Design and construction of the backfilled pit cover system at Whistle Mine, Canada: a case study

Brian Ayres[1], Lisa Lanteigne[2] and Mike O'Kane[3]

[1]O'Kane Consultants Inc., 134 – 335 Packham Ave., Saskatoon, SK, S7N 4S1, Canada
[2]Inco Limited, Copper Cliff, ON, P0M 1N0, Canada
[3]O'Kane Consultants Inc., 1740 – 246 Stewart Green SW, Calgary, AB, T3H 3C8, Canada

ABSTRACT: Inco Limited, Ontario Division is currently in the process of decommissioning the Whistle Mine site located near Sudbury, Ontario, Canada. The most significant component of site decommissioning involved relocating approximately 6.4 million tonnes of acid-generating waste rock to the open pit from two adjacent stockpiles. An engineered cover system was designed for the backfilled pit to reduce the long-term production of acid rock drainage. Geochemical modelling was conducted to assess the effectiveness of various cover options on the long-term water quality of the backfilled pit. Results obtained from performance monitoring of cover system field trials at the site and estimated full-scale construction costs were used to select an appropriate material for the cover system barrier layer. The two-dimensional soil-atmosphere model VADOSE/W was used to develop a calibrated model of covered waste rock based on field data obtained from the cover trials, which was subsequently used to predict net percolation and oxygen ingress through various cover system alternatives for site-specific climate conditions. Erosion and landform evolution numerical modelling was completed to assist in designing the runoff management system and final landform for the pit cover system. The potential impact of various physical, chemical and biological processes on the sustainable performance of the pit cover system was also considered in the design process. This paper provides an overview of the design and construction of the backfilled pit cover system.

1 INTRODUCTION

Inco Limited, Ontario Division (Inco) is currently in the process of decommissioning the Whistle Mine site located approximately 30 km north of Sudbury, Ontario, Canada (Figure 1). The most significant component of site decommissioning involved relocating approximately 6.4 million tonnes of waste rock to the open pit from two adjacent stockpiles. The Whistle Mine waste rock is composed of approximately 80% mafic norite, which has an average sulphide content of 3% (MEND, 1997). Lime was added to the waste rock during the pit backfilling operation to minimize future generation of acid rock drainage (ARD). An engineered cover system is required for the backfilled pit to further reduce the production of ARD by minimizing the entry of atmospheric oxygen and meteoric water to the underlying waste material. This paper documents the design and construction of the Whistle Mine backfilled pit cover system.

2 BACKGROUND

2.1 *Mine history / site description*

The Whistle Mine site is part of the Post Creek watershed, an area of approximately 5,400 ha, which drains into Lake Wanapitei, only 3 km east of the mine. The area immediately surrounding the mine site is undeveloped wilderness. Bedrock outcrops are frequent and typically form hills that rise up to 50 m above the surrounding areas. A thin, discontinuous blanket of glacial till covers the bedrock. The climate in this area is semi-humid,

Figure 1. Location of Whistle Mine in Ontario, Canada.

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 region is approximately 900 mm and 520 mm, respectively. Approximately 30% of the annual precipitation occurs as snow.

The Whistle Mine nickel / copper orebody, originally discovered in 1897, was developed as an open pit mine in 1988. Mining and the production of waste rock at Whistle Mine occurred between 1988-1991 and 1994-1998. All waste rock stockpiled on surface was relocated to the open pit between July 2000 and December 2001. The backfilled pit surface has an area of approximately 9.7 ha and an average slope of 13% from the north to south perimeter. Surrounding bedrock impacted from the storage of waste rock on surface was cleaned between May and December 2002. Some preparatory earthwork for construction of the pit cover system was completed in the fall of 2003, which included blasting rock outcrops and remnants of the former pit crest along the western and northern perimeter of the pit. The collection and subsequent treatment of contaminated seepage water emanating from the former waste rock storage areas and backfilled pit is on-going.

2.2 *Pit cover design objectives and approach*

A “water” cover is the preferred technology for inhibiting the oxidation of sulphide minerals; the water acts as a barrier to the diffusion of atmospheric oxygen to the submerged sulphides (MEND, 2001). Although the climate at Whistle Mine has a moisture surplus on an annual basis, a water cover is not feasible for this site because of the absence of a pit lake and the relatively steep slope of the backfilled pit surface. Therefore, a “dry” cover system is required to minimize future generation of ARD at the Whistle Mine backfilled pit.

Geochemical modelling was conducted to assess the effectiveness of various cover options on the long-term water quality of the backfilled pit (SENES, 2003). Based on the geochemical modelling predictions, the design objectives for the backfilled pit cover system are to:

1) Reduce the ingress of atmospheric oxygen to the underlying waste material to the minimum acceptable level as determined by geochemical modelling;
2) Reduce the entry of meteoric water to the underlying waste material (i.e. net percolation) to less than 5% of the annual precipitation at the site; and
3) Provide a medium for establishing a sustainable vegetation cover that is consistent with the current and final land use of the area.

The first two design objectives can be achieved by incorporating a layer of fine-textured material in the cover system (MEND, 2004). The objective is to utilize the capillary barrier concept to assist with maintaining near saturation within the fine-textured layer under all anticipated climatic conditions, which in turn limits the ingress of oxygen due to low oxygen diffusion conditions. In addition, the lower hydraulic conductivity of the fine-textured soil layer (usually compacted), combined with the lower capillary barrier, provides a control on net percolation to the underlying waste material. In short, the backfilled pit cover system requires a fine-textured soil layer and hereafter will be referred to as the “barrier layer”.

Often in the design and construction of a barrier layer / growth medium dry cover system the focus of the design is on the barrier layer. While the importance of the barrier should not be discounted, neither should the importance of the overlying growth medium. The growth medium layer serves as protection against physical processes, such as wet-dry and freeze-thaw cycling, as well as various chemical and biological processes. An inadequate growth medium layer will not properly protect the barrier layer, leading to possible changes in its performance. In addition, the growth medium must possess sufficient available water holding capacity to ensure a sustainable vegetation cover.

In general, the approach used to design the Whistle Mine backfilled pit cover system followed the approach outlined in O’Kane and Wels (2003). More specifically, the following tasks were completed for this design project:

- Determination of the preferred material for the barrier layer through evaluation of field performance monitoring data obtained from cover system trials and review of estimated costs for full-scale construction of various alternatives;
- Laboratory characterization of the barrier layer and growth medium materials;
- Soil-atmosphere numerical modelling for determination of the minimum cover layer thicknesses based on predictions of net percolation and oxygen ingress;
- Slope stability analyses of the preferred pit cover system;
- Landform evolution and erosion numerical modelling for the development of a sustainable pit cover runoff management system design;
- Design of a performance monitoring programme for the pit cover system; and
- Consideration of the potential impacts of various physical, chemical and biological processes on sustainable performance of the preferred cover system design.

An overview of the methodology used and the results obtained from completion of the above tasks are provided below, with exception for the slope stability analysis.

3 DETERMINATION OF THE PREFERRED BARRIER LAYER MATERIAL

Cover system trials were constructed at Whistle Mine in 2000 to obtain site-specific field information on the construction feasibility and potential performance of alternate dry cover systems, prior to finalizing the design of the full-scale cover system. Three experimental cover systems were constructed over acid-generating waste rock, with each cover having a different barrier layer overlain by a protective layer of non-compacted material (Figure 2). The experimental cover systems were constructed on a waste rock platform with a 20% slope. Further details on the construction of the cover trials can be found in Ayres et al. (2002).

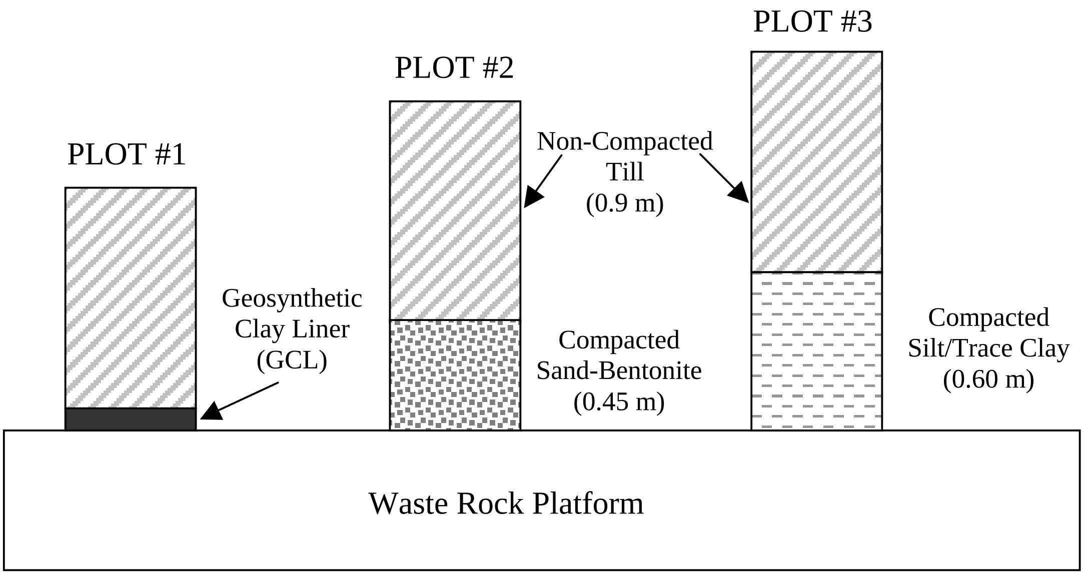

Figure 2. Schematic diagram of the Whistle Mine cover system field trials (from Ayres et al., 2002).

A state-of-the-art monitoring system was installed to evaluate field performance of the cover trials throughout all seasons of the year. This system included continuous monitoring of climatic parameters, gaseous oxygen / carbon dioxide concentrations and moisture / temperature conditions within the cover and waste materials. The quantity of net percolation through each cover trial was also measured with large-scale lysimeters. An interpretation of the preliminary field performance of the experimental cover systems is presented and discussed in Adu-Wusu et al. (2002).

Detailed cost estimates were developed to construct each of the field trial cover systems on a full-scale basis. The construction cost estimate for the GCL barrier, compacted silt/trace clay barrier, and compacted sand-bentonite barrier cover system was $3.3M CDN, $3.5M CDN, and $5.3M CDN, respectively. Each of these barrier layers was underlain with a geotextile and overlain by 0.9 m of granular material (pit-run). Although the GCL barrier cover system was estimated to cost less to construct than the compacted silt/trace clay barrier cover system, soil-atmosphere numeric simulations demonstrated that the latter cover design would provide a much better barrier to the ingress of atmospheric oxygen over the long term. Based on estimated construction costs and the need for a good oxygen barrier, a source of local clay was chosen as the material for the pit cover barrier layer.

Inco established two large clay stockpiles as a result of historic earthworks at their Copper Cliff operations. Samples of this material were characterized in the laboratory for particle size distribution (PSD), Atterberg limits, standard Proctor compaction, mineralogical composition, and saturated hydraulic conductivity. Figure 3 shows that the Copper Cliff material has a nominal clay content (material $<2\ \mu m$) of 24%; the PSD of the pit-run (growth medium) material is also shown for comparison purposes. The Atterberg limits revealed the Copper Cliff material is inorganic clay with low to medium plasticity, with a nominal plasticity index of 10%. An XRD analysis determined the Copper Cliff clay is comprised mainly of quartz, feldspar, chlorite, and kaolinite, with minor amounts of vermiculite and illite. Triaxial permeability testing determined the Copper Cliff material has a saturated hydraulic conductivity of about 5×10^{-8} cm/s. In summary, the Copper Cliff clay has suitable characteristics for use in the construction of the pit cover barrier layer.

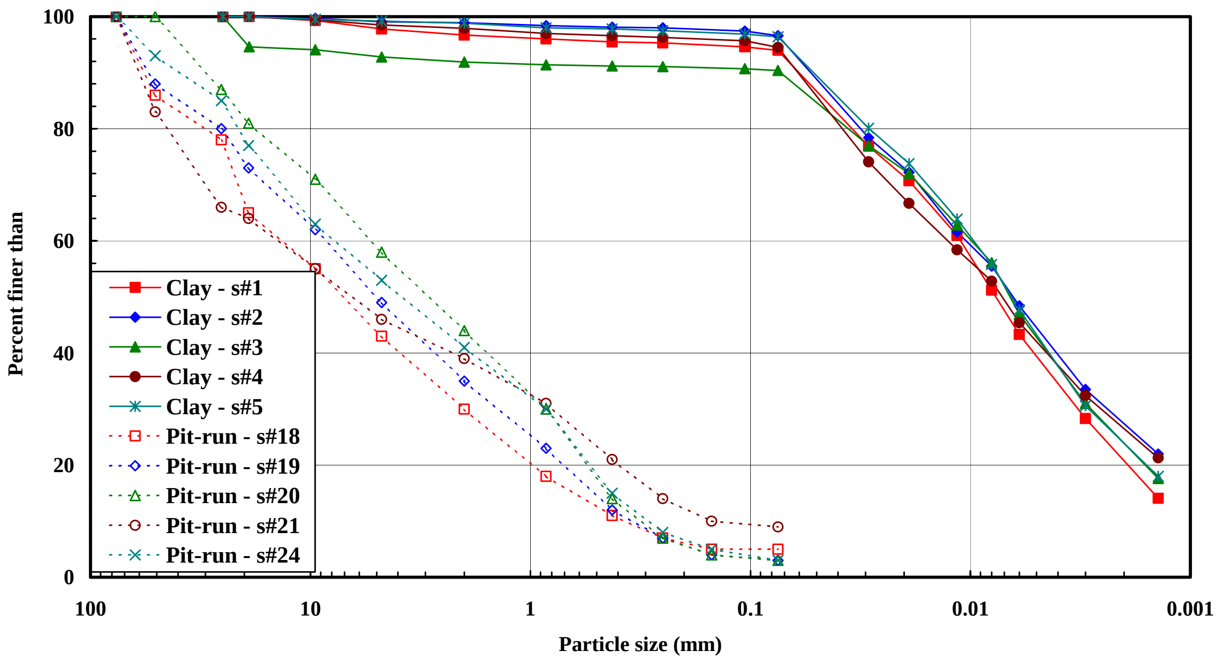

Figure 3. Particle size distribution of the Copper Cliff clay and granular growth medium material (pit-run).

4 COVER DESIGN SOIL-ATMOSPHERE MODELLING

Cover design soil-atmosphere modelling was completed with the two-dimensional (2D) finite element model VADOSE/W (Geo-Slope International Ltd., 2002). 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. The results of field response (calibration) and cover design (preliminary and detailed) modelling are presented and discussed below.

4.1 *Field response modelling*

Field response simulations were completed with VADOSE/W to develop a calibrated soil-atmosphere numerical model based on data collected from the Whistle Mine field trial cover systems. The focus of this modelling exercise was attempting to match field responses (i.e. changes in heat and moisture conditions) measured at the silt/trace clay barrier cover trial. The initial simulation involved the input of one set of material properties for the barrier layer and growth medium layer, which were estimated or measured in the laboratory. Climate conditions measured at the trial cover site were entered into the model and after running the model, the predicted heat and moisture conditions were compared to measured field conditions for each cover layer. Additional simulations were completed until a reasonably good match was obtained between predicted and measured field responses; this was accomplished by "tweaking" model inputs and incorporating additional pseudo-layers in the model as required.

Figure 4 shows a comparison of the predicted volume of water stored within the growth medium, barrier layer and total cover profile, versus measured values for the silt/trace clay barrier trial cover system. The comparison indicates that the model adequately simulated the moisture field responses during the simulation period. The key is that the trends in moisture storage changes measured in the field and predicted by the model for the same climate

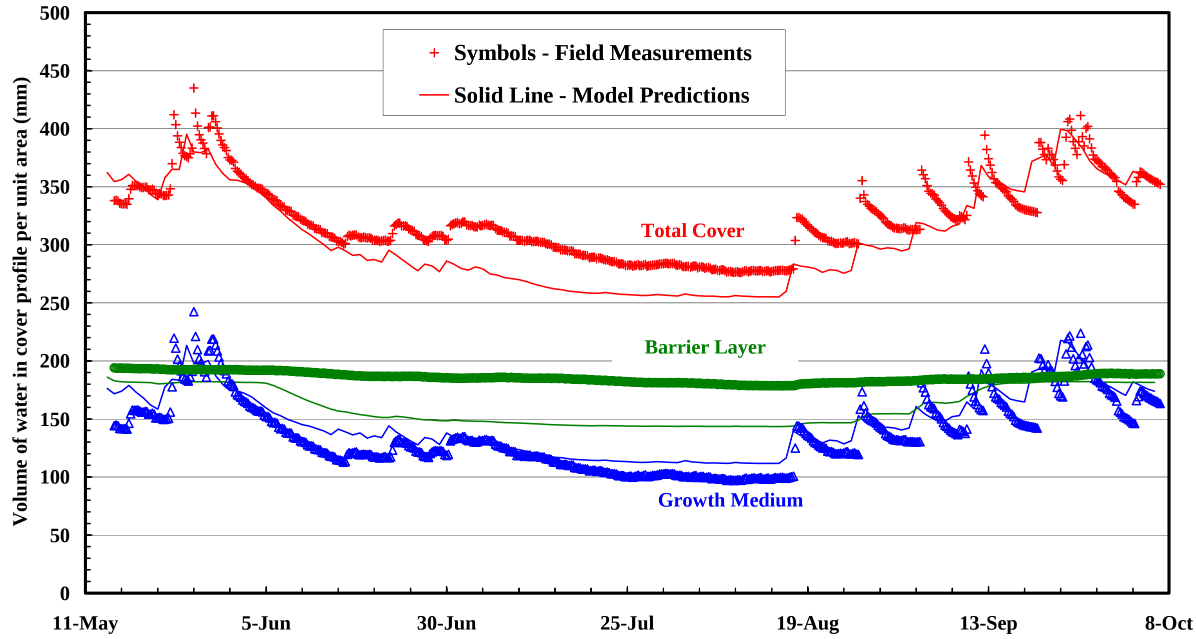

Figure 4. Cumulative water volume per unit area predicted and measured within each layer of the silt/trace clay barrier cover trial during unfrozen conditions in 2001 (from OKC, 2004).

conditions are similar. The largest divergence between the field measurements and simulated results occurred within the barrier layer during the summer; this is attributed to the model simulating a higher water consumption rate for vegetation than actually occurred in the field.

The material properties generated from the cover trial field data and the calibrated models provided the opportunity to significantly increase the confidence in the soil-atmosphere modelling predictions. This is particularly true for the growth medium layer, which is subjected to numerous wet-dry and freeze-thaw cycles that cannot be accounted for during laboratory testing.

4.2 *Preliminary cover design modelling*

Preliminary cover design modelling consisted of transient one-dimensional (1D) VADOSE/W simulations of varying barrier layer (compacted clay) and growth medium layer (non-compacted pit-run) thicknesses. The objective of this modelling exercise was to develop a preliminary cover system design with a barrier layer that maintained a degree of saturation above 85% after three consecutive dry year simulations. MEND (2004) show that an effective barrier to oxygen diffusion will result if the degree of saturation of a soil layer can be maintained greater than 85 to 90%. A “poor” vegetation cover was assumed for all simulations, and the total precipitation for the simulation period is 244 mm.

Results from preliminary soil-atmosphere modelling indicated that a 0.9 m thick growth medium layer for the Whistle Mine site is not thick enough to prevent the barrier layer from de-saturating to unacceptable levels. Therefore, the preferred cover system design alternative, from an oxygen ingress perspective, is a 0.45 m thick compacted clay barrier layer and a 1.2 m thick growth medium layer. Detailed soil-atmosphere numerical simulations were required to confirm this cover system design alternative is suitable for the entire sloping surface of the backfilled pit, from both an oxygen ingress and net percolation perspective.

4.3 *Detailed cover design modelling*

Detailed cover design modelling consisted of transient 2D VADOSE/W simulations of a representative cross-section of the backfilled pit. The longest slope length (300 m) was chosen because as the length of the cover system slope increases, the capacity of the growth medium to transmit flow above the barrier layer can be exceeded; this could result in high values of net percolation and potentially undesirable cover system performance. A series of collection ponds were added at the base of the slope to provide attenuation of peak surface flows, and adequate time for suspended sediments to settle out prior to reaching Post Creek.

The following stratigraphy (from top to bottom) was simulated for the modelled backfilled pit cross-section:

- Non-compacted pit-run amended with topsoil – 0.1 m thick on the slope;
- Non-compacted pit-run – 1.1 m thick on the slope, 0.5 m thick in the pond;
- Compacted Copper Cliff clay – 0.45 m thick on the slope, 0.6 m thick in the pond;
- Non-compacted pit-run – 0.1 m thick on the slope and in the pond; and
- Waste rock backfill – 10 m thick to the lower boundary of the model.

Topsoil was incorporated into the cover design to assist with revegetation efforts. The lower non-compacted pit-run layer, referred to as the levelling course, was required to provide a suitable foundation for a geosynthetic separation medium (geotextile).

A statistical analysis was completed on the Sudbury Airport Environment Canada climate database (46 years) to determine the mean, wet, and dry year, based on the recorded total precipitation and estimated potential evaporation. Based on this analysis, the dry, mean, and wet year consist of 633 mm, 949 mm, and 1,042 mm, respectively, of total precipitation.

Figure 5 presents the assumed initial and predicted final barrier layer oxygen diffusion coefficient for the modelled cross-section assuming dry year climate conditions (worst case scenario for oxygen ingress). The end of summer predicted oxygen diffusion coefficient for the barrier layer at all points along the modelled section is lower than the minimum oxygen diffusion coefficient required, as determined from geochemical modelling. The predicted low oxygen diffusion coefficients for the barrier layer are reasonable considering the thickness of the compacted clay layer, and the predicted end of summer degrees of saturation for the barrier layer (96% on the slope and 100% in the pond).

Table 1 shows that the predicted cumulative net percolation for all three simulations is less than 2.2% of the modelled precipitation for the preferred cover system design. The majority of the net percolation is predicted to occur in the pond area as shown in Figure 6.

Table 1. Predicted average net percolation for the preferred backfilled pit cover system design (from OKC, 2004).

Simulation	**Net Percolation – Slope**		**Net Percolation – Pond**		**Net Percolation – Total**	
	(mm)	**% of Precip.**	**(mm)**	**% of Precip.**	**(mm)**	**% of Precip.**
Dry year	6.3	1.0%	52.3	8.3%	13.8	2.2%
Mean year	10.6	1.1%	53.9	5.7%	17.7	1.9%
Wet year	12.0	1.2%	54.2	5.2%	18.8	1.8%

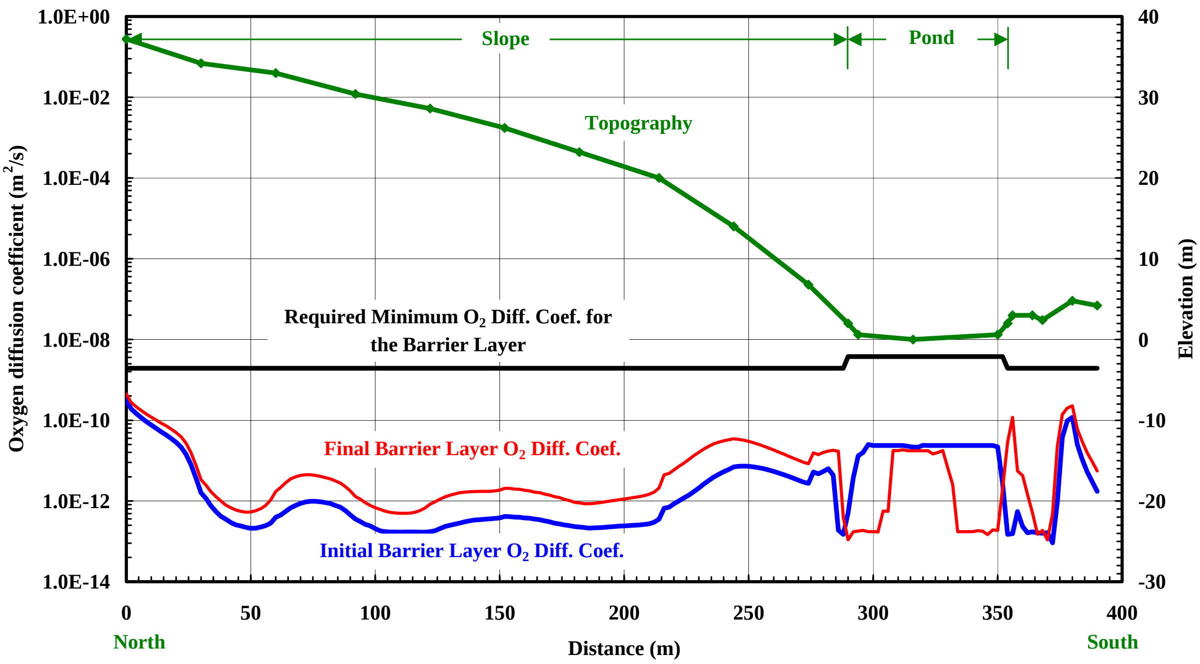

Figure 5. Initial and final predicted oxygen diffusion coefficient for the barrier layer assuming dry climate year conditions (from OKC, 2004).

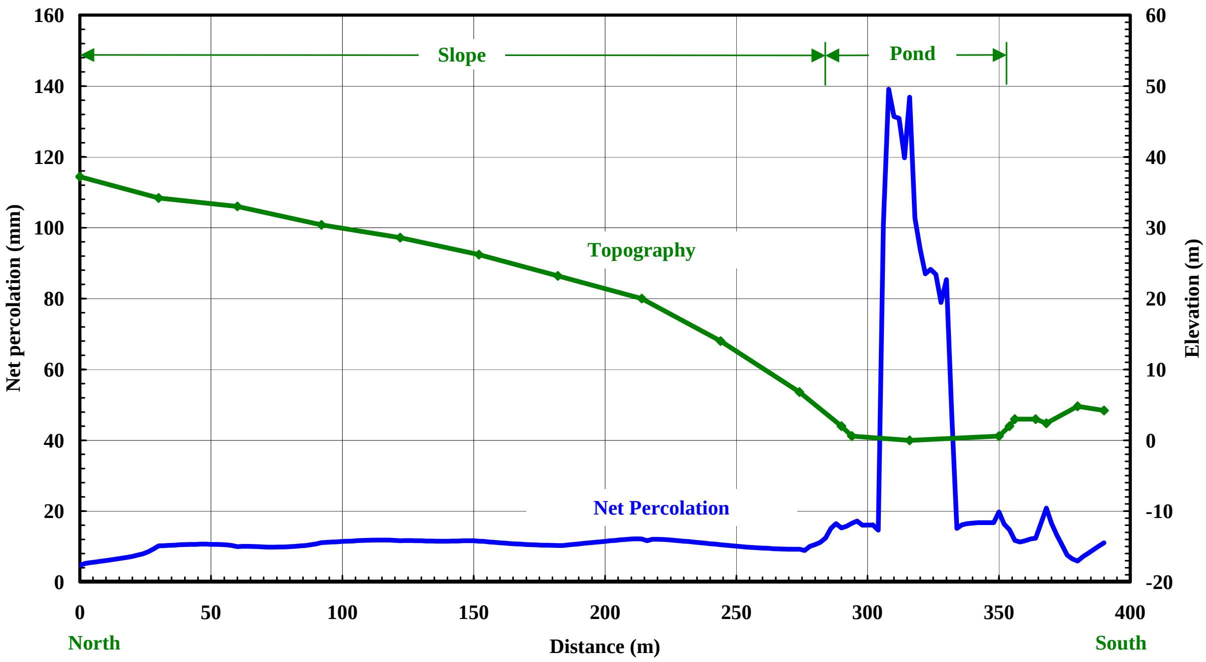

Figure 6. Predicted net percolation for the preferred cover design as a function of distance along the modelled cross-section for mean climate year conditions (from OKC, 2004).

5 LANDFORM EVOLUTION AND EROSION MODELLING

Erosion and landform evolution numerical modelling was conducted for this project to assist in designing the runoff management system and final landform for the pit cover system. The WEPP model (Flanagan and Livingston, 1995) was used to estimate erosion rates from the cover system, while the SIBERIA model (Willgoose et al., 1989) was used to predict the long-term landform evolution. A 100-year climate database for the site was developed using available data from the Sudbury Airport Environment Canada weather station and some extrapolation from equivalent areas in the region. The surface of the cover system was assumed to be bare of vegetation for all WEPP simulations, which is reasonable for short-term and probably somewhat conservative for long-term predictions of erosion rates. WEPP output data were used to generate parameters for the SIBERIA landform evolution model. Two final landform alternatives were evaluated for the backfilled pit cover system.

The first landform alternative examined consists of a highly engineered system to manage runoff generated from spring snowmelt and rainfall events. The landform has lateral diversion berms to capture runoff water and divert it laterally to one of two collection channels oriented parallel to the slope. A perspective view of this landform design is shown in Figure 7. Output from the SIBERIA model showing the evolved nature of this landform design after running the 100-year climate file is presented in Figure 8. The model output shows breaching of the lateral berms, development of gullies and rills, and in general, failure of the landform over a 100-year period. The gullies may armour over the longer term, but acting against this possibility is the relatively large contributing area that will feed some of the gullies.

The second and preferred landform alternative considered for the pit cover system consists of a number of catchments oriented parallel to the slope with a “crest and trough” pattern (Figure 9). This micro-topography is beneficial for revegetation efforts because snow accumulates in the troughs, thereby increasing soil moisture levels, and wind velocities are reduced across the ground surface, thus reducing potential erosion of topsoil and grass seeds. The objective was to develop a landform with catchments that are analogous to natural systems (i.e. avoid “fighting” nature). The size and geometry of the catchments are based on the results of WEPP modelling, which takes into consideration acceptable erosion rates for the cover system and sediment loading that will be delivered to the runoff collection system.

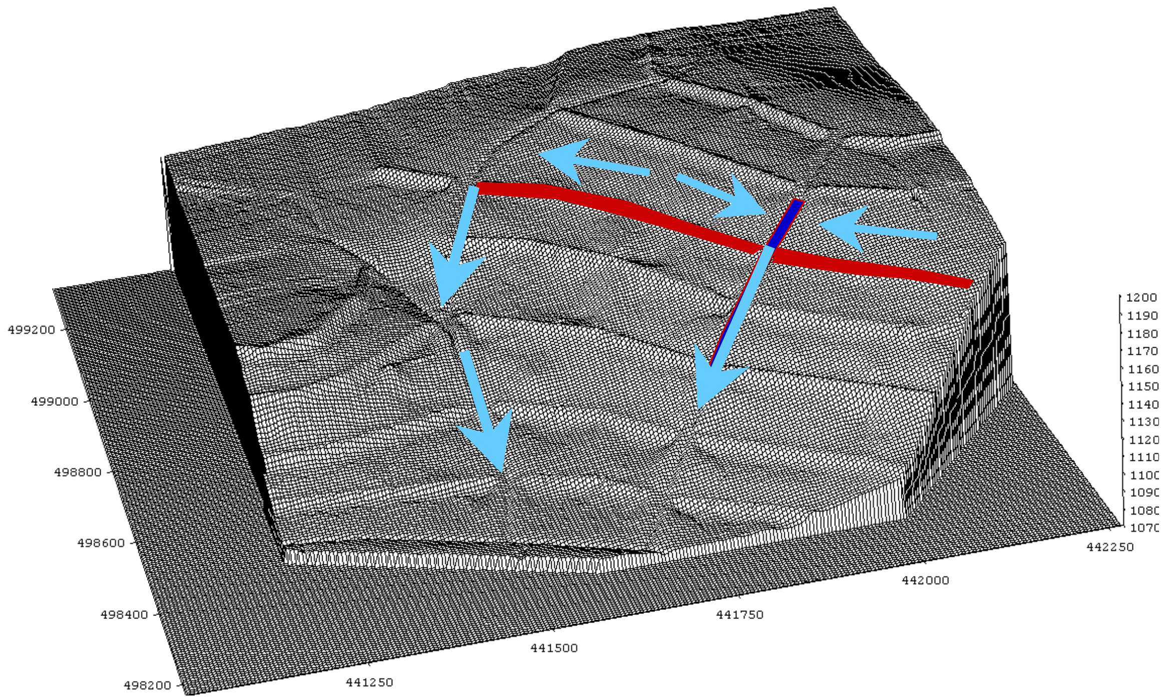

Figure 7. Surface contours (vertically enhanced) for the first landform alternative evaluated for the pit cover system (from OKC, 2004).

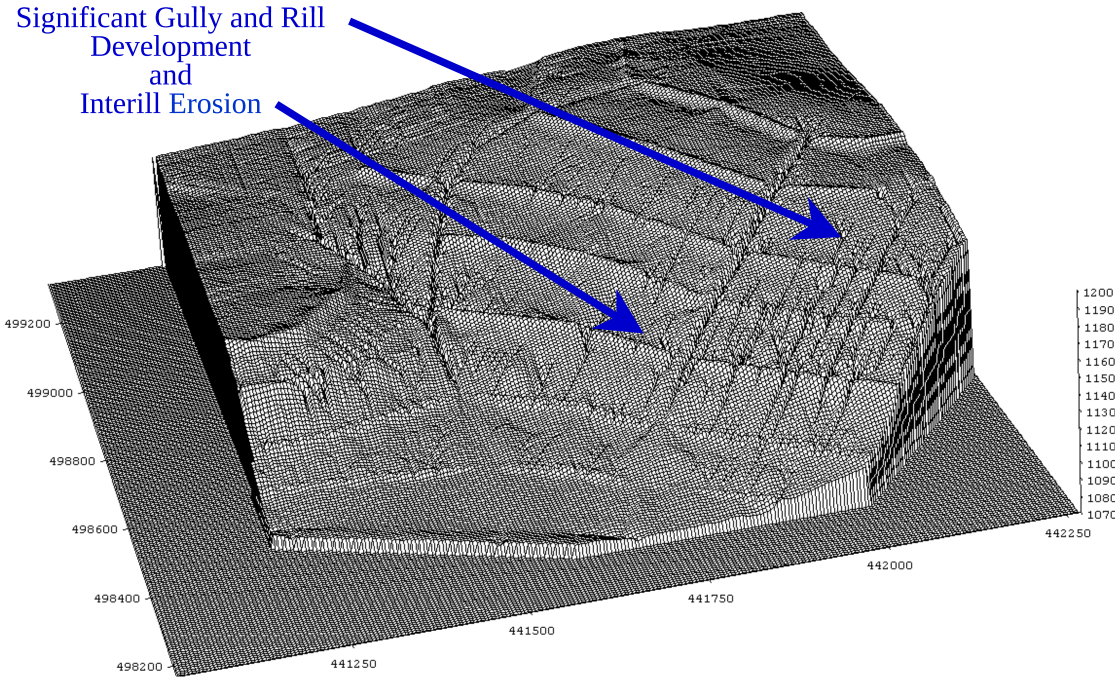

Figure 8. Predicted landform evolution of the first landform alternative for the pit cover system after 100 years (from OKC, 2004).

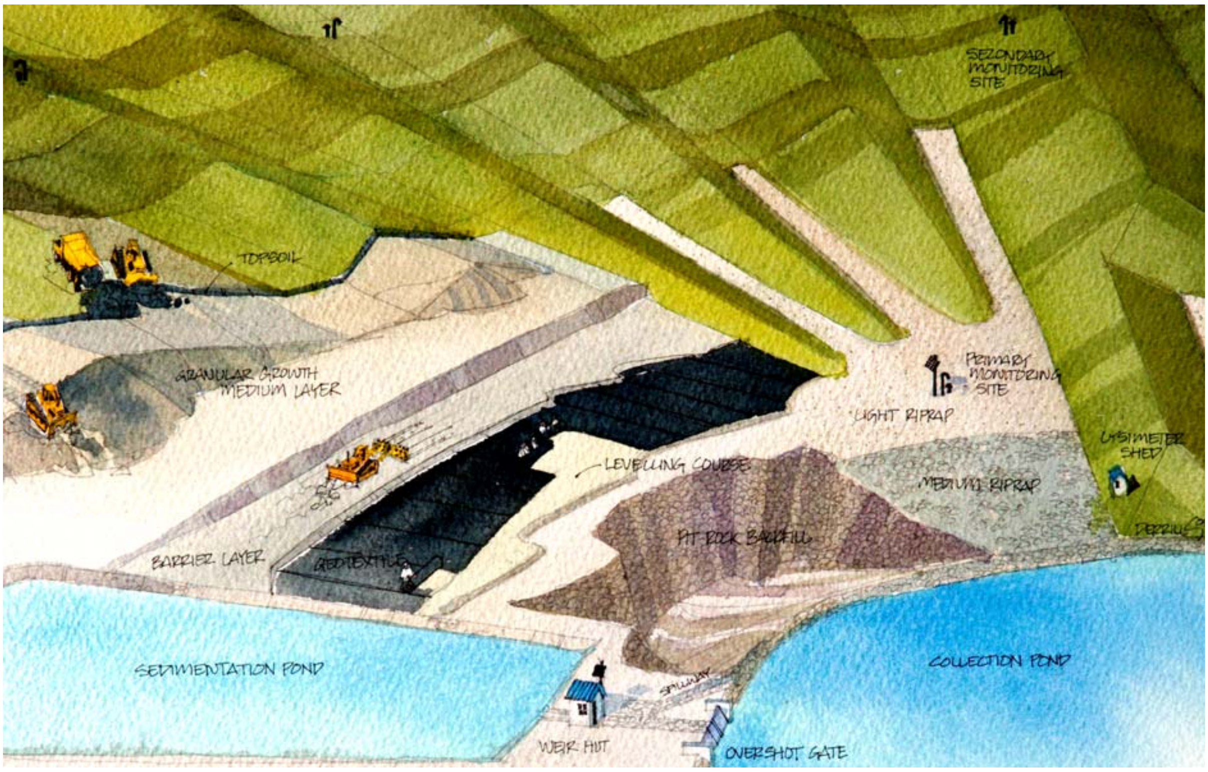

Figure 9. Rendering of the second landform alternative and key components for the pit cover system (from OKC, 2004).

6 ADDRESSING POTENTIAL IMPACTS ON SUSTAINABLE PERFORMANCE

Dry cover systems are designed with the assumption that they will remain intact and the basic physical dimensions and structure of the cover system will not change. However, when long-term performance is considered, it becomes likely that the surrounding environment will alter the cover system in some way. The initial performance of a cover system will change as a result of physical, chemical and biological processes, and result in long-term performance.

INAP (2003) conducted an examination of the processes shown in Figure 10, and discovered that their effects could be related to the change in three key cover performance properties; namely, the saturated hydraulic conductivity and moisture retention characteristics of the cover materials and the physical integrity of the cover system. The saturated hydraulic conductivity and moisture retention curve are key hydraulic properties of a cover system layer. Tests can be completed to assess the likely changes in these properties (if any) over time; however, laboratory measurements more than likely illustrate a range of values for a certain material. INAP (2003) state that developing field-based measurements of the key hydraulic properties is essential for properly designing a cover system.

Various elements were incorporated into the design of the Whistle Mine pit cover system to mitigate the impact of the processes applicable to this site on sustainable performance of the cover system. These elements include erosion control measures and revegetation planned for the surface of the cover system, the design of the growth medium and barrier layers, and the proposed cover performance monitoring system. The growth medium layer and more specifically, its 1.2 m thickness, is the most important element of the design towards sustainable performance of the cover system. The Copper Cliff clay is comprised mainly of quartz and stable clay minerals, which will make the barrier layer less susceptible to chemical processes such as osmotic consolidation and dispersion. Although a geotextile installed beneath the barrier layer will not improve cover performance in terms of reducing net percolation and/or oxygen ingress, it should prevent migration of the clay-size particles in the barrier layer to the underlying coarse material over the long term.

A performance monitoring programme was designed for the pit cover system to obtain a water balance for the site, and develop an understanding for key characteristics and processes that control performance. Table 2 lists the components of the performance monitoring system. The majority of the instrumentation is automated to reduce the time required for Inco personnel to collect monitoring data and facilitate data collection on a daily basis.

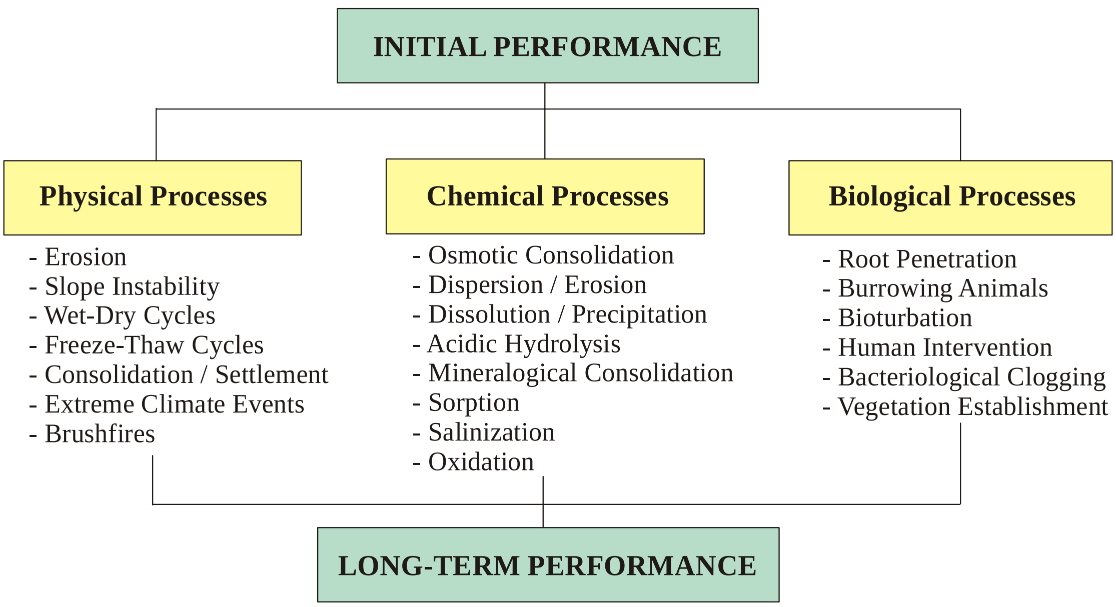

Figure 10. Processes that could impact the sustainable performance of dry cover systems (from INAP, 2003).

Table 2. Details of the performance monitoring programme for the backfilled pit cover system (from OKC, 2004).

Component	Parameters Measured	Details / Comments
Pit backfill monitoring wells	Water quality and hydraulic head	• 3 wells installed in a triangular pattern • Pressure transducer installed in 2 wells for automated head measurements
Meteorological station	Rainfall, snowfall, air temperature, relative humidity, wind speed & direction, net radiation	• All sensors connected to an automated data acquisition system • Snow surveys to be performed in the spring (snow water equivalent)
Weirs	Surface runoff flow	• 2 weirs (one after the Collection Pond and one after the Sedimentation Pond) • Automated stage recording, and weirs enclosed in heated huts
Primary *in situ* cover monitoring sites	Net percolation, volumetric water content, matric suction, *in situ* temperature and O_2/CO_2 gas concentrations	• 1 site upslope and 1 site downslope • Automated measurements for all parameters except O_2/CO_2 gas concentrations
Secondary *in situ* cover monitoring sites	Volumetric water content, *in situ* O_2/CO_2 gas concentrations	• 13 sites across the entire cover surface • Portable soil moisture probe and portable O_2/CO_2 gas analyzer

7 CONSTRUCTION STATUS AND KEY ISSUES

Construction of the backfilled pit cover system at Whistle Mine began in June 2004. Approximately 50% of the cover system had been completed, including topsoil admixing, hydroseeding, and installation of temporary erosion control blankets in the catchment channels, when construction was halted in October 2004 due to the onset of freezing conditions. The meteorological station, one primary *in situ* cover monitoring site, and eight secondary *in situ* cover monitoring sites were installed and commissioned in 2004. Construction is scheduled to recommence in late May 2005 and weather permitting, construction should be complete by October 2005.

A significant amount of preparatory earthwork was completed in 2003 and early 2004 along the pit perimeter. Rock outcrops and remnants of the pit wall were blasted to facilitate construction of the pit cover system in a continuous manner to a minimum of 6.0 m beyond the pit perimeter. A 4.5 m wide band around the entire pit perimeter was cleaned with power washers to ensure intimate contact between the bedrock and clay fill. The objective of this preparatory work is to minimize the entry of atmospheric oxygen and meteoric water to the pit rock backfill along the pit perimeter, following closure of the site.

A test pad for the cover system barrier layer was constructed on the backfilled pit surface prior to full-scale construction activities. The objectives of the test pad programme were to: 1) determine the most appropriate methods for constructing the barrier layer in terms of compaction equipment, number of passes, etc.; and, 2) finalize the compaction criteria (i.e. acceptable range of dry density and moisture content) for full-scale construction of the barrier layer. Results obtained from the compaction test pad proved to be invaluable to both the contractor and engineer.

Another key aspect of construction for this project is cross-slope mixing of 75 mm of topsoil into the surface of the pit-run material. This will minimize erosion of the topsoil prior to development of a sustainable vegetation cover and maximize the root depth available for plant growth. In addition, cross-slope ripping of the growth medium surface will ensure the catchment slopes function as planned, at least in the short term, such that runoff water flows along the rip lines to the erosion-protected channels.

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