Use of Analytical Estimates and Water Balance Components to Simulate Leakage Rates Through Cover Systems Utilizing a Geomembrane

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ABSTRACT

Monitoring performance of cover systems with a geomembrane layer is not common practice as there is an expectation of performance regardless of the site. Re-evaluating performance through a monitoring program validates the design and provides an opportunity for further knowledge to be incorporated in subsequent designs. The remediation of three coal waste rock piles located near Sydney, Nova Scotia, Canada included engineered cover systems that use geosynthetic layers. In general, the cover systems are similar in that they include an engineered 60 mil high density polyethylene geomembrane and a growth medium layer; however, differences are observed in the drainage layer. A granular drainage layer and geocomposite drainage net were used for two of the cover systems respectively, while no drainage layer was included in the third.

Net percolation was simulated over a range of defects using empirical equations and field performance monitoring data. The simulated net percolation was estimated to be less than 0.1% and 5% of precipitation for cover systems with and without a drainage layer, respectively. The unique set of water dynamics observed for the respective cover systems highlight that management of lateral drainage should be one of the primary design considerations for cover systems with a geomembrane barrier layer.
1. INTRODUCTION

The primary purpose for the design and application of engineered cover systems is to minimize any deleterious impact of the mine waste on the receiving environment in the short term and to facilitate recovery of the environment disturbed by mining over the long term. As a result, one of the primary design objectives of a cover system for waste storage facilities is to limit the percolation of water into the underlying waste. For this reason, and because stakeholders require verification of closure success, a high degree of confidence is required when determining cover system performance.

Cover system field monitoring is an essential and necessary method for evaluating performance of cover systems and provides a direct method of verifying the design of the cover system. Field performance monitoring of cover systems is widely accepted and provides the best method for demonstrating performance to stakeholders and developing further understanding for long-term performance. However, performance monitoring is not common practice for cover systems that include a geomembrane. Historically, performance monitoring consisted of the collection of seepage discharged and/or water quality analyses of basal seepage. However, this approach empirically describes a waste storage facility through monitoring of its cumulative effect at the base and does not account for post-closure drain-down within the waste storage facility and potential transformation of the source term in response to physiochemical factors (O’Kane, 2011).

Net percolation for a cover system that includes a geomembrane can occur through 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). As a result, net percolation is primarily attributed to leakage through defects in the geomembrane. Darilek et al. (1989), Giroud and Bonaparte (1989), Brennecke and Corser (1998), and Rollin et al. (1999) reported that even with recent advances in the testing and installation of geomembranes they are almost never installed without defects. Benson (2000) found that the effective saturated hydraulic conductivity of geomembranes may be several orders of magnitude greater due to defects. The primary factors leading to defects in geomembranes are: 1) inadequate welds and attachments to structures; 2) imposed stresses and mechanical damage during construction; and 3) service stresses that induce stress cracking at points of stress and weld separation (Peggs, 2010). In addition to the aforementioned, post-closure defects may be introduced from anthropogenic activities, animal bioturbation, and the effects of vegetation.

As environmental regulations become increasingly strict, cover systems including a geomembrane, as well as other geosynthetic layers, will become more common practice in the mining industry. Field performance monitoring needs to evolve so that an understanding for water and oxygen flux through these cover systems can be developed to support predictions of acid rock drainage and metal leaching (ARD/ML). In terms of net percolation, it could be argued that direct measurement would be challenging given the size of lysimeter required to capture the spatial distribution of defects. Novel monitoring systems designed specifically for cover systems that include geomembranes are required. Meiers et al., (2014) developed estimates of net percolation using measured cover system water balance components, monitored pore-water pressure above the geomembrane layer, and a conservative tracer. A numerical model calibrated to measured field responses below the geomembrane supported the estimated net percolation. The key attribute in the monitoring system was that it allowed for the development of multiple lines of evidence to support the predicted cover system performance. Traditional performance monitoring systems documented in MEND (2012), augmented with other techniques, should be the basis for monitoring the performance of cover systems that include a geomembrane.

This paper explores field performance monitoring data collected from three reclaimed waste rock piles (WRPs) that was used to simulate net percolation over a range of geomembrane defects using empirical equations. The database
of water and thermal responses developed for the cover systems will be key in tracking the evolution of the soil, mineral, and geosynthetic layers in response physical, biological and chemical processes. A key outcome was an understanding of current performance to assist in understanding factors that will contribute to long-term performance of the cover systems and the risk associated with leakage through defects.

2. BACKGROUND

Coal mining in Sydney, Nova Scotia, Canada, has a rich history with operations that date back to 1685. The Sydney Coal fields included over 50 underground mines which produced approximately 550 million tons of coal. The waste rock is acid generating with the potential to continue to leach metals and generate ARD/ML for an extended period. Under the management of Public Works and Government Services Canada (PWGSC), the Franklin, Scotchtown Summit (Summit) and Victoria Junction (VJ) WRPs were reclaimed with engineered cover systems. The WRPs are located within a radius of approximately 10 km of Sydney.

The cover systems are similar in that they include a 60 mil high-density polyethylene (HDPE) geomembrane and a growth medium layer constructed of till. The primary difference in the cover system designs is observed the drainage layer. Franklin has a geocomposite drainage net (GDN), VJ has a nominally 0.4 m thick granular drainage layer (GRDL), and Summit does not include a drainage layer. Figure 1 provides a schematic of the cover system profiles used for closure of the WRPs.

![Figure 1. Schematic of the cover system profiles for the Franklin, Summit and VJ WRPs.](image)

Sydney is in a seasonally humid region of Canada and is classified as humid continental under the Köppen climate classification. Mean annual precipitation and potential evaporation are approximately 1,500 mm and 650 mm, respectively. Less precipitation occurs during the summer (May to September) with approximately 97 mm per month compared to 145 mm for the rest of the year. In the winter (December to March), precipitation occurs as relatively equal proportions of rain and snowfall. The atmospheric demand for moisture during the winter is low, typically less than 20 mm of potential evaporation per month, and increases to greater than 100 mm in the summer months.
2.1 Cover System Performance Monitoring

A multi-phase, multi-discipline monitoring program was implemented in support of evaluating performance and developing confidence with all stakeholders with respect to closure performance of the reclaimed WRPs. The monitoring systems for each WRP are similar and typically include:

- Meteorological station that measures rainfall, air temperature, relative humidity, wind speed and direction, barometric pressure, snow depth, and net radiation;
- Interflow collection systems to quantify lateral drainage above the geomembrane;
- V-notch weir to quantify runoff from the WRP;
- Pressure transducers to quantify positive pore-water pressure above the geomembrane;
- Soil monitoring sites consisting of soil suction / temperature sensors and soil water content sensors;
- Multilevel / multipurpose wells for monitoring groundwater level / quality within the footprint of the piles, and collecting internal WRP pore-gas concentrations (O₂ / CO₂), differential pressure and pore-water;
- Eddy Covariance system for monitoring actual evapotranspiration; and
- Conservative tracer for estimating net percolation.

3. CONCEPTUAL MODEL OF COVER SYSTEM PERFORMANCE

Measurement of volumetric water content and pore-water pressure within a cover system profile provides an initial step in understanding net percolation rates, and subsequently an initial conceptual model of cover system performance. For comparative purposes, Figure 2 is a one-dimensional (1-D) contour of the 2014 volumetric water content profiles for Franklin, Summit, and VJ. One image is provided for Franklin and Summit, while two are provided for VJ. Figure 2(a) shows wet-dry cycling in the till growth medium layer at Franklin in response to atmospheric forcing (i.e. precipitation and evaporation). Water contents within the GDN fluctuate from a high of approximately 0.15 to less than 0.05. This indicates that adequate transmissivity in the GDN is available to limit the head of water that may develop above the geomembrane given the porosity of this layer is approximately 0.8. This is a positive cover system performance aspect for Franklin in that it demonstrates that the head of water above the geomembrane has been limited to less than the thickness of the GDN; hence, net percolation occurring as leakage through defects would be minimized.
Figure 2. 1-D contour of the (a) Franklin, (b) Summit, and (c and d) VJ volumetric water content profiles. Note: ‘drying’ in the growth medium layer in the winter (i.e. February and March) is due to a change in the dielectric constant when pore-water freezes.

Figure 2(b) shows the Summit water content profile. Water contents immediately above the geomembrane are much higher than that observed for Franklin. This would suggest that there is a higher risk for net percolation associated with defects. At VJ (see Figure 2(c)) water contents in the GRDL are low, highlighting adequate lateral drainage capacity. While water contents in the GRDL are low, approximately 15% of precipitation passes through this layer on an annual basis. Figure 2(d) also shows the water content profile at VJ but near the perimeter ditch on the plateau. Water contents in the GRDL are higher compared to that observed in Figure 2(c). The higher water contents are due to a flow restriction at the outlet to the GRDL on the plateau.

Lateral drainage in the GRDL at VJ is directed to a perimeter ditch located around the plateau, where it combines with runoff waters and is directed to drop structures on the side slope. The drop structures create a “bottleneck” or restriction to flow and results in water ponding on the geomembrane. Figure 3 is a conceptual model developed to illustrate the WRP perimeter ditch, drop structures, and projected maximum water level as measured with water level sensors installed around the perimeter of the plateau. Approximately 6% of the WRP surface area experiences water ponding above the geomembrane as a result of the restriction to flow.
Figure 3. Conceptual model of the VJ WRP, perimeter ditch, drop structures and projected maximum water level due to inadequate flow at the GRDL outlet (Vertical exaggeration 7x).

The illustrated water dynamics in Figures 2 and 3 provide an initial conceptual model of performance and understanding for the potential of leakage through defects. Equally important, a database of field responses has been developed to characterize and track the evolution of soil, mineral, and geosynthetic layers in response to site-specific physical, chemical and biological processes.

4. SIMULATED NET PERCOLATION

Empirical equations and measured cover system performance were used to simulate net percolation for the Franklin, Summit, and VJ WRPs. A steady state analysis was used for the Franklin WRP and a transient analysis was used for the Summit and VJ WRPs.

4.1 Steady State Analysis Method – Franklin

The head of water that develops above the geomembrane is a key parameter for estimating leakage and is a function of the transmissivity and infiltration rate through preceding cover system layers. In terms of the Franklin cover system, the “geonet core”, a component of the GDN, has a transmissivity of $1 \times 10^{-3} \text{ m}^2/\text{s}$. There are various physical, chemical, and biological factors that will contribute to reduce the effective transmissivity of the GDN. Reduction factors were used to reduce the laboratory measured transmissivity to account for conditions in the field. The in-service transmissivity can be calculated by:
\[ T_{LT} = \frac{T_{Product}}{R_{IN} \times R_{CR} \times R_{PC} \times R_{CD} \times R_{CC} \times R_{BC}} \]  

[1]

where: \( T_{LT} \) is the long term in-service transmissivity (m\(^2\)/s), \( T_{Product} \) is the specified product transmissivity (m\(^2\)/s), \( R_{IN} \) is the intrusion deformation, \( R_{CR} \) is the creep deformation, \( R_{PC} \) is particulate clogging, \( R_{CD} \) is chemical degradation, \( R_{CC} \) is chemical clogging, and \( R_{BC} \) is biological clogging. Reduction factors specific to the Franklin geonet include: intrusion deformation caused by normal forces acting on the geotextile which can migrate into the geonet core, creep deformation caused by lateral forces acting to compress the geonet core, and biological clogging within the geonet caused by root penetration. Giroud et al. (2000) present a range of reduction factors for a GDN placed within a cover system. Factors specific to Franklin are summarized in Table 1.

Table 1. Reduction factors specific to the Franklin GDN.

<table>
<thead>
<tr>
<th>Application</th>
<th>Normal Stress</th>
<th>( R_{IN} )</th>
<th>( R_{CR} )</th>
<th>( R_{BC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover System</td>
<td>Low</td>
<td>1.0 to 1.2</td>
<td>1.1 to 1.4</td>
<td>1.2 to 1.5</td>
</tr>
</tbody>
</table>

The combined high reduction factor for the Franklin GDN was used and provides an in-service transmissivity of approximately \( 4 \times 10^{-4} \) m\(^2\)/s. Using the in-service transmissivity, the maximum thickness of water and pressure head above the geomembrane was determined based on the methodology presented in Giroud et al. (2000). It was estimated that a downward flux of water to the GDN occurred for approximately 138 days of 2014. As a conservative estimate, the maximum daily steady state flux rate, estimated from the surface balance, was applied to the GDN for each of the 138 days. Leakage from two, 15, and 30 defects/ha, with defects ten millimeters in diameter were evaluated using Giroud et al. (1992). Benson (2000) and Forget et. al. (2005) reported that defects in geomembranes typically range from 2.5 to 25 defects/ha with each defect being approximately 10 mm in diameter. Leakage rates simulated for the geomembrane are based on a poor contact given that a geotextile fabric was placed above the compacted waste rock surface and is determined as follows:

\[ Q = 1.15A^{0.1}h^{0.9}k_{sat}^{0.74} \]  

[2]

where: \( Q \) is the leakage rate (m\(^3\)/s), \( A \) is the area of the defect (m\(^2\)), \( h \) is the hydraulic head (m), and \( k_{sat} \) is the saturated hydraulic conductivity of the underlying material (m/s). Table 2 summarizes the estimated steady state flux rate, calculated head of water, and simulated net percolation for the range of defects. Net percolation attributed to leakage through defects to the underlying waste would be a small component of the water balance. Average annual net percolation should be considered to be in the “very low” range, or less than 0.1% of the annual precipitation.

Table 2. Simulated net percolation for the reclaimed Franklin WRP.

<table>
<thead>
<tr>
<th>Daily Steady State Flux Rate (cm/sec)</th>
<th>Head (mm)</th>
<th>Defects per hectare</th>
<th>Net Percolation (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6 x 10^{-6}</td>
<td>0.2</td>
<td>2</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>0.23</td>
</tr>
</tbody>
</table>

4.2 Transient Flux Rate and Pressure Head Method – Summit and VJ
A transient flux and pressure head was used to simulate net percolation at VJ and Summit. The pressure head above the geomembrane at VJ was calculated using measured flows in the GRDL to estimate the flux rate, except for the area influenced by the GRDL outlet flow restriction (i.e. see Figure 3). In this area measured water levels above the geomembrane were used to estimate leakage.

Figure 4 shows the measured hourly, daily, and cumulative flow in the GRDL for VJ. While variability is observed in the daily flow, the hourly flow is highly attenuated with a maximum rate of approximately 0.3 mm/hr or 8 x 10^{-6} cm/s. Flow was observed in the GRDL for 163 days in 2014. Cumulative lateral drainage above the geomembrane is approximately 228 mm or 15% of precipitation in 2014. These are key performance monitoring aspects in that it demonstrates that the growth medium layer manages approximately 85% of precipitation through runoff and evapotranspiration. This highlights the importance of using a holistic approach in cover system design, which can reduce the dependence on the geomembrane to minimize net percolation.

Figure 4(a) shows the calculated pressure head above the geomembrane and simulated net percolation based on leakage through two, 15, and 30 defects/ha for the area with adequate lateral drainage. The estimated net percolation ranges from 0.03 mm to 0.49 mm for 2 and 30 defects/ha, respectively, and the pressure head primarily remains below 12 mm. The pressure head is deemed accurate given that a response was not observed by water level sensors in this area of the cover system. The pressure transducers are not able to detect a pressure head of 10 mm or less due to the sensor geometry. Figure 5(b) shows that the simulated net percolation is much higher for the geomembrane influenced by the GRDL outlet flow restriction. The measured pressure head surpasses 450 mm and the simulated net percolation is approximately two orders of magnitude greater than that estimated for the rest of the WRP. While the area represents approximately 6% of the landform, it contributes approximately 70% of the total simulated net percolation, as summarized in Table 3. Simulated net percolation for VJ is greater than that of Franklin.
primarily due to differences in the transmissivity of the GRDL and the GRDL outlet flow restriction. In addition, the transient pressured head used for VJ would be more reflective of field conditions compared to the steady state method used for Franklin. While there are differences in the simulated net percolation for Franklin and VJ, rates are considered very low or less than 0.1% of precipitation.

Figure 5. Simulated net percolation for VJ (a) with adequate drainage, and (b) inadequate drainage due to flow restriction at the GRDL outlet.

Table 3. Estimated net percolation based on defects for the reclaimed VJ WRP.

<table>
<thead>
<tr>
<th>Daily Flux Rate (cm/sec)</th>
<th>Head (mm)</th>
<th>Defects per hectare</th>
<th>Net Percolation (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

**Adequate drainage (94% of surface and 30% of total NP)**

- transient transient 0.03 0.24 0.49

**Inadequate drainage (6% of surface and 70% of total NP)**

- transient transient 1.2 9.5 19.2

**Landform**

- transient transient 0.1 0.8 1.6

Net percolation for the Summit WRP was simulated using measured pressured head as illustrated in Figure 6. Given the exclusion of a drainage layer above the geomembrane, extended periods exist where a pressure head is observed. In the late autumn / early winter there is a period of approximately three months where the pressure head
is equal to or near the thickness of the cover system profile. Simulated net percolation for Summit varies from less than 1% of precipitation or 5 mm, to 5% of precipitation or 76 mm. The variability in net percolation creates uncertainty in the long-term loading rates from the WRP and impacts to the receiving environment. There is greater confidence in the performance of the Franklin and VJ WRP cover systems as variability in leakage rates would not result in significantly different loading rates, and therefore impacts to the receiving environment. The larger pressure heads observed at Summit bring into question what should be considered representative post-closure defects for the site.

5. DISCUSSION

Through the use of field performance monitoring data, steady state and transient methods were used to simulate net percolation for the Franklin, Summit, and VJ cover systems. The comparative analysis would suggest that net percolation is very low or less than 0.1% of precipitation for Franklin and VJ, and less than 5% for Summit. The analysis provides an understanding of potential ARD/ML loading from the WRPs and identified key factors that could affect long-term performance. Although still in its infancy, field performance monitoring of cover systems that include geosynthetic layers for the closure of mine waste storage facilities will need to continue to evolve to account for a range of cover system designs, landforms, materials, and climatic conditions.
The comparative analysis was completed using two, 15, and 30 defects/ha, 10 mm in diameter, although there is uncertainty with regards to site specific of post-closure defects over the long term, as well as the service life of the geomembrane. A fundamental outcome demonstrated in the comparative analysis is that the influence of post-closure defects on net percolation is diminished when there is adequate lateral drainage capacity. While there is a considerable range in the estimates of a geomembrane lifespan in the literature, “provided that stress cracking does not occur, it is conceivable (and likely) that a geomembrane may lose strength and become brittle while still performing satisfactory as a barrier” (Rowe 1998). Longer service lives are especially likely when a drainage layer is included to limit the buildup of positive pore-water pressure above the geomembrane and divert water laterally.

Cover systems that include a geomembrane layer limit net percolation by creating a barrier to flow. As a result, a greater demand is placed on the various other components of the cover system, which are equally important to the geomembrane maintaining long-term cover system performance. For example the VJ growth medium layer manages approximately 85% of precipitation through runoff and evapotranspiration and highly attenuates the flux of water to the GRDL. This emphasizes the need for a holistic approach in the design of cover systems that include a geomembrane layer. Understanding that the flux to the drainage layer is a function of the cover system layers placed above the geomembrane and site specific climatic conditions, soil-plant-atmospheric numerical modeling should be implemented to evaluate cover system alternatives for closure of waste storage facilities. The modeling would serve to inform on the risk associated with leakage through defects under long term average and extreme climatic conditions. This is apparent as illustrated by the unique set of water dynamics for the cover systems in this study.

REFERENCES


