Evaluation of in Service Performance of Cover Systems that Utilize a Geosynthetic Layer

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Abstract

Enterprise Cape Breton Corporation (ECBC) implemented a remediation program for the closure of historic coal mines located near Sydney, Nova Scotia. A number of waste rock piles (WRPs) were reclaimed with cover systems; three included a geosynthetic layer.

A field performance monitoring system has been installed to facilitate evaluation of performance over time under site-specific climate conditions at four of the sites. Monitoring includes internal WRP gas, pore-air pressure, moisture, and temperature conditions, as well as near surface conditions in regards to the cover system performance itself (i.e. heat and mass balance).

This paper provides a brief overview of the WRP field performance monitoring systems, followed by interpretation of performance of the cover systems to date. The reclaimed WRPs display unique water balances and water dynamics stemming from subtle design differences; all of which have significant impact on performance in terms of closure. This paper will highlight that in service performance of cover systems that utilize geosynthetic layers is much less about “the holes” that may result during installation, and much more about other aspects of performance, such as lateral drainage, seepage induced erosion, landform stability, and sufficient plant available moisture availability for developing a sustainable vegetation cover.

Introduction

In terms of composite covers, which include a geomembrane layer, water and oxygen can move through the geomembrane by diffusion, but the transmission rates are very low. In general the hydraulic conductivity corresponding to water diffusion is on the order of $10^{-12}$ to $10^{-15}$ cm/s (Giroud and Bonaparte, 1989). Considering that geomembranes are perceived as being essentially impervious when devoid of defects, performance monitoring programs are traditionally focused on water quality analyses of seepage...
discharged from the waste storage facility. However, this rational is somewhat flawed in that net percolation alone does not provide an understanding of cover system performance.

A cover system should provide for a stable landform and the establishment of sustainable vegetation. Landform instability is a common factor leading to failure of mine waste cover systems around the world (MEND, 2004). The greatest physical risk to reclaimed waste storage facilities is associated with surface water management. This is particularly important in composite cover systems where geosynthetics are placed within earthen layers. Cover systems with a geomembrane layer typically include a granular or geosynthetic drainage layer to increase slope stability through limiting the buildup of pore-water pressures. Holding to the conceptual idea that the geosynthetic layers will perform as intended, the longevity of the geosynthetics and subsequent long-term performance of the cover system will be a function of the performance of cover layers placed above the geomembrane.

Given the aforementioned a monitoring program should be designed to measure the water and energy balances, as well as oxygen ingress rates. MEND (2000) provides a detailed overview of field performance monitoring for cover systems. In terms of field performance monitoring for a full-scale cover system, a recommended minimum level of monitoring would include meteorological monitoring, such as determination of the potential evaporation (PE) and site-specific precipitation, cover material moisture storage changes, watershed or catchment area surface runoff, vegetation, and erosion (MEND, 2004).

Background

Cape Breton Development Corporation (CBDC) was established as a Crown corporation in 1967 in order to reorganize and rehabilitate the coal industry on Cape Breton Island. In 2009, CBDC was dissolved and its assets and liabilities were transferred to Enterprise Cape Breton Corporation (ECBC), a federal Crown corporation. Under the transfer arrangement, ECBC acquired stewardship obligations stemming from CBDC’s past operations, including land holdings and environmental remediation.

Properties covered under the environmental remediation program stem from mining operations that began in 1685 and includes over 50 underground mines which produced over 500 million tonnes of coal. The history of coal mining in the Sydney Coal fields included 720 individual parcels of land on which there were 95 coal related operations covering over 1,000 km². Some of the properties required remediation of WRPs produced from the mining operations.

Dry cover systems were implemented as part of the closure plan for seven (7) WRPs. Public Works and Government Services Canada (PWGSC), under ECBC, provided project management for the remediation program. Local engineering consulting firms, through standing offer agreements with PWGSC, were engaged to develop detailed closure plans for the WRPs. In general, there were four cover
system designs utilized for closure of the WRPs. ECBC implement field performance monitoring systems to develop an understanding for the performance of each of the cover system designs utilized for closure. This paper summarizes the field performance of three of the reclaimed WRPs including Lingan, Summit and VJ.

The waste rock within each WRP is currently acidic with the potential to continue to generate acid mine drainage (Phase, 2010). The Lingan WRP is located at the former Lingan Mine Colliery in New Waterford, approximately 16 km northeast of Sydney. The Lingan WRP covers an area of 8.5 ha, is 15 m high and contains approximately 380,000 m$^3$ of waste rock (Senes, 2009). The WRP has a plateau sloping at 3% from the center that transitions to 5:1 (H:V) side slopes. In 2010 the WRP was reclaimed with a 0.5 m nominally thick till growth medium layer placed directly on the waste rock. A perimeter ditch was constructed around the plateau which channels runoff waters to drop structures on the side slopes.

The Summit WRP is located in Scotchtown, approximately 15 km north of Sydney. The Summit WRP was used by the Dominion Coal Company for the placement of coal waste rock from nearby Collieries over the period 1911 to 1973. Between 1981 and 1987 the waste rock was reprocessed to recover residual coal, which resulted in an increase in the footprint. The WRP thickness varies from 1.5 to 10 m with the thickest deposits near the center and covers an area of approximately 44 ha. The WRP plateau has a grade of approximately 2-3% and side slopes of 7:1. The WRP was reclaimed in 2011 with an engineered cover system that includes 60 mil high-density polyethylene (HDPE) layer placed below a growth medium layer constructed of processed till (35 mm minus).

The VJ WRP is located on the site of a historic coal preparation plant, approximately 3 km east of Sydney. The coal preparation plant was commissioned in 1976 and remained in operation until the Phalen Colliery closed in 2000 and then remained a blending facility until 2001. Waste rock was consolidated into a WRP with a footprint of approximately 26 ha and height of 40 m. The WRP plateau has a grade of 7% and 3:1 side slopes. Runoff and interflow on the plateau is collected within a perimeter ditch which channels these flows to drop-structures on the side slope to a collection ditch around the perimeter of the WRP. The WRP was reclaimed with an engineered cover system comprised of a till growth medium layer placed over a granular drainage layer (GRDL) and 60 mil HDPE. Figure 1 provides a schematic of the engineered cover system profiles utilized for closure of the Lingan, Summit and VJ WRPs.
Cover System Performance Monitoring

A multi-phase, multi-discipline monitoring program was implemented in support of evaluating the performance of the cover systems and to achieve the following objectives:

1) Obtain a water balance for the sites, and more specifically, for the cover systems;
2) Identify and characterize key mechanisms and processes that control performance;
3) Track the evolution of cover performance in response to site-specific physical, chemical and biological processes;
4) Obtain a representative set of field performance monitoring data to calibrate a soil-plant-atmosphere numerical model and ultimately predictions of long term cover performance;
5) Improve the design and selection processes of geosynthetics placed within cover systems; and
6) Develop confidence with all stakeholders with respect to closure performance of the WRP.

The monitoring system for each WRP includes a meteorological station, a v-notch weir for measuring runoff flows and interflow, four automated stations for measuring in situ moisture and pore-gas concentrations above and below the HDPE layer. Four systems were installed to allow for monitoring of...
the WRP internal conditions (pore-gas and pressure, ground water quality and levels, and temperature). Measurements of actual evapotranspiration are collected with an Eddy Covariance system. In addition, a conservative tracer was applied to develop estimates of net percolation.

Climate

Cape Breton is in a seasonally humid region of Canada. Mean annual precipitation (PPT) and potential evaporation (PE) are approximately 1,500 mm and 650 mm, respectively. Slightly less PPT occurs during the summer (May to September) with approximately 97 mm of rainfall per month compared to 145 mm for the remainder of the year. In the winter (December to March) relatively equal proportions of rain and snow occur as precipitation. The atmospheric demand for moisture during the winter is low, typically less than 20 mm per month, which increases in the summer to greater than 100 mm. Figure 2 summarizes the 2012 monthly average PPT and PE calculated utilizing the Penman (1948) method for the Summit WRP. Given that actual evapotranspiration (AET) is always less than PE, PPT may exceed AET during the summer periods.

Cover systems constructed within seasonally humid climates, which exhibit variation in atmospheric moisture demand, are required to manage a significant quantity of PPT through components of the water balance (i.e. runoff, interflow, net percolation and changes in cover water storage). Realizing that net percolation rates are low for cover systems that utilize a geomembrane, demands are placed on the landform water management system to ensure the long-term performance / stability of the cover system is sustainable.

![Figure 2: Monthly PPT and PE in 2012 for Summit](image-url)
**Pore-Water Pressure**

Stability and erosion issues can occur in cover systems with a geomembrane layer that do not include a drainage layer in the design. In general, geomembranes are impermeable limiting water ingress to the underlying waste material. The absence of a drainage layer coupled with a low flux barrier layer can lend to the development of positive pore-water pressures within the cover profile above the geomembrane. Positive pore-water pressures reduce the effective normal stress and thus reduce the restraining friction along the geomembrane interface, resulting in a potential slope failure. The Summit WRP characteristic of shallow slopes and a large surface area does not include a drainage layer, except for a small section (~1.5 ha) which provided the steepest slope gradient. It is expected that the exclusion of a drainage layer for the remaining WRP surface area (~42.5 ha) was attributed to the shallow slopes.

While slope failures are generally restricted to steep slope angles where the restraining friction may be exceeded, seepage erosion can occur along shallow slopes. Seepage erosion occurs when particles are carried out of the soil mass under a hydraulic gradient. Particle movement is initiated as soon as the seepage force is greater than the particle self-weight and inter particle forces. A seepage face may occur within a cover system at the toe of the slope or when the height of ponded water within the cover profile exceeds the elevation at the base erosional features, which establishes a hydraulic gradient to flow. Once seepage erosion is initiated a positive feedback loop is established in that further deepening of the erosion feature leads to an increase in the hydraulic gradient. This is further intensified by high surface runoff volumes associated with the *in situ* water dynamics (i.e. limited water storage capacity in the cover profile).

Figure 3 shows the change in the total volume of water and pore-water pressure in the cover profile at Summit. In general, the volume of water fluctuates between approximately 155 mm and 180 mm early in the spring and then decreases to approximately 100 mm in the summer. The trend in water dynamics would suggest that the cover profile exceeds field capacity at water volumes greater than 160 mm; however, given the low slope gradient and absence of a drainage layer excess waters pond above the HDPE layer.

A pressure head of 0.6 m is attained on several occasions, indicating that the entire depth of the cover profile (cover profile 0.6 m thick monitoring location illustrated in Figure 3) is under positive pore-water pressure. Trends in pore-water pressure at other monitoring locations on the cover system are similar to that illustrated in Figure 3. Figure 4 is a photo of a seepage erosion feature observed on the Summit cover system, where the geotextile/HDPE layer was exposed.

In addition to potential erosion issues, vehicle restrictions are imposed on the cover system during periods of positive pore-water pressure due to the realized loss in shear strength. In essence the water dynamics dictate that the cover system layers may be susceptible to anthropogenic damage. Even though the cover system water dynamics will largely control surface erosion, it should be noted that the processed till (35 mm minus) limits the covers ability to self-arm and limit erosion.
Figure 3: Pore-water pressure and volume of water in the Summit cover profile

Figure 4: Seepage erosion feature on the Summit cover system

Figure 5 is a one-dimensional (1-D) contour of the VJ cover profile volumetric water content. Water contents in the GRDL are lower than that of the growth medium. The contrast in water conditions between the growth medium and GRDL are attributed to textural differences, or more specifically, differences in the moisture retention characteristics. Low volumetric water contents observed in the GRDL indicate that the layer is free draining and that positive pore-water pressures have not occurred in the layer.
In general, flow to the GRDL occurs at the breakthrough pressure condition, which is the pressure condition corresponding to the matric suction at the residual water content of the GRDL. A slight increase in water contents in the GRDL occurs in the spring (April) and then consistently decrease until September suggesting the transmissivity of the GRDL is adequate to convey the realized interflow waters under the observed climatic conditions.

**Estimates of Cover System Pressure Head**

The height of ponded water within a drainage or growth medium layer is influenced by climate (surface infiltration), drainage length and slope, and saturated hydraulic conductivity of the layer. A comparative analysis was completed for Summit to determine the effect of potential changes in the saturated hydraulic conductivity of the growth medium layer under a range of steady state infiltration rates on the height of water ponded in the cover profile. The following formula (Metry 1982) was used:

\[
h_{\text{max}} = \frac{L\sqrt{C}}{2} \left[ \frac{\tan^2(\alpha)}{c} + 1 - \frac{\tan(\alpha)}{c} \sqrt{\tan^2(\alpha) + c} \right]
\]

where:

\[
C = \frac{e}{k_{\text{sat}}}
\]

where: \( h_{\text{max}} \) is the average daily head, \( L \) is the drainage distance, \( \alpha \) is the slope, \( k_{\text{sat}} \) is the saturated hydraulic conductivity of the layer, and \( e \) is the surface infiltration rate. Using Equation 1, in advance of
numerical simulations, Table 1 summarizes results of the comparative analysis. The color coded ranges were developed to provide a quick visual comparison of the estimated values. Red indicates that the height of ponded water exceeds cover profile thickness (i.e. 0.5 m), orange indicates that the height of ponded water remains below the cover profile surface but exceeds 0.25 m and green indicates that the height of ponded water remains below 0.25 m.

Table 1: Results of comparative analysis for a range of steady state infiltration rates and k_{sat} of the growth medium on the reclaimed Summit WRP slope sections

<table>
<thead>
<tr>
<th>Ks (cm/s)</th>
<th>Infiltration Rate (mm/day)</th>
<th>Maximum Height of Water in Cover (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td>1E-04</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>1E-03</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>1E-02</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1E-01</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Utilizing the in situ hydraulic conductivity measured for the growth medium layer (approximately 1x10^{-4} cm/s) it is anticipated that the height of ponded water will exceed cover profile thickness even under low steady state infiltration rates, which is consistent with the observed performance. An increase of approximately one order of magnitude (i.e. 1x10^{-3} cm/s) would be required to maintain water levels below the cover surface. Benson et al. (2007) and Meiers et al., (2011) demonstrated that post construction increases in the hydraulic conductivity of a growth medium layer occur within three to four years and that materials with a high initial hydraulic conductivity (i.e. \sim1x10^{-4} cm/s) are limited to marginal increases. Subsequently, the Summit cover system may be prone to periods of water ponding within the cover profile indefinitely based on the relatively high initial hydraulic conductivity and results of the comparative analysis.

In addition to the slope stability and erosion concerns, the drainage of water from above the geomembrane will minimize the head of water above the geomembrane layer and reduce the potential for infiltration through defects. Table 2 summarizes the head of water estimated for the plateau over a range of k_{sat} and steady state infiltration rates. Table 2 shows that the probability of water ponding on the HDPE layer would be high for almost all scenarios.

Table 2: Results of comparative analysis for a range of steady state infiltration rates and k_{sat} of the growth medium on the reclaimed Summit WRP plateau
The Summit HDPE layer was constructed over 0.15 m of bedding sand; hence, leakage through defects would be free draining under ponded conditions. Transmissivity of the growth medium layer and spatial distribution of defects in the geomembrane would be the primary factors controlling infiltration. Benson (2000) reported that defects in geomembranes typically range from 2.5 to 25 defects/ha. Utilizing the aforementioned defects and measured cover system water dynamics, numerical simulations would be utilized to develop an understanding for the anticipated range in leakage rates.

**Water Balance**

A water balance was completed for the reclaimed WRPs using performance monitoring data collected at the sites in 2012. The water balance for a cover system consists of the following components:

\[
PPT = R + \text{AET} + \text{NP} + \Delta S + \text{IF}
\]

(3)

where:  \(PPT\) is precipitation, \(R\) is surface runoff, \(\Delta S\) is the change in water storage within the cover profile, \(\text{AET}\) is actual evapotranspiration, \(\text{IF}\) is interflow or lateral drainage, and \(\text{NP}\) is net percolation.

In the monitoring period runoff volumes were not available; hence, an analytical approach was utilized to estimate a water balance for the reclaimed WRPs. Figure 6 shows the completed water balance for Lingan.

A slightly different approach was utilized for estimating the water balance for Summit and VJ. Net percolation was estimated through soil-plant-atmospheric numerical modeling completed for design of the monitoring system. An effective \(K_s\) of \(2 \times 10^{-9}\) cm/s was used for the HDPE layer based on findings by Benson (2000). Net percolation was estimated to be 8 mm and 20 mm for the reclaimed VJ and Summit WRP, respectively.

Figure 7 compares the water balance for the reclaimed Lingan, Summit and VJ WRPs. AET is similar for each WRP ranging from 40 to 43% of the water balance. There is a substantial difference realized in runoff volumes, which is directly attributed to differences in the cover system design. Summit has the highest estimated runoff at approximately 54% of the water balance. The lower runoff realized at VJ (40%) was primarily attributed to the GRDL allowing for the lateral percolation of water. In comparison, the absence of a geomembrane within the Lingan cover system offset greater runoff volumes through net percolation.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\(K_s\) (cm/s) & 2.7 & 2.0 & 1.4 & 0.7 & 0.27 \\
\hline
\hline
1E-04 & 17.5 & 14.7 & 11.5 & 7.5 & 4.2 \\
1E-03 & 4.2 & 3.6 & 2.8 & 1.9 & 1.1 \\
1E-02 & 1.1 & 1.0 & 0.8 & 0.6 & 0.4 \\
1E-01 & 0.4 & 0.3 & 0.2 & 0.2 & 0.1 \\
\hline
\end{tabular}
\end{table}

Maximum Height of Water in Cover (m)
Net percolation was a significant component of the water balance for the reclaimed Lingan WRP, indicating that cover systems which rely on the process of moisture store-and-release to mitigate net percolation may not be practical within seasonally humid climates. The results demonstrate that the
inclusion of cover layers (i.e. HDPE and GRDL) below a similar growth medium thickness provide for a unique water balance.

**Summary**

Three WRPs located near Sydney, Nova Scotia were reclaimed with dry cover systems. Cover system field performance monitoring data demonstrate that the inclusion of a drainage layer and / or geomembrane layer below a similar growth medium thickness provides for a unique water balance / dynamics. Absence of a drainage layer above the Summit geomembrane resulted in positive pore-water pressures, seepage erosion, high runoff volumes and an increase in the potential for leakage through the geomembrane layer. In comparison, the transmissivity of the granular drainage layer at VJ was adequate to limit positive pore-water pressures, with the interflow volume resulting in a proportional reduction in runoff. Given that surface erosion is a common factor leading to the failure of mine waste cover systems, surface water management strategies should consider the influence of drainage layers on performance of geosynthetic cover systems.

The monitored water dynamics would suggest that the VJ cover system would provide for a more stable landform and minimize leakage through the HDPE layer. However, an understanding of performance under long-term average and extreme climatic conditions, through the use of numerical simulations, would be required to quantify any benefit in performance. On-going monitoring of the reclaimed WRPs will provide a unique dataset for the assessment and design of cover systems that utilize geosynthetic layers.

**References**


