The infiltration of tailings into the waste rock and the migration of tailings through the waste rock may have significant effects on the drainage capacity of the inclusions. This is being investigated using physical modelling supplemented with field observations and site work.

Saleh-Mbemba (2017) used innovative physical models to study the drainage, consolidation and desiccation of tailings alone and tailings in the presence of a waste rock inclusion. Additionally, numerical and analytical solutions were used to validate and verify as well as extend the findings of the physical model. It was found that the presence of the WRI had a significant effect with respect to the dissipation of excess pore water pressures in the tailings in the vicinity of the inclusions.

Physical modelling supplemented with field observations and test trenches to be excavated across inclusions is being used to study the movement of fines (tailings and fine particles of waste rock) and the drainage capacity of the waste rock inclusions.

4.3 Task 3 - Field testing and monitoring

There is an important need for "real world" data to better assess the performance of a tailings impoundment with WRI and to provide verification and calibration of the tools being developed to predict the field response. Accordingly, data from field testing (e.g. CPT) and monitoring as well as instrumentation are important aspects of the research project.

Platforms of waste rock were constructed on top of the tailings on either side of a waste rock inclusion. Eight boreholes were drilled through the platform and the underlying tailings and instrumentation was installed in the boreholes (vibrating wire piezometers and volumetric water content sensors) and on the tailings adjacent to the platform (suction sensors, and displacement plates) as shown on Figure 6. These instruments are read regularly and the data is being used to evaluate the actual effects of the inclusion and to compare the observed and predicted behaviors.

4.4 Tasks 4 and 5 - Numerical modeling, analysis and optimization strategy

Numerical simulations invariably require fundamental assumptions and simplifications (e.g. homogeneity, linear elasticity, isotropy, plane strain, perfect plasticity, and discretization) that may significantly affect the results and the corresponding conclusions. Such factors are explicitly included in the research project.

Data from existing and proposed research work are used to validate, calibrate and modify as necessary the analytical solutions and empirical correlations as well as the conclusions drawn from laboratory testing and physical modeling.

The development of a design strategy and guidelines for the use of waste rock inclusions in future tailings impoundments will be based on extensive numerical simulations of the tailings impoundment of the Canadian Malartic Mine. Simulations are conducted in 2D and 3D and will consider the life cycle of the mine, including the evolution of material properties with time due to consolidation and dyke raising. Simulations consider the actual configuration of the inclusions (see Figure 4) as well as alternative configurations.

5 FINAL REMARKS

The use of waste rock inclusions in tailings impoundments is an innovative method with the potential to reduce the risks associated with tailings impoundments by improving their environment and physical behavior and reducing the environmental footprint of mining.

The is just one of several innovative solutions being developed and validated in the field by the RIME UQAT-Polytechnique and its industrial partners.

6 ACKNOWLEDGEMENTS

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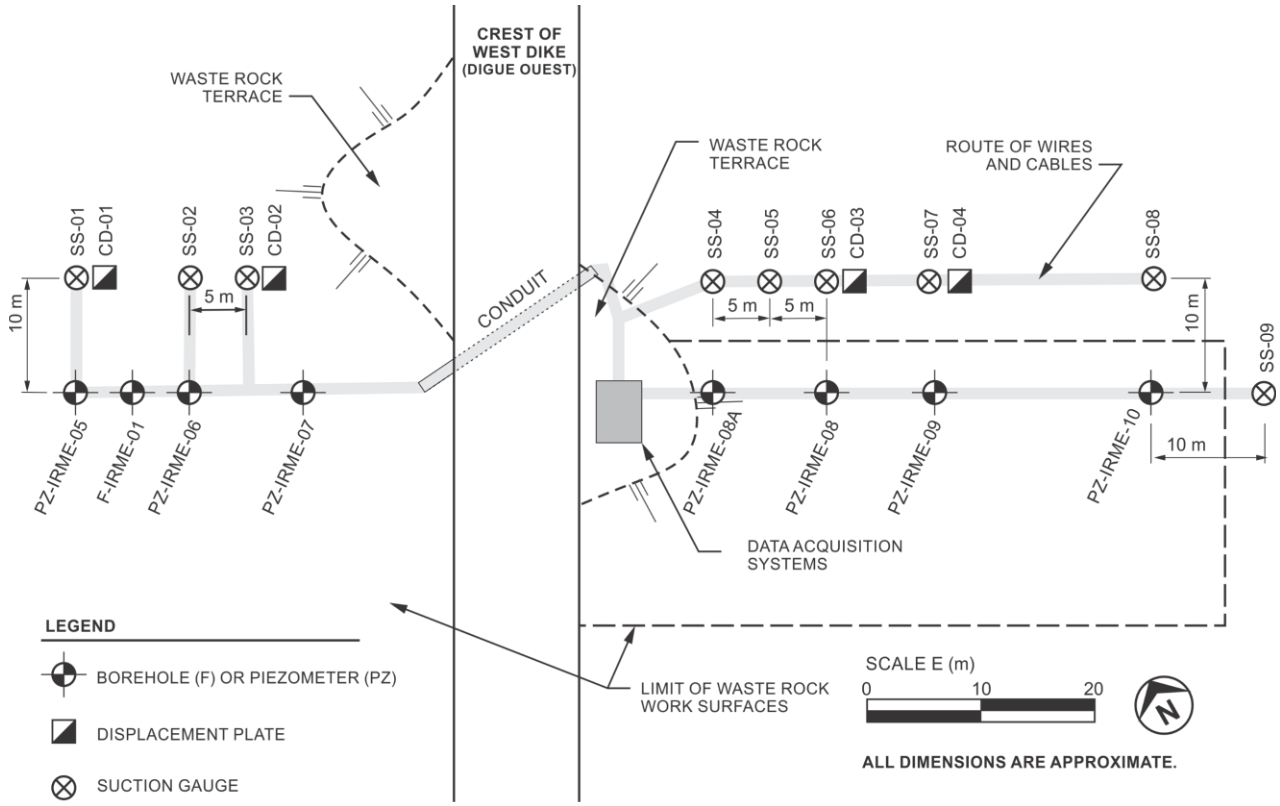

Figure 6. Plan view of instrumentation installed in the tailings near an inclusion (West Dyke)

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