GeoVirtual 2020 September 14-16
Resilience and Innovation

Tailings dike seepage mitigation through adaptive tailings deposition sequencing

Marion Habersetzer & Yves Boulianne
Golder Associés Ltée, Montréal, Québec, Canada

ABSTRACT
This paper presents the summary of a seepage remediation strategy put in place to mitigate the water seepage observed underneath a tailings retention dike at a mine site located in a permafrost environment in northern Canada. Effective seepage mitigation was achieved through adaptive tailings deposition sequencing. Following the first observations of seepage, field investigations and extensive numerical modelling were performed to understand its mechanism, establish appropriate mitigation options and quantify the efficiency of the mitigation strategy over time as the tailings storage facility was operated and sequentially raised. In addition, the seepage mechanism understanding gained was incorporated into a detailed Trigger Action Response Plan for the dike. This paper provides an overview of the evolution of the situation over the operational life of the structure, which is now nearing closure stage, and provides insights about the use of tailings deposition as a seepage mitigation tool.

RÉSUMÉ
Cet article décrit une stratégie de remédiation mise en place dans le but de réduire l'écoulement d'eau sous une digue de rétention de résidus miniers située en environnement de pergélisol dans le nord du Canada. Un plan de déposition des résidus adaptatif a été utilisé pour contrôler l'écoulement. Après l'observation de l'écoulement sous la digue, des investigations géotechniques et une modélisation numérique complète ont été réalisées afin d'en comprendre le mécanisme, d'établir des mesures correctives adéquates et d'évaluer l'efficacité de la stratégie de mitigation au cours de l'opération et des rehaussements séquentiels du parc à résidus. De plus, la compréhension de ce mécanisme a été incorporée dans un plan d'action détaillé. Cet article fournit une vue d'ensemble de l'évolution de la situation au cours de la durée d'opération de la structure, à présent proche du stade de fermeture, ainsi qu'un aperçu de l'usage de la déposition de résidus comme outil de contrôle de l'écoulement.

1 INTRODUCTION

Dam safety and risk management are an increasingly key focus in the mining industry, where tailings dams are often required to manage the by-products of mining operations in tailings storage facilities (TSF).

When an important water seepage was detected at the toe of a tailings retention dike with a potential impact on nearby open-pit operations, concerns arose about implementing mitigation measures without compromising the operation of the TSF, and, in turn, the mine sustainability. Closure of the TSF was also conditional to long-term seepage control.

Conventional approaches to seepage management in dikes often involve foundation treatments such as grout injection in the form of grout curtains or blankets. However, they can be highly labour- and cost-intensive, especially in the presence of high-velocity flows.

This paper describes how, through iterative numerical modelling supported by field investigations and instrumentation, a seepage mitigation strategy based on adaptive tailings deposition was developed to achieve the objective without conventional foundation treatment.

2 DESIGN OF THE STRUCTURE AND GEOTECHNICAL CONTEXT

2.1 Design basis of the dike

The structure is a tailings retaining dike forming part of the TSF of a mine located in northern Canada, along with several other peripheral dikes. It is the highest structure of the facility. The tailings are composed of fine sand and silt.

The dike is constituted of a rockfill structure with a zoned filter system and an upstream low-permeability element (linear low-density polyethylene geomembrane). Along the main body of the dike, the geomembrane is anchored beneath the dike with a low-permeability till key trench over a till foundation and an inverse filter constituted of the same transition materials as the upstream slope is present over the entire width of the foundation. At the abutments, the geomembrane is anchored to the bedrock with an upstream toe tie-in built with low-permeability till, and the inverse filter is present over a portion of the width of the foundation.

The dike is about 900 m long and was built in several downstream raises from 2013 to 2018 up to El. 145 m over an existing cofferdam. Its maximum height is about 45 m. The dike was originally designed to be raised up to El. 150 m.

Normal, expected seepage during operation of the dike was estimated to be within 40 to 100 m^3/h. The original preliminary design included a grout curtain down to a 10 m depth below the bedrock surface, and an inverse filter extending over a section of the dike width. However, seepage modelling done in the framework of the design indicated limited impact of the curtain on the seepage rate, unless the curtain were to extend to a much greater depth into the fractured bedrock unit. As a result, the modified design did not include a grout curtain from the first construction stage, but allowed the installation of a grout curtain later in time to reduce seepage if required by the operations. The inverse filter was extended to the entire width of the dike to account for seepage erosion potential. The design requested the development of a tailings beach of a minimum length of 20 m against the structure at all times to protect the geomembrane and limit seepage.

2.2 Geotechnical and geological settings

The subsurface conditions in the area of the dike are constituted of overburden with variable thickness, overlying bedrock. The overburden is constituted of low strength lakebed sediments, overlying glacial till. The till unit, up to 15 m thick, is constituted of loose to very dense, well-graded material with a low hydraulic permeability, with the presence of localized channels of high hydraulic conductivity material (i.e., coarser zone), and zones of potentially more erodible material (i.e., silt).

The bedrock is composed mostly of quartzite with presence of ultramafic, intermediate volcanic and iron-rich volcanic rocks, and is highly variable in quality. Significant highly fractured zones were observed at variable depths, along with 2 fault zones inferred to cross the dike alignment. The lowest Rock Quality Designation (RQD) values, corresponding to very poor to poor rock quality, were encountered in the upper (0 to 60 m below surface) weathered zone, in ultramafic rock units and in shear zones. The highest rock mass quality was generally associated with quartzite.

A hydrogeological study was conducted during the geotechnical investigation phase with packer tests to assess hydraulic conductivity of soils and bedrock.

The dike is built in an artic environment, where continuous permafrost extends several hundred metres below the surface through the overburden and bedrock. Lakes are usually associated with talik zones, where the foundation remains permanently unfrozen. Due to the dike location within the footprint of a dewatered lake, thermal ground conditions at the time of construction were mostly unfrozen talik conditions. Progressive foundation freeze-back was expected over the operative life of the structure.

2.3 Construction and seepage observations

Construction of the dike included foundation preparation. The lakebed sediments were removed to reach competent till. At that stage, groundwater inflow was noted between Stations 0+620 and 0+825, near the center of the dike alignment. During key trench excavation beneath the future dike centreline, groundwater seepage originating from the upstream slope of the trench and from visible open fractures in bedrock was observed. The major water inflow zones were successfully plugged using low-permeability till before placing material over the foundation. Geotechnical instrumentation (multi-node thermistors and vibrating-wire piezometers) was installed in 2013 to monitor the dike performance.

The dike became operational in 2014 when the tailings started being hydraulically deposited in the TSF. From that moment, water was observed ponding at the downstream toe of the dike, as shown in Figure 1 below, indicating seepage through or below the structure. Chemical signature of the seepage water indicated that it originated primarily from the attenuation pond within the tailings, although no tailings were present in the water, which remained clear to slightly turbid. Observations of groundwater flow during construction suggest that groundwater contributes to a fraction of the seepage. A pumping station was installed in the downstream pond and seepage flow was monitored using a flowmeter. The seepage flow measurements showed that it largely exceeded the design seepage. It reached 800 m^3/h in August 2015. No water was observed reporting to the nearby open pit.

Figure 1: Picture of the downstream pond at the toe of the dike formed by seepage and pumping station

Instruments installed within the dike confirmed the following elements:

- Thawed conditions prevailed in the till and bedrock along the key trench, while a frozen, impermeable barrier of permafrost was present further downstream, near the open pit, preventing seepage from reporting to the pit and promoting surface ponding.
- Simultaneous piezometric level variations on both side of the key trench suggested a hydraulic connection through the bedrock or

till, especially marked in the section between Stations 0+650 and 0+750, which correlates to observations of open fractures in the bedrock and groundwater flow during construction.

The observation of such seepage raised concerns about the potential for erosion of the foundation soils that could jeopardize the integrity of the dike, either from a tailings retention or stability perspectives. The consequences of a dike failure were classified as high due to the presence of the open pit downstream of the dike. By increasing convective heat transfer, a major continuous flow could also delay foundation freeze-back and be problematic for dike closure. In order to address these concerns, extensive numerical modelling was performed to characterize the seepage mechanism and establish mitigation measures, as described in the following section.

3 SEEPAGE NUMERICAL MODELLING AND MITIGATION PLAN

3.1 Pathway assessment

In order to identify the seepage mechanism, four seepage pathways were first considered:

- Defect in the geomembrane;
- Defect in the cofferdam at the base of the dike;
- High permeability granular channels in the foundation till that may have been isolated until critical pore-water pressure was reached;
- High permeability fractured zones in the bedrock.

Piezometric data interpretation indicated that a geomembrane or cofferdam defect were unlikely due to the unrealistically large defect that would be required to justify the observed flow.

A geophysical survey was conducted and identified two main seepage pathways: one between Stations 0+780 and 0+830 in the shallow bedrock, and one between Stations 0+580 and 0+620 in deep bedrock.

Through hydrogeological simulations and comparison of computed pathways with field observations, high permeability channels in the foundation till were considered to contribute to the seepage. Additional geotechnical investigations confirmed in 2017 that the most significant pathway is through the upper fractured bedrock (refer to Section 3.3).

3.2 Hydrogeological seepage modelling (2015)

In order to assess the risk of foundation erosion, numerical modelling of the seepage was done in 2015 on a cross-section of the dike located at Station 0+650, within the area associated with the most significant seepage and geophysical anomaly, as well as the highest dike section. The finite-element SEEP/W module of the Geostudio software developed by the company Geoslope was used to compute steady-state hydrological conditions. Calibration of the model was based on piezometric data and typical material saturated hydraulic conductivities from the design study and literature.

Hydraulic gradients in foundation soils at the downstream toe of the dike were computed for several scenarios:

- current configuration (model calibration);
- different elevations of the downstream pond water level;
- different stages of operation of the dike, with projected tailings elevation;
- assumed conditions at the end of operations (final design dike crest elevation of 150 m).

The primary failure mechanism assessed was piping of the foundation till at the downstream toe of the dike. The secondary failure mechanism was shearing at the till and bedrock interface.

The modelling indicated that hydraulic gradients at the toe would remain inferior to 0.5 provided that the downstream pond level was above El. 115 m, due to the loss of hydraulic head in the tailings. Therefore, short- and long-term risk of erosion-induced dike instability was low. Due to the low expected flow velocities (10^{-4} to 10^{-3} m/s), no shearing issue or contact erosion was anticipated. The inverse filter was deemed adequate to protect the foundation soils against erosion beneath the dike.

Based on the modelling results, mitigation measures put in place were as follows:

- Maintain the downstream pond level at El. 115 m by adjusting pumping to control hydraulic gradients exiting at the downstream toe;
- Monitor frequently the seepage rate using the pumping station flowmeter;
- Modify the tailings deposition sequence to promote not only the development of tailings beaches against the structure, but also a tailings blanket over the TSF foundation, targeting zones of suspected high permeability features. It was expected that the fine slurry would fill granular till channels and fractures in the bedrock, reducing their hydraulic conductivity;
- Install additional instrumentation in the preferential seepage area.

The modelling results were used to compute the expected evolution of the seepage rate over time as the tailings level increases in the facility. The predicted and measured seepage rates as of 2015 are plotted in Figure 2 below.

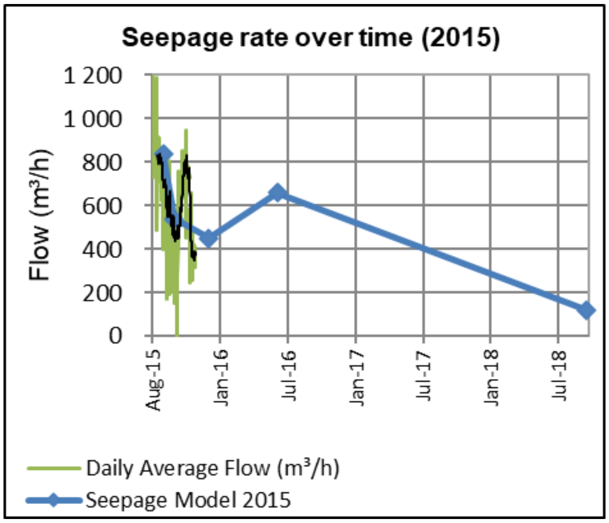

Figure 2: Seepage data up to the development of the 2015 seepage model and predicted evolution

3.3 Update of the seepage model and development of alert thresholds (2017)

In 2017, a field hydrogeological and geotechnical investigation was conducted that included geotechnical boreholes, hydraulic conductivity tests and televiewer survey in the bedrock. The purpose was to better identify and characterize the discontinuities responsible for the seepage in the upper fractured bedrock. The additional bedrock information was used to compute a 3D model of the geological setting integrating lithologies, faults, RQD data, packer data, geophysical pathways, and instrumentation data. The 3D model allowed visualization of bulk seepage features and to refine hydrogeological analyses.

Using this additional information, the seepage model was updated to reflect the preponderant role of the fractured upper bedrock in the seepage mechanism.

The FEFLOW software, a finite-element groundwater flow simulator, was used to produce a hydrogeological model of the same cross-section which was analyzed in 2015 (i.e., Station 0+650). Additional instruments installed since 2015 along this section allowed for a precise calibration of the model. Two steps were involved in the calibration:

1) Steady-state analysis to reproduce the measured seepage rates;
2) Transient analysis to reproduce the hydraulic heads measured in the piezometers in 2015 and 2016.

A sensitivity analysis performed on the seepage pathway width indicated that the dimensions of the high permeability features do not significantly control the model output.

Predictive modelling was done for several upcoming stages of the tailing storage facility, including closure stage, for the following scenarios:

- Normal water volume in attenuation pond within tailings;
- No supernatant water in tailings;
- Water against exposed till foundation and bedrock (areas without tailings blanket).

Post-closure stage was evaluated with no water in the tailings, as the attenuation pond will have been drained at that stage.

The modelling results were used to update the expected evolution of the seepage rate over time as the tailings level increases in the facility, up to the closure stage. Figure 3 below presents the predictive seepage trend plotted against measured seepage rates at the time of the modelling.

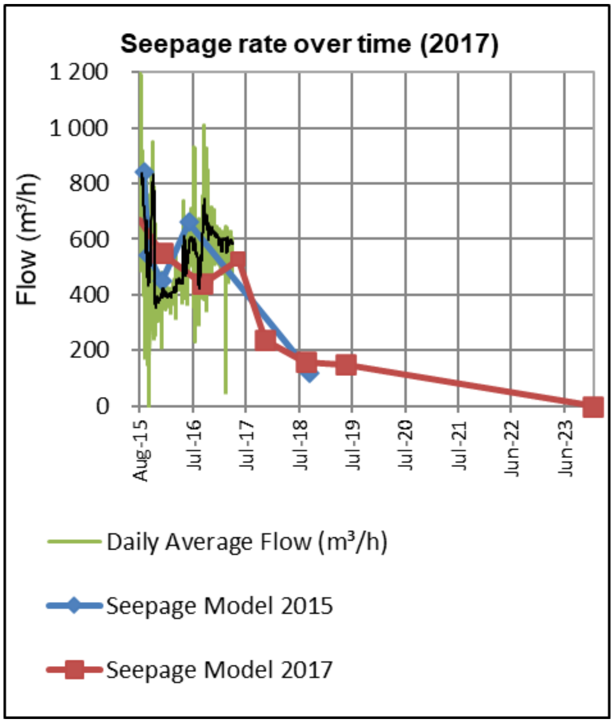

Figure 3: Seepage data up to the development of the 2017 seepage model and predicted evolution

Coupled stability analyses were then performed using the SLOPE/W module of Geostudio to establish pore-water pressure thresholds within the foundation till unit that would cause the factor of safety against foundation failure to fall below the trigger levels defined in the mine's Trigger Action Response Plan (TARP). Pore-water pressure values computed in FEFLOW were imported in SLOPE/W, and the pressure in the foundation till unit was increased incrementally until the limit factor of safety for stability was reached for each TARP level. The current and final (closure) dike configurations were analyzed. The obtained critical pressure levels were quantified in terms of piezometric head in relevant instruments and these results were integrated into the TARP (refer to Section 4.3 for more details).

The risk of erosion was re-assessed using the updated stratigraphic information and relevant methods proposed by Fell et al. (2015), Wan and Fell (2004, 2007) and Guidoux et al. (2010). Backward erosion, suffusion and contract erosion of the foundation soils were evaluated for the current and closure configurations. For both configurations, suffusion and contact erosion were shown to be irrelevant, while backward erosion was unlikely in the normal, expected hydrogeological conditions. Similarly to the stability analyses, pressure in the till unit was increased to identify threshold levels in terms of backward erosion onset (refer to Section 4.3 for more details).

Based on the updated modelling results, mitigation measures put in place were as follows:

- Continue to maintain the downstream pond level at El. 115 m and to monitor seepage rates;
- Continue adapting deposition sequencing to target in priority exposed bedrock and areas showing seepage features within the existing tailings surface;
- Monitor instruments frequently to compare piezometric levels with the alert thresholds and set up automatic alarms for each TARP level in the event of pressure exceedance.

3.4 Seepage management and deposition strategy

Although the design included the possibility to install a grout curtain during operations to reduce seepage, important technical challenges were expected with grouting through a high velocity flow, and concentration of seepage during the process was identified as a major potential issue. Instead, in collaboration with the designer, the mine opted for seepage management based on pumping instead of grouting, associated with an adjusted tailings deposition and an adequate emergency response plan. The permanent seepage pumping station installed at the downstream toe of the dike, within the pond, was equipped with a flowmeter and an autonomous system adjusting pumping rates to maintain the pond level at El. 115 m. Both the pond level and pumps status were remotely monitored and equipped with automated alarms to ensure the performance of the seepage management system at all times.

Based on the numerical modelling results, it was decided to continue depositing tailings in the TSF with a focus on developing a thick tailings blanket over areas of the foundation with suspected entry points, in addition to tailings beaches along the dike. Monitoring of the seepage rate and the formation of seepage features within the tailings would serve as key performance indicators for the seepage mitigation effort and guide the adaptive aspect of the strategy implementation as described in the following section.

4 IMPLEMENTATION OF ADAPTIVE TAILINGS DEPOSITION

4.1 Adaptive deposition sequencing

The tailings were deposited hydraulically into the TSF from deposition points installed on the peripheral dikes and natural topography. The spacing between deposition points along the structures was about 150 m. A tailings transportation system with numerous lines connected to a central valve allowed rapid and flexible switching between outlets. With this system, adaptive deposition sequencing could be performed satisfactorily without requiring significant operations to move pipelines and outlets between deposition points.

A baseline deposition sequence was established to optimize the TSF storage capacity. Then, through monthly strategic sequence updates, the active deposition point was switched at selected times based on suspected entry points and observed seepage features such as depressions in tailings. These depressions, an example of which is depicted in Figure 4 below, indicate a loss of water through the fractured bedrock and a priority zone for the tailings blanket development.

Figure 4: Localized tension cracks and circular depression features in the tailings surface, indicating entry points into the underlying foundation

The duration of deposition at a single point was variable and sometimes did not exceed days at a time. Especially as the tailings level reached close to the design freeboard, deposition became more challenging due to ice entrapment and a very close monitoring of tailings and water levels was required to adjust the sequence. A flexible tailings transportation system such as the one used in this case is deemed necessary to perform the level of reactivity required by this integrated seepage mitigation method.

Through selective tailings deposition, the attenuation pond was progressively pushed back to the section of the TSF farthest from the dike of interest. Amendments to the design of the TSF were done to technically enable this measure. The purpose of this measure was to reduce the hydraulic gradient further, since modelling indicated a significant hydraulic head loss through the tailings as their thickness increased. At the end of the tailings deposition in the TSF, all foundation within 1,100 m of the dike had been covered with tailings. Their total thickness directly upstream of the dike reaches about 45 m in the middle of the dike alignment, where most of the seepage was observed, and gradually thins out towards the abutments.

Tailings deposition in the TSF ended in 2019, although additional tailings deposition could be done occasionally to promote surface profiling for TSF closure.

4.2 Compliance with numerical models

With the instrumentation of the seepage management system in the downstream pond, the seepage rate could be continuously compared with its anticipated evolution. Data from August 2015 to February 2020 are plotted against the predictive models in Figure 5 below.

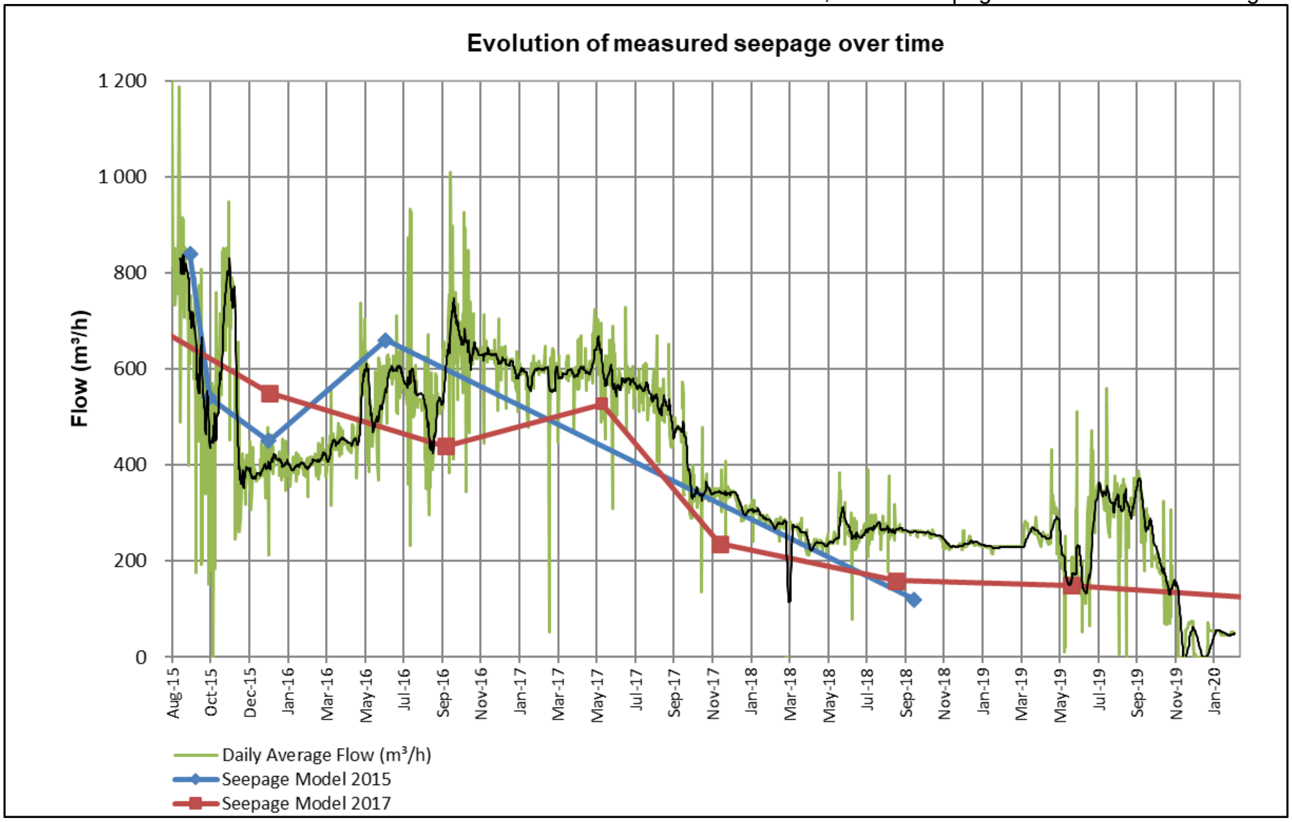

Figure 5. Measured seepage over time and computed seepage models

The seepage rate generally exhibits seasonal variations, with an increase in summer as the snowpack melts and frozen pathways thaw and re-open. Small-scale variations in the observed seepage rates can be related to several elements that were not considered in numerical analyses, such as:

- Fluctuations in water inflow into the TSF due to water management strategies on the mine site, which included intermittently pumping water from other mine areas into the TSF.
- The effect of unevenly frozen ground along the dike on local pore-water pressure, hydraulic conductivity and water flow.
- Localized seepage features with a transient behaviour that cannot be represented in a steady-state analysis. For example, piezometric data indicated that some fractured bedrock areas act as a temporary reservoir associated with intermittent water flow.
- Unusual climatic conditions.

The latter is considered to have impacted seepage rate measurements in 2019, when a significantly wetter year than normal coincided with an increase in the seepage rate compared to 2018. This could be attributed to some extent to the higher runoff water volumes that reported to the downstream pond as well as the large inflow into the TSF. At the end of the year 2019, with the onset of winter and the ongoing removal of the supernatant water in the now-inactive TSF, the seepage rate decreased again dramatically to about 50 m^3/h.

The seepage rates show an evolution over time that compares well with the predictive models. Between 2015 and 2016, they followed the trend of the 2015 seepage model with an average that was slightly lower than the predictive values by about 7%. After 2016, they follow the anticipated general trend of the 2017 seepage model, with an average that was generally higher than the predictive values by up to 25% in 2018. Despite the differences in averaged measured and modelled trends, the predictive values for both models were always within the range of the actual measured values. As a result, the observed seepage rates were in good compliance with the predictive models.

Seepage rate reduction by 2016 was 25% of the initial seepage rate (800 m^3/h in August 2015), 28% in 2017 and 66% in 2018. After the temporary increase over the summer of 2019, seepage rates decreased to the lowest recorded value since 2015. As of February 2020, the seepage is stable at 50 m^3/h and has thus been globally reduced by 94% since the development of the issue. With the TSF free of supernatant water, it is expected that the residual seepage will be primarily fed by groundwater flow and the rates will remain low.

4.3 Integration of seepage management into the Trigger Action Response Plan

The main goal of the development of a TARP is to guide the TSF operations team in determining when to take an action relative to the identified level of alert. The TARP levels were developed as a combined effort between the mine and the designer and used to develop a detailed emergency response plan. Seepage modelling results and coupled stability and erosion analyses performed in 2017 (described in Section 3.3) were integrated into the TARP.

TARP levels are developed under three main categories: seepage, dike stability and environment (which is beyond the scope of this paper). The alert levels and potential action plan were determined and developed using observable aspects. The observable aspects of the seepage category refer to observations that can be made at the downstream pond (change in inferred seepage rate, total water pumped at downstream toe, downstream pond elevation, and compliance to seepage model). For the dike stability category, the alert level is set according to visual observations (e.g., loss of tailings, settlement, downstream toe displacement, cracks, sloughing, sinkholes) and according to monitoring instruments like piezometers (rotational failure of till foundation, backward erosion) and thermistors.

The potential stability issues caused by the seepage were considered in the dike's TARP for the two identified potential failure modes, namely:

- An increase in the pore-water pressure in the foundation till unit that could lead to foundation failure;
- A backward erosion phenomenon within the till unit that would in turn destabilize the dike.

TARP levels related to both failure modes are based on critical piezometric heads in selected instruments associated with factor of safety against stability failure and backward erosion respectively of 1.5 (green level), 1.3 (orange level), 1.1 (yellow level) and 1.0 (red level). Automated alarms were set up for the different TARP thresholds.

5 PATH FORWARD TO CLOSURE

The design of the dike involved progressive freezing of the entire TSF through the foundation, then the tailings and finally part of the rockfill structures. After the initial observations of the large seepage beneath the dike, concerns arose that freeze-back of the foundation would no longer be achievable within the planned closure timeframe.

The TSF is currently inactive and all supernatant water in the former attenuation pond has been removed from the cell. Water removal aims at promoting tailings drainage in preparation for the TSF final rockfill cover and reducing further the convective heat transfer through the seepage. As heat transfer is impeded by seepage reduction and foundation cover, both by rockfill and tailings, it is expected that freeze-back in the foundation will accelerate and eliminate residual seepage. Predictive models indicate that groundwater seepage will reverse from the pit towards the TSF foundation once the water level on the downstream side of the dike is restored to the original lake level after closure. A marked cooling trend has already been ongoing for years within the bedrock on the downstream side of the dike. Due to the effective seepage reduction, it is deemed that the original closure strategy based on foundation freeze-back is still applicable. Additional instruments will be installed within the dike and foundation to monitor the thermal evolution of the dike during the transition into closure. Seepage management by pumping and monitoring per the TARP will continue during that phase.

6 CONCLUSION

This paper presents a case study of a tailings retaining dike in a permafrost environment where a water seepage developed though the foundation bedrock. Hydrogeological and geotechnical numerical modelling was performed and updated over the dike's operational life to locate seepage pathways and quantify the potential for foundation failure and internal erosion, as well as to develop an adequate emergency response plan. Based on two detailed seepage models and continuous visual and instrumental monitoring, the tailings deposition sequencing was adapted over time to seal bedrock fractures. Seepage management was done in parallel through pumping at the downstream toe to control hydraulic gradients. This integrated seepage mitigation strategy was effective in reducing the seepage rates by 94%, ensuring the dike structural safety without requiring additional foundation treatment and allowing for TSF closure conditions to be met.

Key success factors in this approach are extensive monitoring of the structure through instrumentation and adaptive, detailed tailings deposition with a high level of reactivity.

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