Geotechnical Studies for Reclamation of the Nickel Plate Mine Tailings Facility

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Abstract: Reclamation activities at the Nickel Plate Mine tailings facility included tailings cover construction, post- closure seepage control and surface water management. Several geotechnical studies were carried out for these reclamation activities. These studies included the development of a tailings consolidation model, post-closure seepage estimates, tailings cover settlement predictions and on-going assessment of embankment stability.

Mine tailings that are unconsolidated or only partially consolidated at closure will continue to consolidate after closure, resulting in on-going settlement of the tailings surface and the generation of consolidation seepage. The degree of consolidation of a tailings deposit at closure is therefore a key consideration for reclamation, particularly when surface capping is to be carried out or estimates of post-closure consolidation seepage rates are required. Predictions of the consolidation rate, the magnitude of surface settlement and seepage flows after closure were facilitated by means of in-situ field testing using the Cone Penetration Test (CPT), laboratory testing of tailings samples and detailed one-dimensional finite difference consolidation modelling. Instrumentation and monitoring data were used to evaluate the post closure stability of the tailings facility and to demonstrate that its overall stability was improved with the removal of the supernatant pond and construction of the tailings cover.

Introduction

The Nickel Plate Mine is a former gold producing operation owned by Homestake Canada Inc. The mine is located 3 kilometres north-east of Hedley, B.C. at the southern end of the Thompson Plateau, in south-central British Columbia. During its 9 year operating life, from April 1987 to October 1996, the average daily tailings production rate was approximately 3500 tons/day, generating a total of almost 12 million short tons of solids that were deposited into the tailings facility. After closure of the tailings facility there was a need to provide a water treatment plant for removal of cyanide and other contaminants from tailings water stored in the facility and seepage collected by collection ditches, drains and sumps.

Reclamation activities since the end of operations have included tailings cover construction and the monitoring and treatment of seepage water. Surface capping commenced in May 1998. Between the end of operations and the commencement of tailings cover construction the free water (supernatant) pond was almost entirely removed from the tailings surface. The remaining pond currently covers only a small area in the northern end of the facility. The primary objective of the reclamation activities is to return the site to an area of productive cattle grazing and wildlife use similar to the pre-mining use and productivity.

Geotechnical studies required for reclamation of the tailings facility included the following:

- Tailings Cover Construction
- Post-Closure Seepage
- Water Management
- Embankment Stability

Post-closure seepage rates and tailings cover settlements were predicted using a tailings consolidation computer model developed for the facility. The progress of consolidation of the tailings and the corresponding reduction in seepage provides an estimate of the time frame required for on-going water treatment at the site.

Tailings Consolidation Analyses

On-going settlement of the tailings surface due to consolidation is an important consideration for reclamation of a facility at closure. Consolidation occurs continuously within the tailings deposit during deposition and will continue after completion of operations until all excess pore pressures have dissipated. Expulsion of pore fluids during consolidation produces settlement of the tailings surface and seepage from the tailings mass. The magnitude of consolidation settlement of the tailings surface after closure is largely dependent on the characteristics and degree of consolidation of the tailings mass at closure.

Consolidation seepage from the tailings mass will continue as long as consolidation is occurring, and will continue after closure until complete tailings consolidation is achieved. However, the consolidation seepage rate tends to decrease with time as the soil becomes less permeable at lower void ratios. Estimates of these on-going consolidation seepage rates are necessary to predict water treatment requirements following closure of the facility.

Tailings consolidation settlements and seepage rates during and after closure of the facility were estimated using the following methodology:

a) Field measurements using the CPT to establish in-situ tailings properties and existing pore water pressures;
b) Laboratory testing of representative tailings samples to determine their consolidation characteristics;
c) Computer analyses using a large-strain finite difference consolidation model.

The results of geotechnical site investigations and laboratory testing of the tailings were used to develop a tailings consolidation model. This model was used to predict the magnitude and rate of tailings surface settlements and consolidation seepage rates.

Field Measurements

Field measurements collected during cone penetration testing were used to establish the existing conditions, in particular the pore water pressures within the tailings deposit. The cone penetration test comprised pushing an electric piezocone downward through the tailings and recording measurements of penetration resistance, sleeve friction on the cone and dynamic pore pressure (excess pore pressure due to cone advancement) at regular intervals. The data obtained from this testing were used to evaluate the in situ geotechnical properties of the tailings and to define existing pore water pressures within the tailings mass. Static pore pressures within the tailings mass were measured at selected depths by suspending cone penetration and allowing the pore pressure at the cone tip to dissipate and achieve equilibrium pressure. The pore pressure distributions with depth were then developed. An estimate of the horizontal coefficient of consolidation (c_h) was also calculated from the pore pressure dissipation data. This estimate provided information on the consolidation characteristics of the tailings mass.

CPT programs were conducted in June 1994 and June 1996, the latter occurring 4 months prior to the end of operations. Due to the presence of an active tailings pond, access was only available on the tailings beach area around the periphery of the facility. The CPT data indicated that the tailings were generally well consolidated, with measured pore pressures within the deposit in the range of 50% to 100% of hydrostatic. Information obtained from these CPT programs was used to make preliminary estimates of consolidation seepage rates from the facility.

An additional CPT program was carried out in September 1999 to determine conditions within the tailings after construction of the tailings cover and to investigate the progress of tailings consolidation since the end of operations in October 1996. For this investigation the majority of the tailings pond was accessible, enabling CPT soundings to be taken within finer tailings in the centre of the facility. Measured pore pressures in the coarser beach tailings adjacent to the perimeter embankment were generally about 30% to 60% of hydrostatic, indicating a reduction in pore pressures since the CPT program in 1996. Approximately hydrostatic pore pressures were recorded in the finer tailings furthest from the embankment.

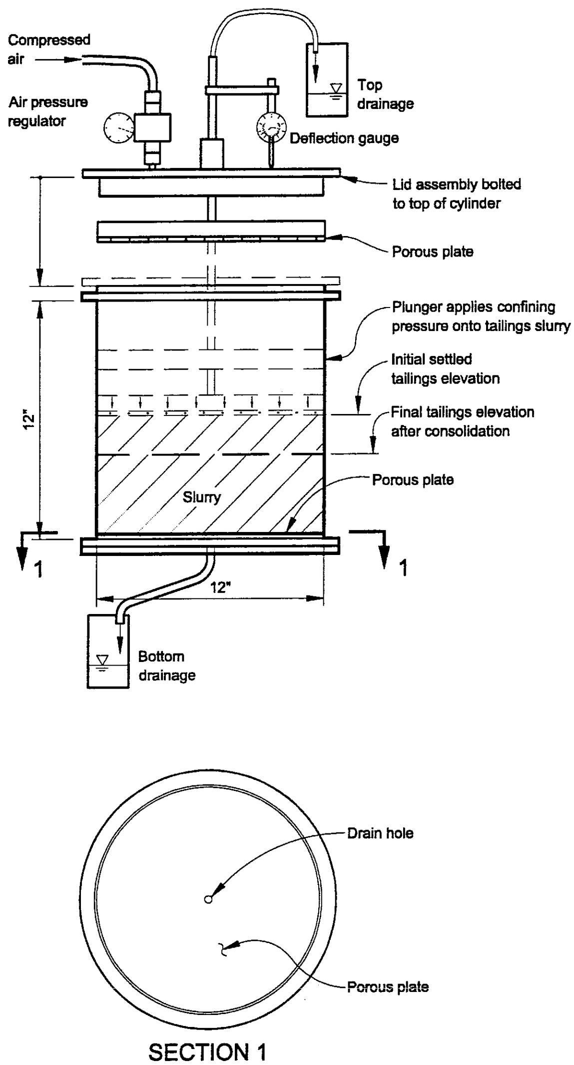
Laboratory Testing

Representative tailings samples were retrieved from the tailings facility during operations in 1993 for laboratory testing. The tests included basic index testing and slurry consolidation tests. Index tests were performed to assess the physical properties of the tailings, such as specific gravity and particle size distribution. The consolidation characteristics of the tailings were determined from a specialised slurry consolidometer test. A schematic of the slurry consolidometer test arrangement is shown in Figure 1. The consolidometer tests were supplemented by bench scale slurry settling tests and slurry consolidation cylinder tests, which provided settling and consolidation parameters at very low effective stresses, corresponding to the initial stages of tailings settling and consolidation. The settling tests provided an estimate of the density to which the tailings would initially settle in a subaqueous environment after discharge into the facility.

The consolidation testing yielded tailings consolidation parameters over a range of effective stresses and provided the following information for use in the computer modelling:

- Initial density of settled tailings
- Void ratio-effective stress relationships
- Void ratio-coefficient of consolidation relationships

Fig. 1. Schematic of slurry consolidation test.



Two tailings samples were tested: beach tailings sampled close to the perimeter embankment and a finer tailings sample retrieved further from the perimeter embankment. Coefficients of consolidation (c_v) calculated for the finer tailings ranged from about 10 m^2/year at low effective stresses to about 50 m^2/year at high stresses. For the coarser beach tailings, values ranged from 20 m^2/year at low stresses to 250 m^2/year at high stresses.

Computer Modelling

A one-dimensional finite difference computer model was used to predict the magnitude of tailings consolidation settlements and consolidation seepage rates from the tailings deposit. The computer model incorporates measured void ratio versus effective stress and coefficient of consolidation relationships, actual or predicted tailings deposition rates and large strain consolidation theory. The appropriate consolidation parameters determined from the laboratory testing were incorporated into the computer model and analyses of the tailings deposit were conducted for the operating period of the mine, using operating records of deposition rates. Both beach tailings and finer tailings were considered. Foundation drainage conditions for the deposit were represented by an impeded drainage boundary condition, as supported by measured pore water pressures. The computer model was initially calibrated to conditions within the tailings mass by comparing with measured in-situ tailings pore pressure profiles recorded during the 1994 and 1996 CPT programs during operations and the 1999 CPT program carried out after placement of the tailings cover. Calibration of the model was carried out by multiplying the laboratory derived coefficients of consolidation by a factor (typically about two) to account for field conditions. In-situ coefficients of consolidation for tailings are typically higher than predicted in the laboratory due to interlayering effects of coarser free-draining tailings, which enhance horizontal drainage. A pore pressure profile predicted by the computer model and corresponding in-situ pore pressure data obtained from the 1999 CPT soundings in fine tailings are shown in Figure 2.

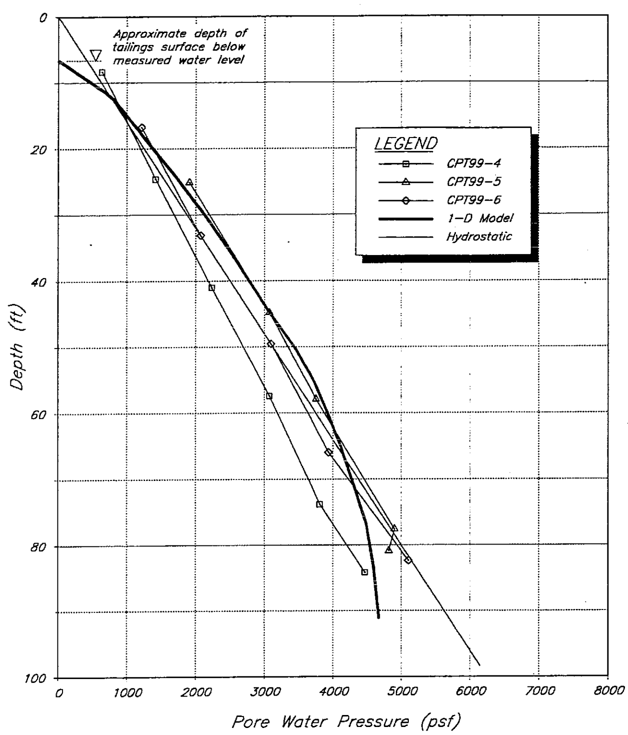
Self-weight consolidation settlements in the deepest part of the tailings deposit were predicted to be approximately one foot, one year after the end of operations. Bathymetric survey data collected at the end of operations and again one year later indicated that the tailings surface had settled by about one foot in the deeper tailings areas, providing confidence in the calibrated consolidation model. The calibrated model was subsequently used to predict the magnitude of tailings consolidation settlements and consolidation seepage rates at the end of operations, after placement of the cover layer and for several years after closure of the facility. The influence of surcharge loading on the tailings surface due to placement of the cover layer was included in the model. A similar computer model for settling ponds is described by Yong et al. (1983).

Additional information on the tailings consolidation modelling is presented by Brown et al. (1998). Post-closure consolidation seepage rates and settlements predicted by the consolidation model are discussed below.

POST-CLOSURE SEEPAGE

Seepage flows from the tailings facility include consolidation seepage from the tailings and steady state seepage through the tailings, perimeter embankment and foundation soils.

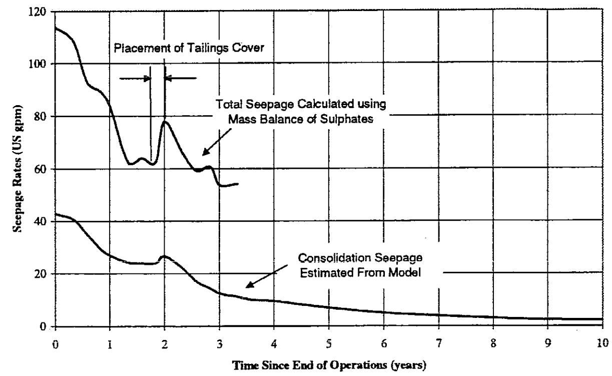
Fig. 2. Tailings pore pressure profiles from CPT data and consolidation model.



Consolidation analyses predicted that the majority of the tailings deposit would achieve a high degree of consolidation within about 5 years after the end of operations, particularly the beach tailings closest to the embankment. Estimates of tailings consolidation seepage rates indicated that they would reduce rapidly after closure, reaching minimal levels after approximately 5 to 10 years. The majority of the seepage is from the finer tailings located furthest from the embankment, which are estimated to be contributing over 60 percent of the total consolidation seepage from the tailings deposit. Predicted consolidation seepage rates from the tailings facility were about 40 US gpm at the end of operations, decreasing to less than 10 US gpm within 5 years. Estimated seepage rates for the first 10 years following the end of operations are shown in Figure 3. During and shortly after the period of cover construction in 1998 estimated seepage rates increased due to surcharge loading from the cover, accelerating tailings consolidation particularly in the finer, less consolidated tailings.

An independent analysis was also conducted to predict the magnitude and trend of total seepage flows from the tailings facility. This was carried out by examining sulphate concentrations recorded in seepage recovery wells and natural creeks downstream of the facility. Sulphate concentrations in the tailings pore water and background water were determined from historical water quality data for the site. Using these data and considering the mass balance of sulphates, the seepage emanating from the tailings facility was estimated. The estimated total seepage rates since the end of operations are included in Figure 3.

Fig. 3. Estimated seepage rates since the end of operations.



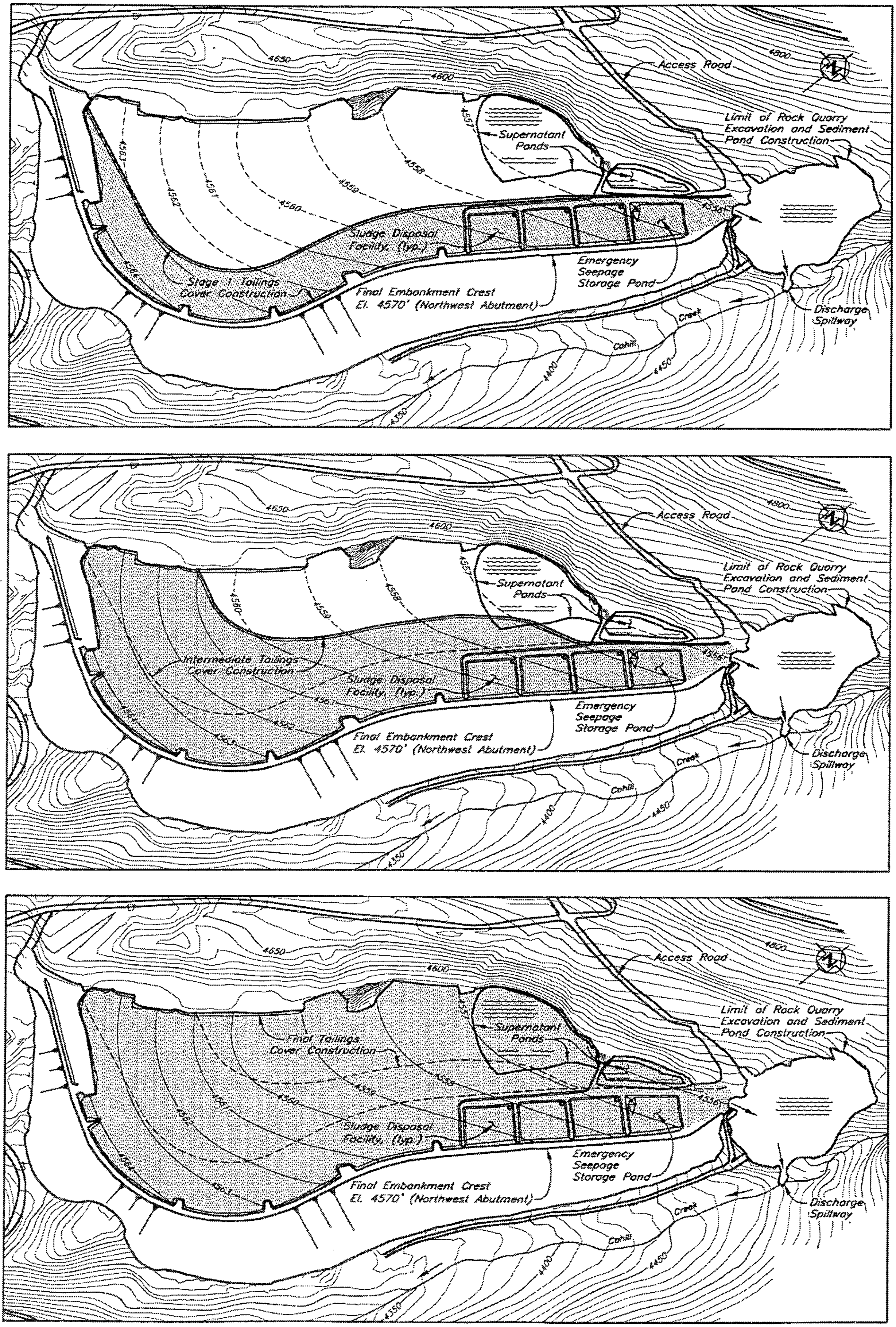
The total seepage rates inferred from the mass balance calculation are approximately two to three times the predicted consolidation seepage rates. This indicates that a significant proportion of the total seepage is due to steady state seepage flows. Both analyses show a trend of decreasing seepage flows over time. Similar to the consolidation analysis, the mass balance calculation clearly shows a short term increase in seepage as a result of the placement of the tailings cover in the late summer of 1998.

TAILINGS COVER SYSTEM

A cover on the tailings surface was required for reclamation to provide both short term and long term solutions to water management issues. An efficient tailings cover was designed to provide positive drainage of surface runoff from the facility, using materials that would support vegetation growth. A staged construction plan was implemented for the cover construction to enable a flexible construction strategy, as shown by Figure 4.

The effectiveness of using locally borrowed till materials for the top layer of the cover was confirmed by Homestake Canada Inc. from their results of test plots carried out on alternative cover arrangements. The cover design described in the approved reclamation plan is a 2 feet thick rock layer over the tailings, covered by a 2 feet thick till layer. The rock layer is intended to behave as a capillary break between the vegetation layer and the tailings materials to prevent metals uptake by the root system.

Fig. 4(a,b,c). Staged development of the tailings cover.



Development of Tailings Cover

The tailings cover was constructed in stages, as shown in Figure 4, with the initial portion constructed adjacent to the tailings embankment. Subsequent stages extended the cover further towards the natural slope on the west side of the facility. The progression of cover construction generally started above the coarser more consolidated beach tailings and moved towards the finer tailings, which were deposited further upstream. This provided additional time for the finer tailings to consolidate and dewater and to develop a more trafficable working surface. The development of tailings surface strength from consolidation and evaporative drying was expedited by the removal of the supernatant pond.

A series of diversion ditches and ponds were used in conjunction with pumping to control surface drainage during the interim stages of cover development. The primary objective of the diversion schemes was to minimize the amount of surface water requiring treatment.

The final tailings cover arrangement is shown in Figure 4c. It was designed with a gentle slope of approximately 0.5% at the south end and 0.25% near the spillway. The final surface directs surface runoff both in a westerly and northerly direction so that all flows are guided away from the embankment wall and towards the final spillway.

Construction

Construction materials for earthwork activity were borrowed locally. The rock was borrowed primarily from the existing quarry at the north end of the facility and from required excavation during spillway construction. Till was obtained from a previously developed borrow area.

The tailings cover was constructed by advancing a rockfill causeway from the northeast corner of the facility, along a line approximately 300 feet from the facility perimeter to the south west, as shown by Figure 5. The area between the causeway and the tailings facility perimeter was progressively covered with rockfill to an average depth of 2 feet. Once the rockfill cover was established in an area, a 2 feet thick layer of soil comprising till and loamy topsoil was placed on the rockfill. The condition of the tailings surface and pond area prior to any fill placement for cover construction can be seen on Figure 5.

The fill materials in the cover were nominally compacted by truck trafficking. The tailings surface was generally quite stable. However, on several occasions local instabilities occurred resulting in localised slumps of the advancing face of the rockfill. Also, when two advancing faces of rockfill met, in some cases, minor tailings flows

and sand boils were observed due to the generation of excess pore pressures. When these conditions were observed, the area was left for a brief period of time and the excess pore pressures rapidly dissipated, allowing construction to continue. Where soft tailings contaminated the rockfill cover, this material was removed to waste and replaced with clean rockfill. By the end of the 1998 construction season approximately 80% of the cover had been placed. A view of the revegetated tailings cover is shown in Figure 6.

Fig. 5. Start of tailings cover construction.

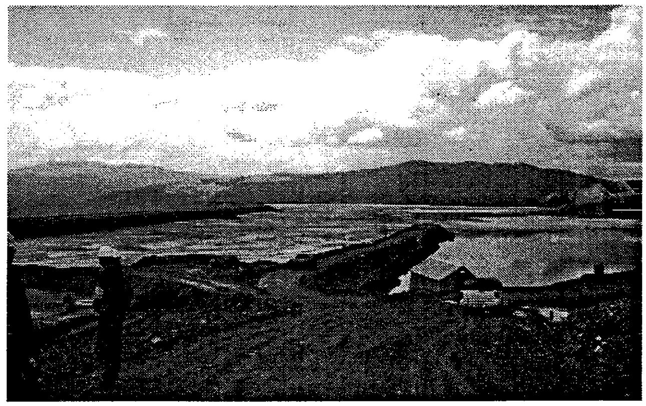


Fig. 6. Reclaimed tailings surface with vegetated cover.

Tailings Cover Settlement

The tailings consolidation model was used to predict the magnitude and rate of tailings cover settlement. This was required to ensure that positive drainage of surface runoff from the cover is maintained after settlements have occurred. Tailings settlements from the loading provided by the cover were predicted to be approximately 1 foot after the initial advance of cover, as shown in Figure 4a. For development of the final tailings cover, maximum settlements were predicted to be about 1 to 2 feet, with the largest settlement occurring in partially consolidated fine tailings. The majority of the tailings settlements were predicted to occur rapidly during and shortly after placement of the tailings cover. Thereafter, the rate of settlement reduced rapidly, with on-going settlements predicted to be negligible after about one year for the beach tailings and two years for the finer tailings.

Survey monuments installed on the completed tailings cover have been used to monitor settlements since the completion of cover construction in October 1998. Observed settlements of the tailings cover have been minor and less than the maximum predicted values. In the two years following cover construction, maximum settlements of approximately 0.5 feet were recorded, with most of this settlement occurring during the first year. These maximum settlements occurred where the cover is constructed on fine tailings in the centre of the facility. It is likely that much of the initial cover settlement occurred before the survey monuments were installed on the final cover. The observed settlements are not large enough to affect positive drainage from the cover.

WATER MANAGEMENT

Tailings solution management

The collection and treatment of tailings water and seepage have been on-going since closure. The mine utilizes a combined aerobic and anaerobic biological treatment system to remove residual cyanide and other contaminants such as thiocyanate, ammonia and nitrates. The treatment system is coupled with a High Density Sludge (HDS) process that removes residual metals. The end products of the system are treated water, that is monitored and released under permitted guidelines, and a high density sludge that is contained at the site in a sludge disposal facility. The full-scale treatment system commenced in October 1996 and the discharge of treated water started in February 1997. The design and treatment process is detailed by Given and Meyer (1998).

Seepage from the facility is collected at points downstream of the embankment. Seepage is pumped from the collection wells back into a lined holding pond constructed on the tailings surface adjacent to the sludge disposal facility. The pond is designed to temporarily store up to 1.5 million US gallons of untreated seepage water prior to pumping to the treatment plant. A small area of the tailings pond is all that remains at this time, and serves as a backup holding pond in the event that collected seepage cannot immediately be returned to the treatment facility and the designated holding pond has reached its capacity.

Sludge disposal facility

Provisions for the storage of sludge produced by the water treatment plant were made at the northeast corner of the tailings facility. Three HDPE lined storage ponds were constructed directly on the tailings surface, each incorporating the upstream face of the tailings embankment wall as an enclosure along one length. Each pond has a storage capacity of approximately 6000 cubic yards.

Sediment control and emergency spillway

An abandoned rock quarry, situated at the northeast end of the tailings facility was reshaped to serve as a sediment control facility for post-closure management of surface water draining from the reclaimed tailings surface. The discharge spillway from the sediment pond is excavated in both native rock and fill and directs the outflow to Cahill Creek.

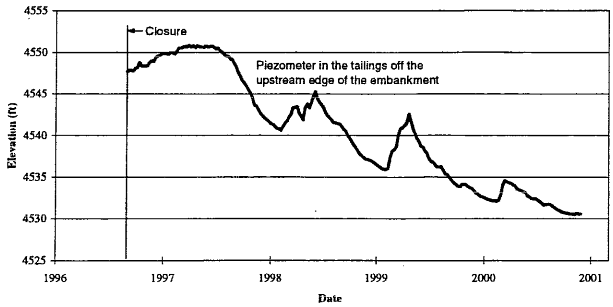
EMBANKMENT STABILITY

Instrumentation and monitoring data have been used to evaluate the post closure stability of the tailings facility. The stability of the tailings embankment has been reviewed annually since closure using the most recent pore pressure conditions and changes to the tailings facility as a result of removal of the free water pond and tailings cover construction.

At the end of operations in 1996, embankment stability analyses indicated that the minimum factor of safety was approximately 1.3 for a potential slip surface through the embankment and underlying foundation soils. For long term performance of the tailings embankment after closure a minimum factor of safety of 1.5 is required. By the end of 1997, the size of the free water pond had reduced significantly as water was conveyed to the water treatment plant. This resulted in the development of larger exposed tailings beaches and a corresponding decrease in piezometric levels within the tailings embankment. Approximately one year after the end of operations the minimum factor of safety had increased to 1.41. The factor of safety increased to 1.46 by the end of 1998, after construction of the tailings cover. The required factor of safety of 1.5 was achieved soon after this time. Piezometric data indicates that pore water pressures continue to drop, as shown by Figure 7. Periodic peaks in the piezometric elevations are attributed to seasonal increases in the pond volume as a result of freshet.

The analyses indicate that the stability of the embankment has improved since closure and has achieved the minimum required factor of safety of 1.5 for long term stability within approximately two years after the end of operations. The overall embankment stability will continue to improve with time, as piezometric levels decrease in the tailings deposit and embankment.

Fig. 7. Typical piezometric record in tailings upstream of embankment.



SUMMARY

Reclamation activities at the Nickel Plate Mine tailings facility since the end of operations in 1996 have included tailings cover construction designed to ensure long-term management of surface water runoff using materials that would support vegetation, post-closure seepage collection and surface water management comprising a sediment control pond and emergency spillway.

Several geotechnical studies were carried out for the reclamation activities at the tailings facility. These included development of a tailings consolidation model, post-closure seepage estimates, tailings cover settlement predictions and on-going assessment of embankment stability. Predictions of the progress of consolidation of the tailings deposit and estimates of seepage rates provide an estimate of the time frame required for on-going water treatment at the site. Estimated and observed settlements of the tailings cover confirmed that positive drainage of surface runoff is maintained. Instrumentation and monitoring data were used to evaluate the post closure stability of the tailings embankment and demonstrate that its stability has improved with the removal of the free water pond and construction of the tailings cover.

ACKNOWLEDGEMENTS

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