Reducing the Long Term Risk and Enhancing the Closure of Tailings Impoundments

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ABSTRACT: Tailings impoundments typically provide long-term storage for saturated, semi-fluid fine grained materials. Closure of these tailings impoundments represents an ongoing priority and challenge for owners and professionals due to the potential for the impounded tailings to fluidize and flow in the event of a dam failure. This paper provides a case study for the decommissioned Nye Tailings Impoundment at the Stillwater Mine. The closure plan includes capping the loose, saturated tailings with a thick waste rock layer to stabilize the impounded tailings, mitigate potential dusting and provide for water management.

Following closure, a Waste Rock Storage Area (WRSA) can be developed on top of the tailings impoundment as part of the final closure cap. This approach would provide for additional waste rock storage within the existing mine disturbance area, thus minimizing the need for additional site disturbance. At the same time, the progressive and controlled placement of waste rock over the capped tailings would enhance the stability of the tailings by promoting additional consolidation induced dewatering and densification. This would reduce the flowability of the tailings, thus reducing the potential consequences of a post-closure dam failure event.

RÉSUMÉ : Les parcs de résidus permettent un stockage à long terme pour les matériaux à grain fin saturés et semi-fluides. La possibilité que les résidus enfermés se fluidifient et s'écoulent en cas de brèche du barrage représente une priorité continue et un défi pour les propriétaires et les professionnels pour la fermeture de ces parcs à résidus. Ce document fournit une étude de cas pour la fermeture du parc de résidus de Nye à la mine Stillwater. Le plan de la fermeture comprend le recouvrement des résidus saturés et meubles avec une couche épaisse des roches stériles afin de stabiliser les résidus retenus, d'atténuer la formation de poussière, et de gérer l'eau.

Après la fermeture, une zone de stockage de stériles peut être aménagée au-dessus du bassin de retenue des résidus dans le cadre de la couche de fermeture définitive. Cette amélioration permettrait un stockage supplémentaire de stériles dans l'aire de perturbation actuelle des opérations minières, minimisant ainsi le besoin de perturbations supplémentaires du site. En même temps, la mise en place progressive et contrôlée des stériles renforcerait la stabilité des résidus en favorisant la densification et le dénoyage par la consolidation. Cela réduira la fluidité des résidus, réduisant ainsi les conséquences potentielles d'un événement de brèche de barrage après la fermeture.

1 INTRODUCTION

Tailings impoundments store fine grained materials that remain from mining operations after the economic minerals have been extracted from the ore during processing. The stored tailings often comprise fine-grained sand, silt, and clay sized rock fragments mixed with water to facilitate slurry transport and deposition into the tailings impoundment. The settled tailings deposit may consist of soft, saturated, semi-fluid tailings in a lined impoundment. Storing these soft, saturated tailings poses a physical risk because of the potential mobility of the material. This risk must be managed throughout the life of the mine and at closure. An ultimate goal for the long term closure of the facility is to provide for long-term public safety and protect the environment including air, surface water, and groundwater resources.

Risk considers the both likelihood of a failure event occurring as well as the consequences resulting from that event. Demonstrating long-term stability during closure for time periods ranging from decades to centuries is challenging given the complexity and uncertainty associated with future performance predictions. During the post-closure period, there is the potential for changes in the local environment, land use, meteorological conditions, topography, geology, and state of practice. These factors can contribute to the uncertainty and may increase the likelihood (positively or negatively) of a failure event occurring for even the most rigorous design. However, increasing the density and reducing the flowability of the settled tailings within a tailings impoundment would reduce the consequences from such a hypothetical future event and thus will also reduce the overall long term risk relating to the facility.

This paper presents a case history for the closure design and proposed closure enhancement for the Nye Tailings Impoundment at the Stillwater Mine. The closure design for the Nye Tailings Impoundment involves removing the supernatant pond and constructing a closure cap to stabilize the tailings surface and limit dusting. While the closure cap would improve the upper tailings to provide a stable and trafficable surface for future land use, it would not impact the deeper tailings.

The Stillwater mine will continue to operate following closure of the Nye Tailings Impoundment. As such, there is an opportunity to enhance the closure and reduce the long term risk relating to the Nye Tailings Impoundment by storing additional waste rock from the ongoing mine operations over the capped tailings. Placement and storage of waste rock at the closed tailings impoundment would cause additional consolidation, dewatering, and densification of the underlying tailings. This would further stabilize and de-risk the closed tailings impoundment by reducing the potential for the impounded tailings to flow during a dam failure scenario. As a bonus, using areas already affected by the mine operations for waste rock storage would reduce the need for additional site disturbance and reduce the overall environmental impact of the ongoing mining operations. These improvements would lead to a reduction in the risks associated with the project, during operations, closure, and post-closure phases.

2 PROJECT OVERVIEW

The Stillwater Mine is an underground platinum and palladium mine located approximately 5 miles southwest of Nye, Montana (MT) (Figure 1). The mine in owned and operated by Sibanye Stillwater. The mine comprises a 3,000 tpd concentrator, the Nye Tailings Impoundment, the Hertzler Tailings Impoundment, the East Waste Dump and other ancillary facilities to support the operation. The mine site layout, including the Nye Tailings Impoundment and the East Waste Dump, is illustrated on Figure 2.

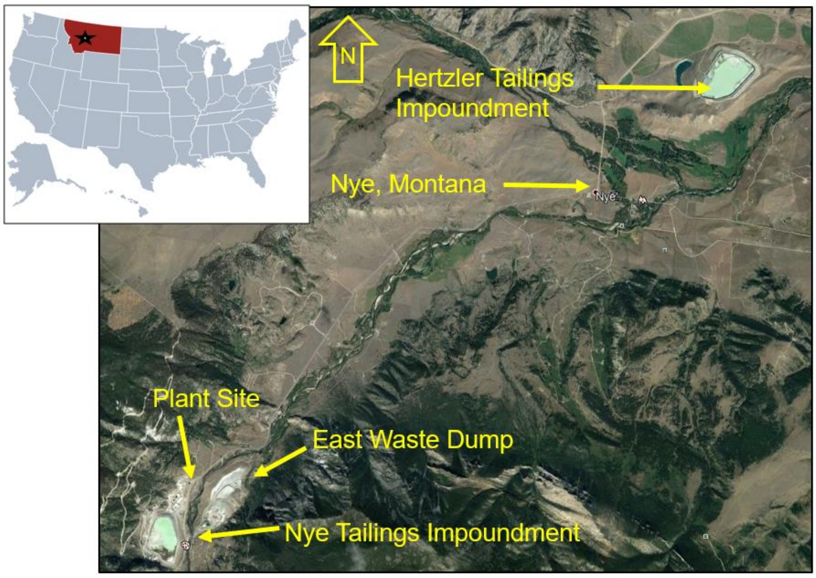

Figure 1 Stillwater Mine Location Map

Figure 2 Nye Tailings Impoundment (looking East)

Waste rock from the mine operations is stored at the East Waste Dump. The coarse (sand) fraction of the tailings is pumped underground for backfill to support the underground mining operations, while finer tailings slimes are deposited into the tailings storage facilities, including the Nye Tailings Impoundment located adjacent to the Stillwater River.

The Nye Tailings Impoundment was commissioned in 1987 and operated as the primary tailings impoundment until 2001. The new Hertzler Tailings Impoundment was commissioned in 2002. Since then, the Nye Tailings Impoundment has been used to provide mine water management and short-term operational flexibility for tailings storage. Closure of the Nye Tailings Impoundment commenced in 2018 and will be advanced over the next several years.

The Nye Tailings Impoundment includes an earthfill and rockfill embankment constructed using the downstream construction method to a maximum embankment height of approximately 136 ft. (42 m). A typical cross section is shown on Figure 3. The crest elevation is approximately

El. 5,108 ft. (El. 1,557 m) and the minimum crest width is approximately 30 ft. (9.1 m). The downstream slopes vary from 1.7H:1V to 2H:1V and will be graded at a least 2H:1V or flatter during closure of the facility. The impoundment is lined with a 100 mil (2.5 mm thick) High Density Polyethylene (HDPE) geomembrane liner to minimize seepage from the basin and does not include an underdrain system.

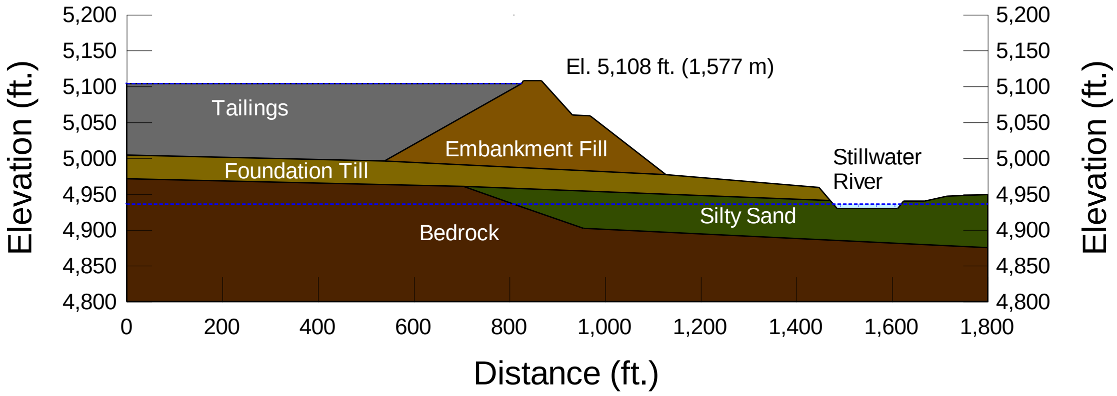

Figure 3 Typical Nye Tailings Impoundment Embankment Cross Section

3 TAILINGS CHARACTERIZATION

The Nye Tailings Impoundment contains predominately fine grained tailings consisting of fine sands, silts, and clay sized rock fragments. Site investigations were completed to investigate and characterize the tailings. Amphibious vehicle mounted equipment was used to complete site investigations over the exposed tailings surface at the southern end of the tailings impoundment. Barge mounted equipment was used to complete the site investigations at the northern area of the tailings surface which was covered by the supernatant water pond.

The site investigations included a total of 24 Cone Penetration Test (CPT) soundings, 12 geotechnical drillholes, and two vibrating wire piezometer (VWP) installations. Undisturbed samples were collected in Shelby Tubes using a piston sampler to improve recovery in the soft tailings. Disturbed samples were collected to support rheological testing using an aqua lock sampler. Vane testing was also completed to measure the in situ strength of the tailings and to support calibration of the CPT measurements.

Laboratory index, strength, deformation, and rheology testing was completed on samples collected during the site investigations. Direct Simple Shear (DSS) and Cyclic Direct Simple Shear (CDSS) testing was completed to measure the strength of the consolidated tailings under static and dynamic loading. Slurry consolidometer and Constant Rate of Strain (CRS) testing was completed to visualize and measure the deformability of the tailings over a range of applied stress. Rheology testing including Vane Yield Stress, Boger Slump, and Transportable Moisture Limit (TML) testing was completed to evaluate the yield stress and flowability of the tailings at a range of solids contents.

The phreatic surface within the tailings was observed at surface and the tailings are fully saturated with hydrostatic pore pressure conditions, consistent with normally consolidated tailings contained within a fully lined tailings impoundment. The tailings are low plasticity to non-plastic and generally contain greater than 80% silt and clay sized particles with a specific gravity of solids ranging from 2.8 to 2.9. The undrained shear strength ranges from less than 5 kPa to greater than 10 kPa and increases with depth which is also consistent with a normally consolidated tailings deposit. The peak undrained shear strength ratio (S_u/σ'_v) is estimated to be 0.1 based on the CPT interpretation, field vane measurements, and laboratory testing results. The tailings are considered to be potentially liquefiable under dynamic (i.e. earthquake) loading or static loading. The liquefied strength ratio ($S_{u,liq}/\sigma'_v$) is estimated to be 0.05 based on the CPT data and the laboratory testing results.

4 CLOSURE PLAN

Closure capping at the Nye Tailings Impoundment is in progress. The closure plan has been developed to provide for long-term public safety and to protect air, surface water, and groundwater resources at the site and on adjacent lands. The permitted closure plan includes removal of the supernatant pond and construction of a rockfill closure cap over the tailings surface. The permit requires that the closure cap consist of an average 4 ft. (1.2 m) thick waste rock cap placed over a geotextile to improve trafficability. The waste rock will be placed in 2 ft. (0.6 m) thick lifts using low ground pressure equipment. Construction will be advanced in stages over 4 or more years to allow time for removal of the supernatant pond and to enhance the trafficability of the tailings surface.

Once completed, the closure cap will provide a stable trafficable capping layer to minimize dusting potential and to provide long term water management. A sump and overflow swale will be installed in the closure cap to assist with surface water management. Water that is collected from precipitation and consolidation of the tailings will migrate to the surface sump during capping. Water collected from the sump will be used to supplement process water in the concentrator or will be transferred to the Hertzler Tailings Impoundment. The configuration of the closure cap during operations is illustrated on Figure 4.

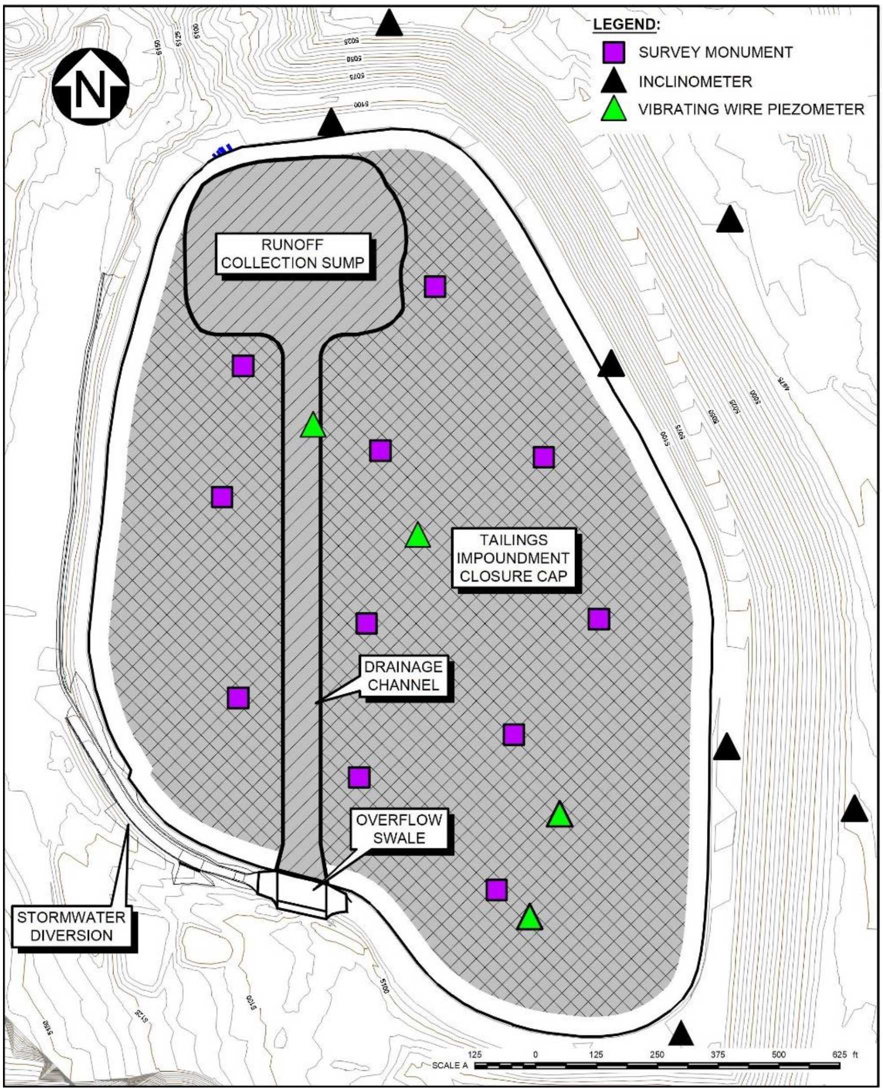

Figure 4 Initial Closure Cap Configuration

Placing the rockfill closure cap over soft, saturated tailings is expected to present challenging construction conditions. The tailings surface and tailings impoundment embankments will be closely monitored using survey monuments, VWPs, and slope inclinometers during and following construction.

Construction of the initial 2 ft. (0.6 m) thick lift began in late 2018 and was focused on the exposed tailings surface along the south end of the impoundment as shown on Figure 5. A woven geotextile was placed over the tailings surface and a tracked crawler carrier with 360 degree rotation and excavator were used to place rockfill over the geotextile. This combination of geotextile reinforcement and low ground pressure hauling equipment has thus far yielded positive results with no significant trafficability or safety issues during construction.

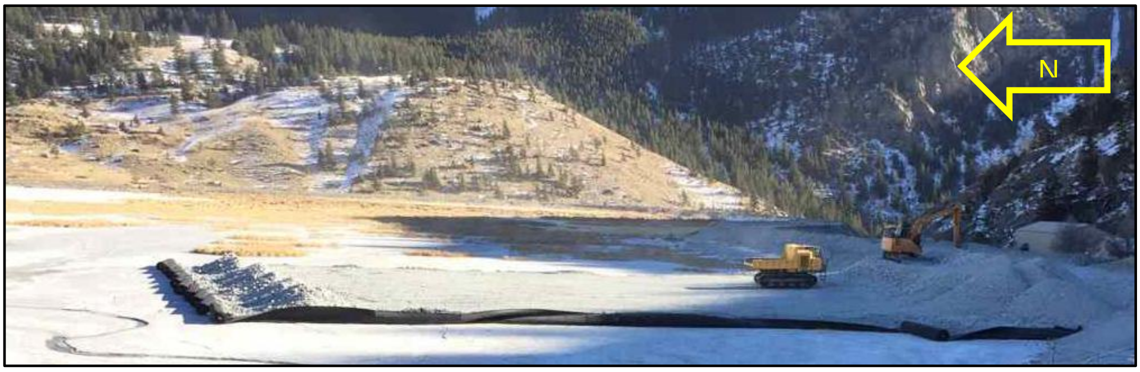

Figure 5 Closure Cap – Initial Construction Progress

5 RISKS AND TAILINGS FLOWABILITY

5.1 *What is risk?*

Risk considers the likelihood of a failure event occurring, as well as the consequences relating to that event:

Risk = Likelihood x Consequences

In general terms, risk increases as either the likelihood and/or the consequences of failure increase. Conversely, the risk decreases when the likelihood and/or the consequences of failure decrease.

It is extremely unlikely that a failure of the Nye Tailings Impoundment embankment would occur at closure. Removal of the operating pond and grading the surface to provide surface water management will eliminate the potential for failure mechanisms such as overtopping. Further, the Nye embankment incorporates a robust design section using strong, durable construction materials and has been progressively developed using the downstream construction method. Thus, the likelihood of a post-closure dam failure is extremely low.

Nevertheless, if a post-closure dam failure were to occur, any loose, saturated tailings materials could be fluidized and released from the impoundment. Fluidized tailings materials would then flow and could potentially impact downstream areas depending on the degree of fluidity. Under this scenario, the overall risk is related to both the likelihood that a failure may occur and the potential consequences of the outflow as follows:

- Likelihood - The likelihood for a dam failure can be minimized by achieving an adequate Factor of Safety (FoS) against instability.
- Consequence - The consequences of a dam failure can be reduced by consolidating and densifying the tailings to reduce the flowability of the impounded tailings so they have reduced potential to flow. This would reduce the volume of tailings that could be released following a

dam failure and would also reduce the travel distance and the extent of the downstream impact area.

5.2 *Tailings Flowability*

The ability for tailings to fluidize and flow decreases as the solids content increases and the moisture content decreases and the slurry transitions from a fluid state to a soil state. This behavior can be demonstrated using the slurry consolidometer laboratory test as illustrated on Figure 6.

Figure 6 Tailings Slurry Consolidation Test – Photo Summary

Slurry tailings are poured into the consolidometer mold and the tailings are allowed to settle under self-weight with drainage to the top and bottom of the mold. This simulates deposition and settling to reach equilibrium under self-weight loading for the near surface tailings. The tailings are then incrementally loaded with continued drainage to the top and bottom of the mold to simulate the additional settling that occurs at depth in an accreting column. Two-way drainage would apply to a TSF with underdrainage, but one-way drainage is more applicable for the Nye TSF. Once loading is complete, the consolidated tailings are extruded from the consolidometer mold and observed. This process simulates a reduction in confining stress similar to what would occur during a dam failure event. The photos on Figure 6 illustrate tailings loaded to 150 kPa, equivalent to 23 ft. (7 m) of waste rock at the tailings surface.

The slurry consolidometer test demonstrates that consolidation loading is an effective means of densifying tailings to change the behavior from a fluid-like slurry to a soil-like solid under unconfined conditions.

5.3 *Flow Types*

The change in flow characteristics from a viscous fluid slurry to a more soil-like solid were defined by O'Brien (1986) and are summarized in Table 1.

Table 1 Summary of Flow Types (adapted from O'Brien, 1986)

Flow Type	Solids Content Range (by Mass)	Descriptions
Water Flood	Less than 41%	Water flow with suspended sediment (solids) load.
Mud Flood	41 to 69%	Fluid-like flow of water and solids. Large particles (i.e. boulders) settle. Spreads on a horizontal surface but maintains an inclined surface.
Mudflow	69 to 76%	Transition to soil-like behavior. Slow, sustained creep of saturated or partially saturated sediments and water. Deforms under self weight.
Landslide	Greater than 76%	Soil-like behavior, will not flow. Slow creep possible.

The flow type continuum is illustrated on Figure 7. Photographs of historic water and tailings dam failures are included to provide field scale examples of the different flow types and to illustrate the relative consequences for dam failure events for a range of material types.

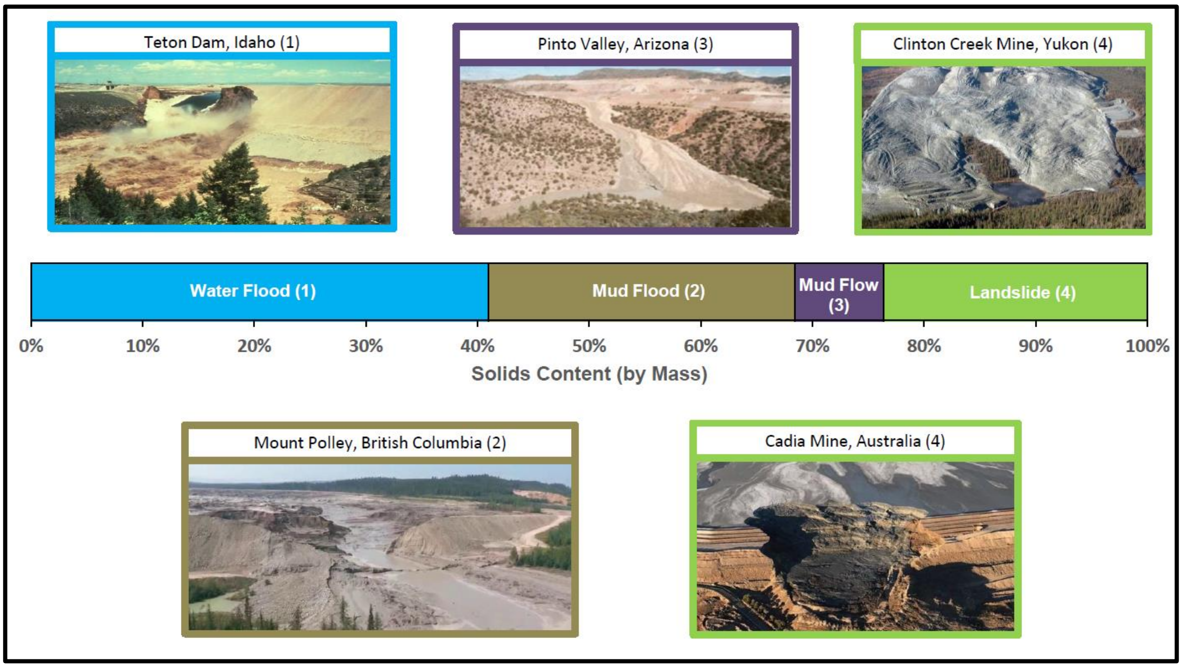

Figure 7 Flow Type Continuum with Examples of Historic Failures

The historic failures illustrated on Figure 7 are briefly summarized below:

- Teton Dam, Idaho - The water-retaining Teton Dam failed on June 5, 1976. The failure occurred as a result of seepage through to the downstream face (piping failure) that occurred during the initial filling. The failure resulted in the rapid release of all impounded water, devastating the downstream communities (USBR, 2018).
- Mount Polley, British Columbia - The northern perimeter embankment of the Mount Polley Tailings Storage Facility (TSF) failed on August 4, 2014. The failure was triggered after the embankment expansion incorporated an over-steepened downstream slope which was inappropriate for the weak foundation materials. The failure occurred when ponded water flowed over the localized embankment slump. The consequences of the failure were exacerbated by poor operating practices and inadequate regulatory oversight, which resulted in the accumulation of a large water pond that inundated the tailings beaches (CIM, 2015; AG, 2016; EGBC, 2018). The dam failure resulted in a sudden loss of containment and released water and eroded tailings solids from the TSF that flowed downstream and impacted multiple water bodies.
- Pinto Valley, Arizona - The Pinto Valley TSF was decommissioned in the 1970's. The TSF embankment failed in 1997 while a waste rock dump was being placed over the historic tailings surface. The failure resulted in the release of under-consolidated fluid tailings slimes that flowed out and impacted one mile of the adjacent Pinto Creek (RCM, 2014). Excess pore pressures were generated in the saturated tailings slimes which ultimately burst through the thin sand shell zone of the upstream constructed tailings embankment.
- Cadia Mine, Australia - The Cadia Mine TSF embankment failed on March 9, 2018 (Newcrest, 2018). The failure occurred along a section of the embankment with a wide, drained tailings beach. No ponded surface water was released. The failure resulted in a localized slump of tailings and embankment material.
- Clinton Creek Mine, Yukon - In 1974, the Clinton Creek Tailings Pile slumped and blocked the downstream Wolverine Creek. The tailings materials continue to deform and water flowing along the creek continues to erode the toe of the slump (Government of Yukon, 2018).

6 WASTE ROCK STORAGE AREA AND CLOSURE ENHANCEMENT

6.1 *General Arrangement*

The proximity of the Nye Tailings Impoundment to the underground mine makes it an ideal location for future waste rock storage for ongoing operations at the Stillwater Mine. Re-purposing the closed Nye Tailings Impoundment to incorporate a Waste Rock Storage Area (WRSA) would achieve the following objectives:

- Reduce the overall disturbance area required to support ongoing mine operations
- Provide a new waste rock storage area located within a short haul distance from the shaft and underground portals
- Enhance the closure of the Nye Tailings Impoundment by further consolidating, densifying, and dewatering the tailings contained within the closed impoundment to further reduce the flowability of the settled tailings.

The total mass and geometry of waste rock that can potentially be stored over the closed Nye Tailings Impoundment depends on the strength, deformability, and drainage characteristics of the underlying tailings, the rate of waste rock placement, and the ability of the impoundment embankment to support the additional load. The proposed arrangement for the Nye WRSA is illustrated on Figure 8. The proposed arrangement includes a lower slope angle of 2.5H:1V and an overall upper slope angle of 24H:1V.

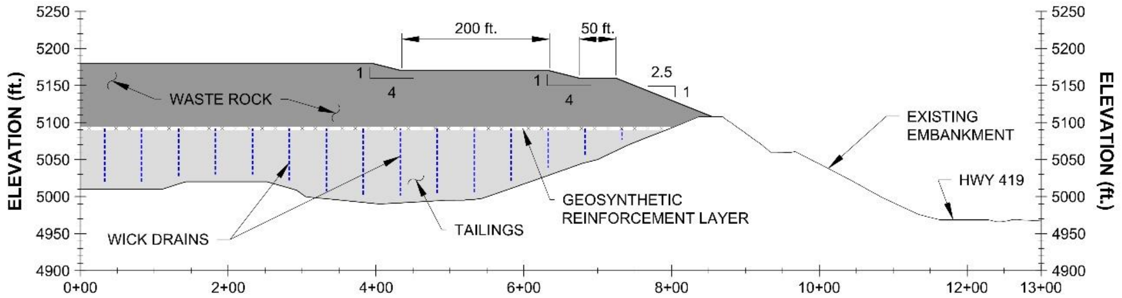

Figure 8 Proposed Nye WRSA Arrangement Cross Section

Wick drains can be installed to enhance drainage and accelerate pore pressure dissipation in the tailings during loading. The waste rock placement schedule will be developed as necessary to allow time for excess pore pressures that develop in the underlying tailings to dissipate.

6.2 *Expected Behaviour – Stability*

Limit equilibrium slope stability analyses were completed to evaluate the stability of the Nye Tailings Impoundment Embankment and the Nye WRSA. In Montana, a minimum FoS of 1.5 is required for static loading conditions and a minimum FoS of 1.2 is required for post-peak, static loading conditions (MT, 2017). The computed FoS for the Nye Tailings Impoundment embankment exceeds the minimum required values for the existing condition, with the Closure Cap, and with the proposed Nye WRSA. Though construction of the Nye WRSA past will reduce the overall FoS, the computed FoS meets or exceeds the minimum required values for peak and post-peak loading conditions, as shown on Figure 9. The waste rock pile can be safely placed over the Nye Tailings Impoundment without negatively impacting the stability of the impoundment.

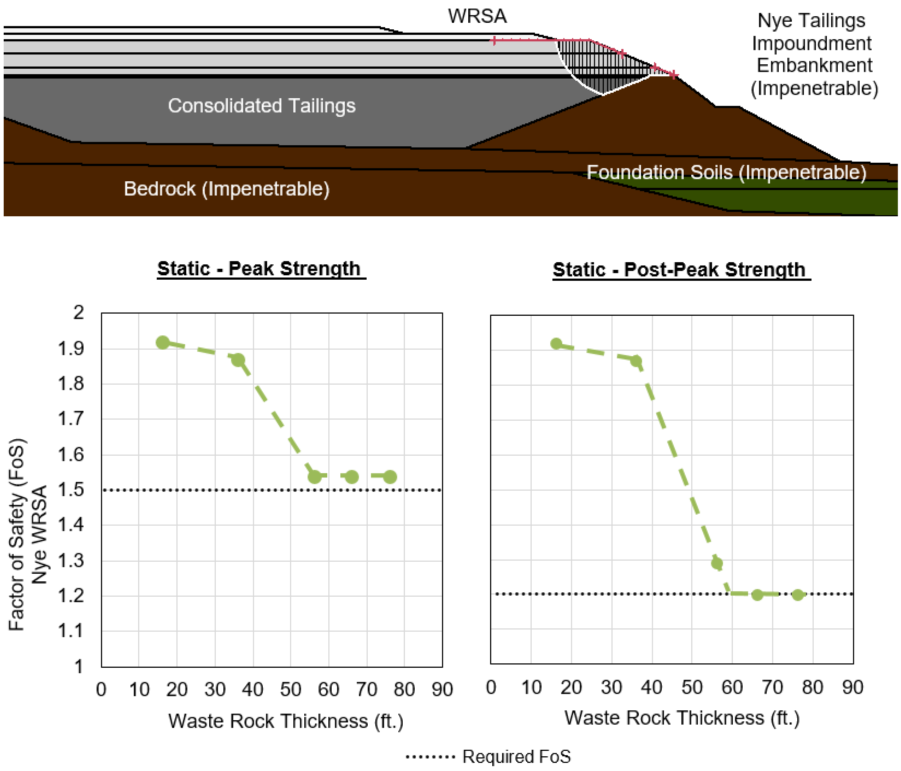

Figure 9 Summary of Slope Stability Results for the Nye WRSA

6.3 *Expected Behaviour –Flowability*

One-dimensional consolidation analyses were completed to evaluate the expected response in the tailings as a result of the loading applied by the closure cap and further placement of waste rock. The results of the consolidation analyses are illustrated on Figures 10 and 11. Photographs of the unconfined Nye Tailings sampled at different depths (stress conditions) and different solids contents are provided for reference.

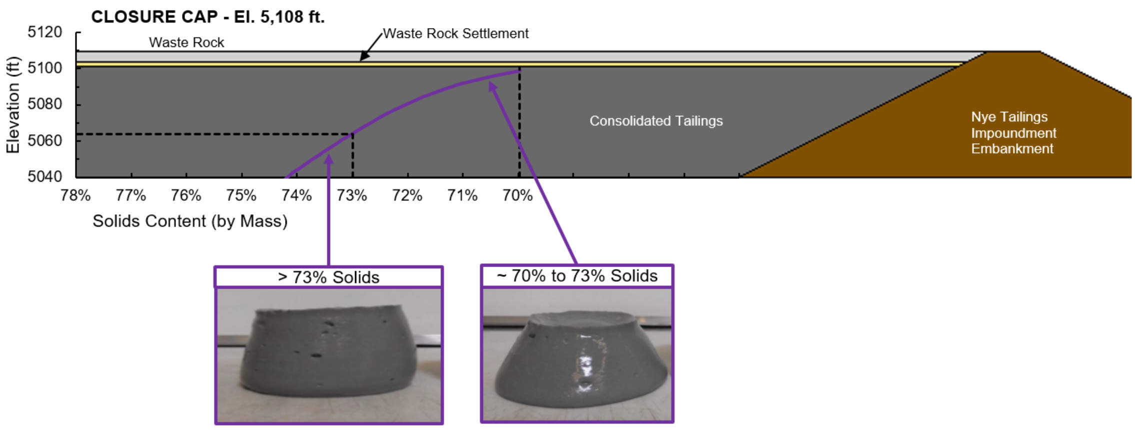

Figure 10 Tailings Solids Content and Flowability – With Closure Cap

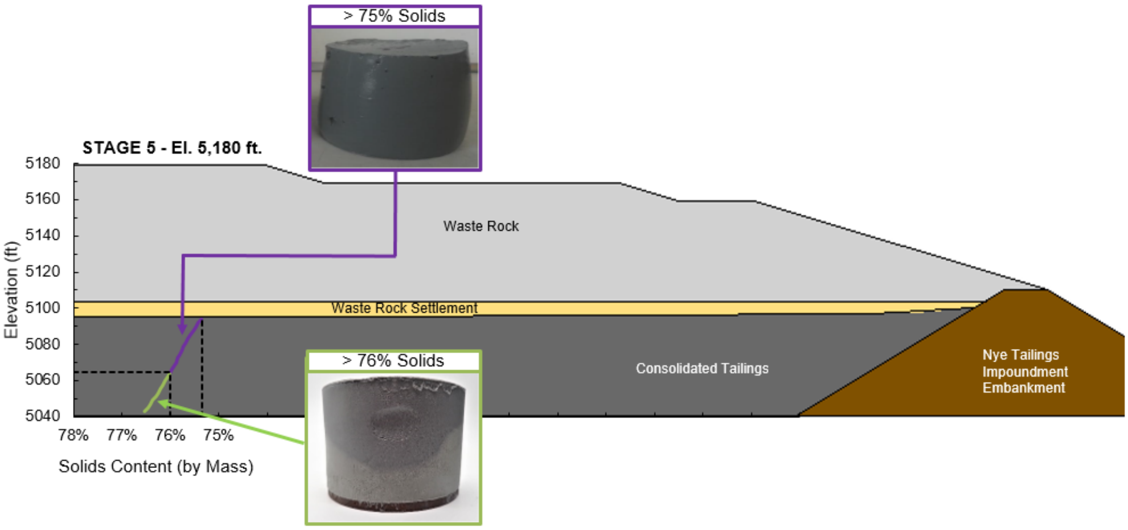

Figure 11 Tailings Solids Content and Flowability – With Nye WRSA

The analyses indicate that placement of waste rock over the tailings surface would increase the tailings solids content and reduce the potential for the tailings to flow. Construction of the closure cap is expected to result in a tailings solids content ranging from approximately 70% in the near surface tailings to 74% in the tailings at depth. Tailings within this solids content range are expected to behave similar to a mudflow (see Table 1 and Figure 7). Placement of additional waste rock to construct the Nye WRSA would further reduce the solids content to between 75 and 76 % as illustrated on Figure 8. Tailings within this solids content range would be expected to have transitioned from mudflow type behaviour toward landslide type behaviour as defined by O'Brien (1986) (See Table 1 and Figure 8). Consolidating the tailings reduces the volume of water stored within the tailings mass, thus increasing the solids content and reducing the fluidity and potential for the tailings to flow, especially for the near surface tailings.

It is noted that the potential for the tailings to contract and liquefy in response to a triggering event will remain even after consolidation is complete. The preliminary stability analysis results indicate that the proposed configuration would remain stable and achieves the minimum required FoS for the post-peak loading condition using reduced (i.e liquefied) undrained shear strength parameters.

7 SUMMARY AND CONCLUSIONS

The Nye Tailings Impoundment provides storage for historically deposited tailings consisting of saturated, fine grained silt and clay sized particles. The tailings are contained by a 136 ft. (42 m) high embankment located adjacent to the Stillwater River. Closure of the Nye Tailings Impoundment is being advanced over the next several years. The closure plan involves removing the supernatant pond and constructing an average 4 ft. (1.2 m) thick rockfill closure cap. Construction of the closure cap over soft, saturated tailings is expected to be challenging and as such will be advanced in stages to allow time for removal of the existing supernatant pond and corresponding consolidation and strengthening of the tailings surface. The settled tailings and impoundment will be closely monitored during and following construction of the closure cap.

Once complete, the closure cap will provide a trafficable surface, minimize dusting, and provide long-term water management via a collection sump and overflow swale. The closure plan for the Nye Tailings Impoundment facilitate the development of a stable tailings surface, and will provide for long-term public safety while protecting air, surface water, and groundwater resources at the site and on adjacent lands.

The Stillwater Mine will continue to operate following construction of the Nye Tailings Impoundment closure cap. The proximity of the Tailings Impoundment to the underground mine makes it an ideal location for future waste rock storage. Following construction of the closure cap, it is possible that the Nye Tailings Impoundment could provide storage for waste rock generated from the ongoing mining operations. The placement of additional waste rock is expected to densify and further dewater the tailings, increasing the solids content and reducing the potential fluidity (flowability) of the tailings. This would reduce the overall risk of the facility by reducing the potential consequences of a post-closure dam failure event, as the tailings will no longer be flowable.

This integrated waste management strategy for the Stillwater Mine would provide operational benefits for ongoing waste rock management while concurrently stabilizing the impounded tailings to enhance the reclamation objectives for the mine site.

8 REFERENCES

Auditor General (AG), 2016. An Audit of Compliance and Enforcement of the Mining Sector. May. British Columbia. Bellringer, C.

Chief Inspector of Mines (CIM), 2015. Mount Polley Mine Tailings Storage Facility Breach. November 30.

Resolution Copper Mining (RCM)., 2014. Tailings Design and Operation Safety. Resolution Copper Mining. November 12. Retrieved from: http://superiorazcwg.org/wp-content/uploads/bsk-pdf-manager/2017/02/Tailings-Design-Operations-Safety_Frank-Deal_11-12-14.pdf (accessed November 29, 2018).

Engineers and Geoscientists British Columbia (EGBC), 2018. In the Matter of the Engineers and Geoscientists Act R.S.B.C. 1996, Chapter 116 and In the Matter of Todd Martin, P.Eng., P.Geo. - Notice of Inquiry. September 25. Ref. No. 004949-0003/00223576.

Government of Yukon, 2018. Clinton Creek: Care & Maintenance. Energy, Mines, and Resources. Retrieved from: http://www.emr.gov.yk.ca/aam/clinton_creek_care_maintenance.html (accessed December 18, 2018).

Newcrest Mining Limited (Newcrest), 2018. Market Update - Cadia Northern Tailings Facility. March 15.

O'Brien, J.S., 1986. Physical Processes, Rheology, and Modeling of Mud Flows. Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado.

State of Montana (MT), 2017. Montana Code Annotated (MCA) Title 82. Minerals, Oil, and Gas Chapter 4. Reclamation. Part 3. Metal Mine Reclamation.

United States Bureau of Reclamation (USBR), 2018. Teton Dam History. Reclamation - Managing Water in the West. February 15. Retrieved from: https://www.usbr.gov/pn/snakeriver/dams/uppersnake/teton/index.html (accessed December 18, 2018).