Cover and final landform design for the B-zone waste rock pile at Rabbit Lake Mine

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Abstract. A detailed study was undertaken to evaluate various cover system and final landform designs for the B-zone waste rock pile at Rabbit Lake Mine in Canada. Several tasks were completed including physical and hydraulic characterization of the waste and potential cover materials and numerical modelling to examine erosion and slope stability. Soil-atmosphere numeric simulations were conducted to predict net infiltration and oxygen ingress rates through several cover system alternatives. A seepage numerical modelling programme was completed to predict current and future seepage rates from the base of the pile for alternate cover system designs. Several final landform alternatives were developed for the pile along with a preliminary design for a surface water management system. The potential impact of various physical, chemical, and biological processes on the sustainable performance of the final landform was also considered. This paper provides an overview of the investigations completed towards the development of a cover system and final landform design for the B-zone waste rock pile.

Introduction

Rabbit Lake Mine, owned and operated by Cameco Corporation, began operation in 1975, and is the longest operating uranium production facility in Saskatchewan, Canada. The operation is located 700 km north of Saskatoon (Fig. 1). Historic and current operations at this site include four open pits, one underground mine, several mine waste storage facilities, and a mill.

Cameco is developing a decommissioning plan for the B-zone area at Rabbit Lake Mine, which includes a flooded open pit, a waste rock pile, and an ore stor-

age pad. Proper closure of the B-zone waste rock pile (BZWRP) will be important to minimize the impacts of seepage emanating from the stockpile on the long-term water quality of the flooded open pit and other nearby surface water receptors. The BZWRP will be decommissioned in-place meaning that an engineered cover system is required for closure.

A multi-phase study is underway to determine the optimum landform and cover system design for the BZWRP. Several field investigations have been completed to evaluate the geochemical, physical and hydraulic characteristics of the waste rock and locally available cover materials, as well as the hydrogeological setting of the stockpile. Various numerical modelling programmes have been initiated to predict net infiltration, oxygen ingress, and erosion rates for various cover system

Fig. 1.   Map of northern Saskatchewan showing the location of Rabbit Lake Mine.

Case studies: active and abandoned Uranium mines

alternatives, source terms for contaminants of concern in the stockpile, and environmental loadings to the receiving environment. All of these studies are linked, with the ultimate goal being to develop cover performance criteria based on minimizing impacts to surface water and groundwater receptors. Another key aspect for closure of the BZWRP is design of the final landform; poor surface water management and landform instability are common factors leading to failure of cover systems around the world (MEND 2004).

The key investigations completed towards developing a cover system and final landform design for the BZWRP are reviewed in this paper.

Background

Rabbit Lake Mine is surrounded by lakes and wetlands as well as low relief glaciated landforms comprised mainly of sand and gravel. The climate in the area is semi-humid, sub-arctic, characterized by generally wetter conditions in the fall, winter and spring, and drier conditions during the hot summer months. The mean annual precipitation and potential evaporation for the site is approximately 540 mm and 400 mm, respectively. About 33% of the annual precipitation occurs as snow.

The current BZWRP landform is between 18 and 30 m high with 37° side-slopes, covers a surface area of approximately 22 ha, and has a volume of about $4.6 \times 10^6 \, m^3$. The water quality of seepage emanating from the pile is characterized by elevated levels of several metals and radionuclides, notably As, Ni, Mn, ^{226}Ra and U, and a pH typically between 3.3 and 5.5. Metal leaching, as opposed to acid rock drainage, is the primary catalyst for the production of contaminated seepage. Therefore, the primary function of the pile cover system is to reduce the net infiltration of meteoric water, as opposed to limiting the ingress of atmospheric oxygen. Limiting surface erosion and providing a medium for sustainable vegetation are also important functions.

Mine waste covers can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming organic materials (MEND 2004). Factors that control the economic and technical feasibility of a particular cover system include site climate conditions, availability of cover material(s) and distance to borrow source(s), cover and waste material properties and conditions, and vegetation conditions. Cover material(s) and therefore cover performance will evolve over time due to the impacts of site-specific physical, chemical, and biological processes, which should be considered in the design process (INAP 2003). Cover system alternatives evaluated for the BZWRP include varying thicknesses of non-compacted local soils and/or compacted waste rock on the stockpile surface.

Waste rock and cover material characteristics

Field sampling / testing and laboratory testing was conducted to determine the physical and hydraulic characteristics of the near surface material in the BZWRP and potential cover materials at the site. Field testing examined the *in situ* moisture content, density and permeability of the materials. The laboratory programme included tests for particle size distribution (PSD), specific gravity, compaction characteristics, saturated hydraulic conductivity (K_{sat}), and moisture retention characteristics. Fig. 2 shows typical PSD curves for the near surface waste rock and sandy-gravel till borrow (cover) material.

The near surface material across the top of the BZWRP is relatively heterogeneous, indicative of weathered sandstone and basement rock materials. Geochemical studies conducted by Cameco suggest that, at a minimum, a thin till cover will be required for the BZWRP to prevent post-closure contamination of surface water in the vicinity of the waste rock pile. The matrix of the surface material is relatively well-graded from cobble down to silt and clay size particles with a median diameter on a mass basis of approximately 4 mm. The K_{sat} of the waste rock material ranges from 5.0×10^{-5} cm/s for a lower density condition to 6.0×10^{-6} cm/s for a higher density condition.

An ideal material for a "simple" cover system, in terms of moisture store-and-release and long-term stability, has a well-graded PSD (i.e. an equal representation by mass for all particle sizes). Based on the results of the PSD test programme and field observations, the most promising borrow source for cover material is a drumlin located six kilometers from the BZWRP (material sample TP14-1). The matrix of the till borrow material is relatively well-graded from cobble down to silt and clay size particles with a median diameter on a mass basis of approximately 0.4 mm. The K_{sat} of the till borrow material ranges from 6.0×10^{-3} cm/s for a lower density condition to 3.0×10^{-5} cm/s for a higher density condition.
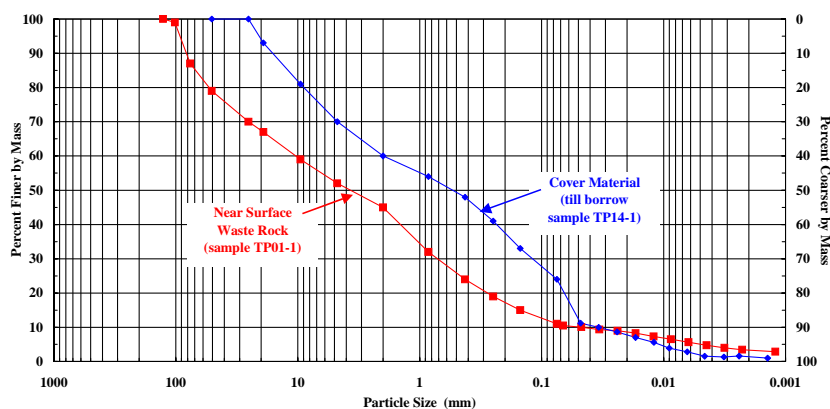

Fig. 2.   Typical PSD curves for the near surface waste rock and till cover materials.

Surface erosion numeric analyses

Erosion numerical modelling was completed to estimate the distribution and magnitude of erosion from various cover surfaces and final landform alternatives for the BZWRP under historical precipitation conditions and significant storm events. The Water Erosion Prediction Project (WEPP) model (Flanagan et al. 1995), a two-dimensional, process-based computer program, was used in this study. WEPP models erosion from interrill areas, and detachment and transport from overland flow and channel flow in rill areas. The following three material and surface types were examined in the modelling programme: 1) waste rock with a bare surface, 2) till with a bare surface, and 3) till with a "poor" stand of grass vegetation. The modelling programme included 3H:1V and 4H:1V linear slope configurations and one concave slope, featuring a steep upper segment (2H:1V) and a gentler lower segment (5H:1V).

   The erosion modelling programme predicted the bare till surface is more erodible than the bare waste rock surface under historical precipitation conditions, but less erodible under significant storm events. The addition of a "poor" stand of grass vegetation to the till surface greatly reduces the predicted erosion to rates well below the simulated bare surfaces (Fig. 3). Minimal difference in the erosion rate was predicted between each of the simulated side-slope configurations for a given climate year or storm event. This is attributed to the relatively small difference in the surface gradients between all three alternatives, as well as the relatively small height of the pile and corresponding short slope lengths. A sensitivity analysis showed that the climate year (i.e. precipitation) has the largest influence on the predicted erosion rates.
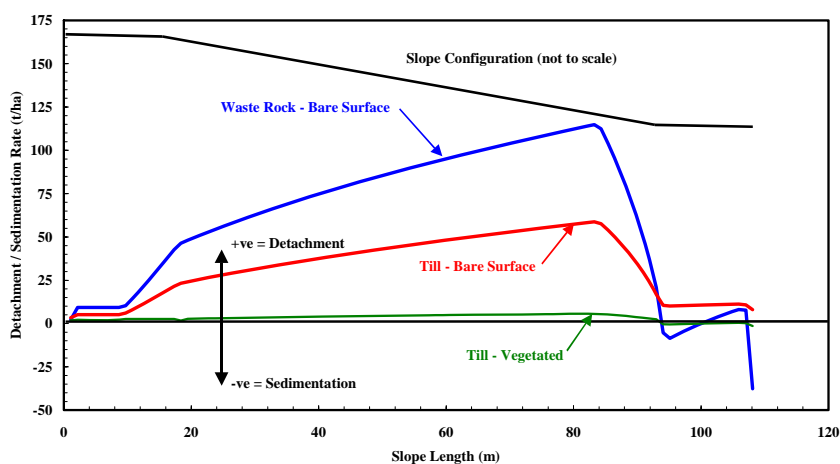

Fig. 3.   Predicted soil loss rate by position on the 4H:1V linear slope for the waste rock and till materials during the 100-year, 24-hour storm event.

Soil-atmosphere cover design numerical modelling

Soil-atmosphere modelling was completed with the two-dimensional finite element model VADOSE/W (Geo-Slope International Ltd. 2004a), to evaluate the performance of alternate cover system designs for the top (or plateau) and various re-contoured side-slope configurations for the BZWRP. A key feature of VADOSE/W is the ability of the model to predict actual evaporation and transpiration based on potential evaporation and predicted soil suction, as opposed to the user being required to input these surface flux boundary conditions. Predicted net infiltration rates were used as the primary indicator of cover system performance; however, oxygen ingress to the underlying waste material was also evaluated. Each simulation was run for 365 days, with the simulation period beginning November 1st and ending October 31st of the following year. This simulation period best suits a cold northern climate by allowing the formation of snowpack during the winter season, occurrence of snow melt in the spring, and extending through the frost-free period at the site. The entire snowpack was applied for each simulation assuming no drifting or sublimation of the snowpack. Runoff water produced from the spring freshet and storm events for simulations involving a cover system was removed from the model, which is deemed to be representative of the 2-3% slope planned for the top of the final BZWRP landform. The bare waste rock simulations considered two options for spring freshet and storm runoff: restricting flow causing a pool of water to be formed on the surface and allowing runoff water to drain. Vegetated-surface simulations assumed a "poor" grass vegetation cover, which has a leaf area index of 1.0 during the growing season.

Table 1 summarizes the key predictions from VADOSE/W for the bare waste rock surface condition and four cover system alternatives for the top of the pile. The net percolation prediction for the bare surface condition is indicative of the waste rock matrix (i.e. this does not account for large macropores or "drains" in the pile that would act as preferential flow paths for infiltration during significant storm events). Net percolation and oxygen ingress rates decrease as the quality of

Table 1. Net percolation and oxygen ingress model predictions for the bare waste rock surface condition and four cover system alternatives for the top of the pile.

Cover System Alternative	Net Perc. (mm)	Net Perc. (% of AP*)	O_2 Ingress (mol/m²)
Bare waste rock (WR) – no runoff	200	37.3	-
Bare WR – runoff	150	28.1	-
0.3 m till cover	85	15.9	208
1.0 m till cover	55	10.3	39
Compacted WR with 0.5 m till cover	54	10.1	35
Compacted WR with 1.0 m till cover	34	6.6	14

* AP = annual precipitation

the cover system increases, as expected. However, there is not a significant difference between the predicted net percolation through the 1.0 m till cover system and that predicted through the 0.2 m compacted waste rock with 1.0 m till cover system. This is attributed to the relatively high K_{sat} of the non-compacted till and *in situ* waste rock material, and the assumption that field compaction of the near surface waste rock will only reduce its permeability by one order of magnitude. The highest quality cover system evaluated for the BZWRP is expected to reduce the net percolation of meteoric water to the underlying waste material by 83% compared to the current or bare waste rock surface condition (no runoff).

A sensitivity analysis found the presence of vegetation and the K_{sat} of the compacted waste rock have the largest influence on the predicted net percolation through the cover systems. Although not shown, the compacted waste rock with 1.0 m till cover system is predicted to have the best performance on the re-contoured stockpile side-slopes, followed by the thick till cover system and the compacted waste rock with 0.5 m till cover system.

Waste rock pile seepage numerical modelling

Numerical seepage modelling was completed for this study to evaluate current and post-closure seepage rates from the base and toe of the BZWRP. SEEP/W (Geo-Slope International Ltd. 2004b), a two-dimensional seepage model, was used for this purpose. A representative two-dimensional cross-section of the pile was modelled to examine groundwater flow immediately surrounding the BZWRP, as well as the mounding characteristics of groundwater within the pile itself. The material properties within the model were estimated by calibrating predicted heads to measured piezometric heads in the BZWRP and immediate surrounding area.

The simulation of future conditions found that there is a significant reduction in the elevation of the phreatic surface, as well as seepage from the base and toe of the BZWRP for the first 10 to 20 years following placement of an engineered cover system. These values continue to slowly decrease with time until they tend to approach an equilibrium condition 60 to 65 years following closure. Long-term equilibrium total flux rates from the waste rock pile for a "higher" quality cover were approximately one order of magnitude less as compared to that predicted for a "moderate" quality cover system.

Evaluation of BZWRP final landform alternatives

The following guidelines were used to develop final landform alternatives for the BZWRP:
- Landform / surface materials must be able to withstand flow velocities associated with the 1:100 year, 24-hour design storm event (88 mm);

- Results of erosion numeric simulations and slope stability analysis should be considered in developing the final landform;
- Minimize expansion of the current pile footprint and as much as possible, remain inside the footprint defined by the perimeter collection ditch;
- Minimize picking up waste rock (i.e. more economical to re-contour with a large dozer provided the material pushing distances are not significant);
- Minimize ponding of water on the landform (i.e. promote runoff);
- Balance the cut/fill earthmoving material volumes; and
- Incorporate features of local glaciated landforms into the final pile landform design where possible for aesthetic purposes.

The software packages Eagle Point 2001 and AutoCAD 2004 were used to create a digital terrain model (DTM) of the existing landform, and then create several new landform designs based on the existing DTM and specified design constraints and criteria. The model selected for estimating the peak flow and total runoff volume from the design storm event is the one described by the United States Department of Agriculture Technical Release 55 (TR-55) – Urban Hydrology for Small Watersheds (USDA 1986).

Preferred cover system and final landform design

The preferred cover system design for the BZWRP is a 0.2 m thick layer of compacted *in situ* waste rock overlain by 1.0 m of non-compacted sandy till. This cover system is predicted to perform the best on the plateau and side-slopes of the final BZWRP landform in terms of reducing the net percolation of meteoric water and remaining stable against erosive forces. The preferred cover system design is based primarily on the available borrow materials at the site and the results of surface erosion and soil-atmosphere cover design numeric simulations, but also takes into consideration the potential impacts of various processes on sustainable performance as discussed below.

Based on the landform criteria described above and the results of numeric simulations of surface erosion and analyses of slope stability, the preferred final landform design for the BZWRP is shown in Fig. 4.

The landform consists of:

- Two catchments on the landform each approximately 4.4 ha that are "dished" to channel runoff water to a central light armoured drainage channel and subsequently to the north or south heavily armoured slope drainage channels (plateau slope ranges between 2 and 5%);
- Linear 20% (5H:1V) slopes on both the north and south slope of the landform to manage runoff volumes / flow velocities for the design storm event using 75 mm median stone size for riprap armouring; and
- Concave east and west slopes comprised of a 50% (2H:1V) sloped segment for the upper quarter and a 20% (5H:1V) sloped segment for the lower three-quarters of the slope.

Addressing potential impacts on sustainable performance

INAP (2003) conducted an examination of the processes shown in Fig. 5, and discovered that their effects could be related to the change in three key cover performance properties; namely, the K_{sat} and moisture retention characteristics of the cover materials and the physical integrity of the cover system. The K_{sat} and moisture retention curve are key hydraulic properties of a cover system layer. A sensitivity analysis should be conducted as part of the soil-atmosphere modelling programme to examine the potential impact on cover performance due to changes in the material hydraulic properties. Consideration of the effects of long-term changes in biological and chemical processes on performance has been generally dealt with in a qualitative manner, if addressed at all (MEND 2004). The key processes that could impact on sustainable performance of the BZWRP cover system and final landform are erosion, freeze-thaw and wet-dry cycling, root penetration, and bioturbation.
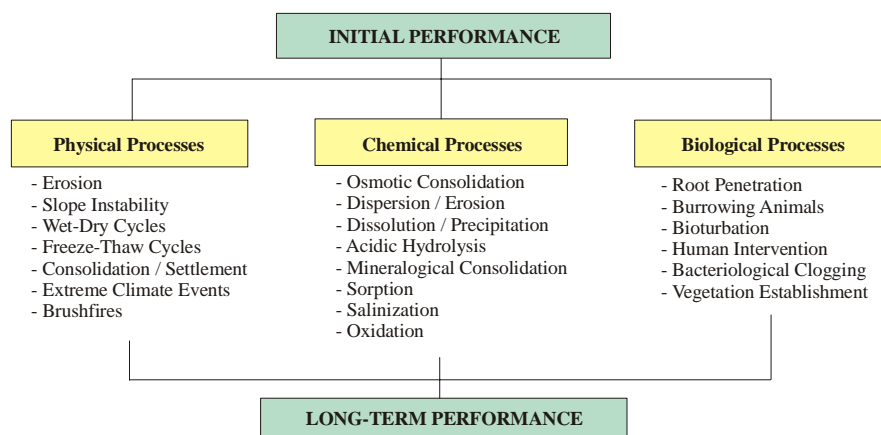

Fig. 5.   Processes that could impact the sustainable performance of soil cover systems (from INAP 2003).

The design of the preferred final landform directs runoff water from the plateau to heavily armoured drainage channels sloping to the north and south ends of the pile. This reduces the amount of runoff water reaching the concave east and west side-slopes resulting in decreased overall erosion for the landform. The proposed final landform design reduces the average slope gradient and slope length for runoff waters as compared to a conventional "domed" landform design.

It is proposed that the compacted waste rock layer be covered with 1.0 m of non-compacted till for protection and the establishment of vegetation. The 1.0 m thick layer of non-compacted till is required to ensure long-term performance of the cover system as a whole, because of the inevitable presence of woody species. The coniferous and deciduous woody species native to the site are prone to lateral and shallow root development, as they anchor themselves to the surface. The 1.0 m of non-compacted till does not guarantee that woody species roots will not develop in the compacted layer, but it is likely that more than 85% of the woody species root development would be contained in the upper non-compacted layer.

The proposed cover system design for the BZWRP comprises a layer of compacted waste rock material, which has little to no clay content and thus should possess resistance to cracking during drying. The compacted waste rock layer will undergo freeze-thaw cycles. There has been minimal research on the effects of freeze-thaw cycles on compacted granular material. However, it is anticipated that the change in material properties will be minimal. In addition, there is no supply of water (i.e. a saturated underlying material) to support large-scale frost heave of the compacted waste rock material, and in general, alterations in the void ratio due to freezing.

Concluding remarks

A detailed study has been completed to evaluate several cover system and final landform alternatives for the B-zone waste rock pile at Rabbit Lake Mine. The ultimate cover system and final landform design have not been finalized yet because other studies are in progress that are evaluating potential impacts on the receiving environment based on the predicted performance of varying cover and landform designs.

It is common for numerical modelling to be dismissed as being "useless" due to a lack of predictive accuracy. However, the key advantage to the numerical modelling results obtained for this study is the ability to enhance judgement. Hence, rather than a focus on the absolute results predicted, it is recommended that the modelling results be viewed as a tool to understand key processes and characteristics that will influence performance of the BZWRP cover system, and develop engineering decisions based on this understanding.

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