

# Natural analogue of a cover with capillary barrier effects to improve the long-term performance evaluation and the design of the cover

**M-K Cissé** *Université du Québec en Abitibi-Témiscamingue, Canada*

**M Guittonny** *Université du Québec en Abitibi-Témiscamingue, Canada*

**B Bussière** *Université du Québec en Abitibi-Témiscamingue, Canada*

## Abstract

*To manage acid mine drainage, some mine sites in Québec, Canada, have been reclaimed using a cover with capillary barrier effects (CCBE). The performance of this oxygen barrier cover system relies on maintaining a fine-grained material layer with a high degree of water saturation. However, after mine closure, CCBEs can be colonised by the surrounding ecosystem (plants, animals, and microorganisms) that can influence its hydraulic properties. Plant roots, for instance, can pump water and decrease the degree of saturation in fine-grained materials. Since CCBEs are expected to perform for hundreds of years, their designs must anticipate long-term environmental changes. Projections of how a changing environment could influence CCBE performance are crucial. Current numerical models to predict water balance can integrate vegetation effects but long-term environmental changes, such as climate change, soil development, and ecological succession, are usually not considered. Model input data associated with future environmental scenarios at reclaimed sites are required. Natural analogues are natural ecosystems that provide clues for more effective cover designs or indicate long-term changes in cover environment. A natural analogue (NA) of a CCBE can help to obtain data representative of long-term environmental changes that may influence the CCBE performance. In this paper, the methodology used to obtain an NA of a CCBE, including the influence of mature vegetation, is presented. The criteria developed to check the analogy between a constructed CCBE, and a natural equivalent are explained (for example, the water table level, hydrogeological properties of materials, and the required contrast between these properties). An example of vegetation data obtained from the natural CCBE analogue is described. Finally, the benefits of using NAs information for the design of engineered cover systems are discussed.*

**Keywords:** *mine reclamation, cover with capillary barrier effects, natural analogue, mature jack pine, boreal ecosystem, root development, cover performance.*

## 1 Introduction

One of the most common issues associated with solid mine wastes, such as tailings, is the generation of acid mine drainage (AMD), which occurs when oxygen and water react with iron sulphide minerals in the wastes. However, these reactions can be limited by introducing engineered cover systems such as covers with capillary barrier effects (CCBEs). CCBEs are comprised of three to five layers of materials with contrasting hydrogeological properties (Aubertin et al. 2002, 2016; Morel-Seytoux 1992; Nicholson et al. 1989). In humid regions, where the water budget is net positive (e.g. much of southern Québec), the main goal of a CCBE is to significantly reduce oxygen fluxes reaching the underlying tailings (Demers & Pabst 2021). The effectiveness of a CCBE as an oxygen barrier is based on its capacity to maintain a (fine-grained) moisture-retaining layer (MRL) at a high degree of saturation by using a phenomenon called the capillary barrier effect (Demers & Pabst 2021). The CCBE significantly reduces the oxygen diffusion coefficient through the cover because oxygen migrates  $10^3$  to  $10^4$  times more slowly in water than in air (Chapuis & Aubertin 2003). Capillary barrier effects are observed when a fine-grained material is placed over a coarser layer in unsaturated conditions (Aubertin et al. 2016; Mbonimpa et al. 2020). The particular hydrogeological contrast

between coarse and fine-grained soils is thus used in the CCBE to create the oxygen barrier. In a CCBE, a second layer of coarse-grained material is placed above the MRL to limit water loss due to evaporation and transpiration (Morel-Seytoux 1992; Bussi re et al. 2007). Four- or five-layer CCBE designs confer additional functions through the addition of a protection layer and/or surface layer; however, these extra layers do not play an active role in maintaining capillary barrier effects (Demers & Pabst 2021). Instead, they are used to protect the three core layers from erosion and bio-intrusion or to promote the establishment and growth of vegetation.

Prior work has demonstrated that efficient and effective CCBEs must remain permanently highly saturated ( $S_r \geq 85\%$ ) in the MRL (Aubertin et al. 1998, 2016; Bussi re et al. 2007; Demers & Pabst 2021). However, after mine closure, plants, animals, and microorganisms from the surrounding ecosystem (Smirnova et al. 2011; Proteau et al. 2020b) may colonise the CCBE and alter its hydraulic properties. For example, plant roots can pump water towards the surface and decrease the  $S_r$  (degree of saturation) of the MRL (Guittonny et al. 2019; Proteau et al. 2020a). Root colonisation can also modify the materials' in situ hydrogeological properties, such as the saturated hydraulic conductivity ( $k_{sat}$ ) and water retention curve (WRC), that control cover performance (Bussi re & Guittonny 2021; Proteau et al. 2020a).

Few prior studies of cover performance have documented the evolution of their hydrogeological properties with respect to ecological processes (Benson et al. 2002; DeJong et al. 2015). However, the ability to predict how ecological changes to the environment could affect a CCBE's performance is crucial given that cover systems are expected to be effective over hundreds of years. Although current numerical models used to predict the unsaturated hydrogeology of covers can integrate vegetation effects, long-term environmental changes like climate change, soil development and ecological succession are usually not considered. The development and improvement of these models requires input data associated with future ecological scenarios at reclaimed sites; however, these data can be difficult to acquire by conventional methods (e.g. long-term monitoring studies).

The use of natural analogues (NAs) may present a suitable, practical alternative for gathering these data. NAs are natural ecosystems that provide clues for more effective cover systems designs or are indicative of long-term changes in cover systems environments (Albright et al. 2010). These cover systems are one of the reclamation options used for the decommissioning of mine waste storage facilities to control AMD production (Aubertin et al. 2016). Thus, studying NAs of a cover system can help to obtain valuable data on the long-term ecological changes that might occur in cover systems. These data could be used to understand how long-term ecological change influences the hydrogeological properties and effectiveness of CCBEs and could be used in predictive models. The objective of this paper is, first, to develop criteria for natural analogues of CCBEs, second, to present the methodology used to identify potential NA sites and third, to describe an example of substrate characterisation and vegetation data obtained from a natural CCBE analogue. Finally, the benefits of using NA information for the design of engineered cover systems are discussed.

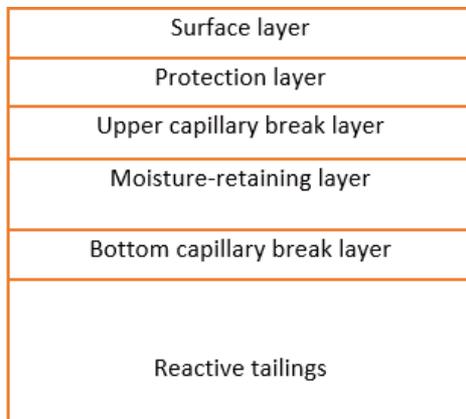
## **2 Presentation of CCBE cover systems and criteria developed to check the analogy between a constructed CCBE and a natural equivalent**

This section briefly presents the generic configuration of CCBE cover systems, and then discusses criteria developed to check the analogy between a constructed CCBE and a natural equivalent. These criteria are the water table level and hydrogeological properties of materials and the required contrast between them.

### **2.1 Configuration of CCBE**

A schematic illustration of a five-layer CCBE placed on acid generating tailings is presented in Figure 1. Each layer has a specific function in the cover system. The core of the CCBE is composed of three layers (upper capillary barrier layer, MRL and bottom capillary barrier layer) (Bussi re & Guittonny 2021). The MRL is a fine-grained material placed between two layers of coarse-grained material (used as the upper and bottom capillary barrier layers) to maintain a high (e.g.  $>85\%$ ) degree of saturation ( $S_r$ ) in the MRL and create an

oxygen diffusion barrier (Bussi re et al. 2003; Proteau et al. 2020a). CCBEs are recommended to reclaim sites that are exposed to positive water budget that allows for periodic water recharge of the MRL, as well as sites with water table levels naturally several metres below the surface of the reactive mine wastes to be reclaimed. CCBEs have previously been discussed in detail by several authors. The interested reader can refer to the work of Demers & Pabst (2021) in particular for a discussion of CCBE design and the factors that influence cover performance.



**Figure 1 Schematic representation of a CCBE with five layers (adapted from Demers & Pabst 2021)**

### 2.1.1 Surface layer

The surface layer is a protective layer. It is not directly involved in the reduction of oxygen flux but protects the cover against water and wind erosion (Demers & Pabst 2021). It separates the lower layers from the surrounding ecosystem, reduces the influence of ecosystem natural processes and integrates the surface of the site to the local landscape (Aubertin et al. 2002). It is usually made of soils containing organic matter (15–20 cm) that facilitates the establishment of vegetation (Aubertin et al. 2015; Demers & Pabst 2021).

### 2.1.2 Protection layer

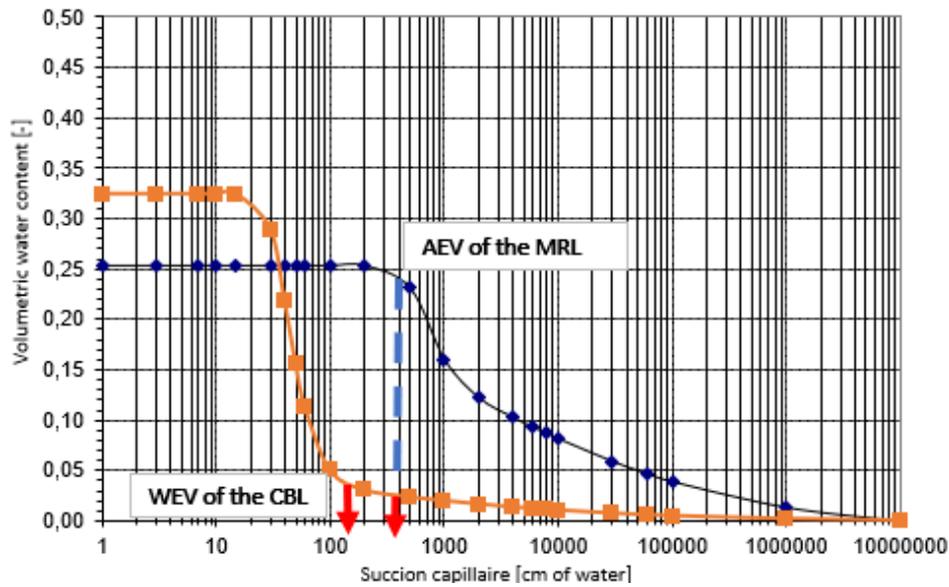
The protection layer aims to protect the core of the cover system against climatic conditions, animals, plant roots and temporarily retain or store infiltration water (Aubertin et al. 2002, 2015). It is made of coarse-grained materials (such as sand and gravel with cobbles) (Demers & Pabst 2021). The thickness of this layer is variable and can sometimes be 1 m thick.

### 2.1.3 Upper capillary break layer

The upper capillary break layer is the first essential functional component of the CCBE and plays a fundamental role in CCBE performance. It is a vertical and lateral drainage layer of granular (sand and gravel or crushed inert waste rock) material that controls water inflow (Demers & Pabst 2021) because this layer has a high saturated hydraulic conductivity ( $k_{\text{sat}} > 10^{-3}$  cm/s) (Aubertin et al. 2015). This coarse-grained layer also acts as a capillary break that prevents moisture loss by evaporation from the MRL. Its thickness is generally between 30 and 50 cm.

### 2.1.4 Moisture-retaining layer

The MRL is the actual oxygen barrier layer of the CCBE. The material for this layer should have hydraulic properties that allow keeping a high degree of saturation, like low  $k_{\text{sat}}$  (e.g.  $10^{-5}$ – $10^{-6}$  cm/s for the Lorraine site CCBE, Nastev & Aubertin 2000) and thus reducing oxygen fluxes. It is made of compacted natural materials such as silt and clay, as well as fined-grained materials that have similar hydrogeological properties like tailings. Its thickness varies from 50 to 100 cm. Compared to the capillary barrier layers, the MRL material should have a lower saturated hydraulic conductivity ( $k_{\text{sat}}$ ) (i.e.  $k_{\text{sat}}$  2–3 orders of magnitude lower than the capillary break layer [CBL] materials), an air entry value (AEV) higher than the water entry value (WEV) of the CBL, and a significant moisture-retaining capacity (Demers & Pabst 2021) (Figure 2).



**Figure 2** Schematic hydraulic functions for the moisture-retaining layer (MRL) and the CCBE (air entry value (AEV) of the MRL > water entry value (WEV) of the capillary break layer (CBL)) (adapted from Mbonimpa et al. 2020)

### 2.1.5 Bottom capillary break layer

The bottom CBL is the CCBE support layer placed on the tailings. This layer is made of a coarse material (such as sand and/or gravel) to provide the required contrast to create a capillary barrier effect and prevent desaturation of the MRL (Bussière et al. 2003; Demers & Pabst 2021). Also, it prevents the rise, by capillarity, of contaminated water from the tailings present underneath. Its saturated hydraulic conductivity should be relatively high ( $k_{sat} \geq 10^{-3}$  cm/s, like that of CBL) (Aubertin et al. 2015; Demers & Pabst 2021). A thickness of 30–50 cm is often suggested to favour drainage.

## 2.2 Criteria developed to check the analogy between a constructed CCBE and a natural equivalent

To the authors’ knowledge, criteria for identifying NAs of CCBEs have not been previously established. Thus, the first goal of this study was to develop and propose a set of criteria for defining NAs. Based largely on the essential properties of a CCBE, several parameters were identified as key criteria. These criteria are summarised in Table 1.

**Table 1** Criteria developed to check the analogy between a constructed CCBE, and a natural analogue

Characteristics	NA water table level	Hydrogeological properties of analogue materials			
		Typical materials	Typical $k_{sat}$	Typical thickness	Required contrast between materials
Criteria	Water table level below -3 m from the surface	Sand (UCBL)	$k_{sat} \geq 10^{-3}$ cm/s	$\geq 0.3$ m	$\Psi_r \text{ Sand} < \Psi_a \text{ Silt}$
		Silt (MRL)	$k_{sat}$ 2–3 orders of magnitude lower than $k_{sat}$ of the sand	0.5–1 m	$\Psi_a \text{ Silt} > \Psi_r \text{ Sand}$
		Sand (BCBL)	$k_{sat} \geq 10^{-3}$ cm/s	$\geq 0.3$ m	$\Psi_r \text{ Sand} < \Psi_a \text{ Silt}$

UCBL: Upper capillary break layer; BCBL: Bottom capillary break layer.

The first criterion is the water table level. NA water table level was targeted below -3 m from the surface in early summer because the CCBE method is usually chosen to reclaim unsaturated tailings, that is, on a site where the water table is at least below -2 m from the surface for tailings, depending on their AEV (Demers &

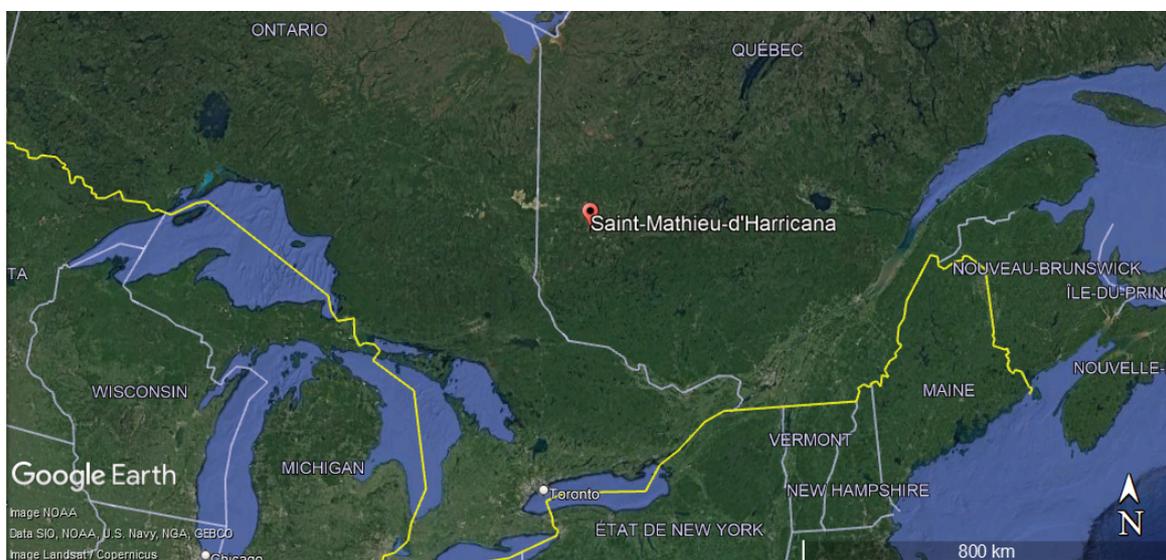
Pabst 2021). In a boreal climate, the water table tends to reach the lowest level during summer when precipitation is low and evaporation is high.

The second criterion concerns hydrogeological properties of NA materials. First, the NA should have multilayered configuration with coarse-grained materials (like sand) below and above fine-grained material (like silt). The thickness of the silt layer should be between 0.5 and 1 m, while the thickness of the sand layers can be more variable, with a minimum required value of 0.3 m. Indeed, an upper CBL layer thicker than 0.3 m would be representative of CCBE configurations including sandy protection layers. The functions of the bottom sand layer, i.e. to act as a capillary barrier and isolate the MRL from the water of the deeper layer, are expected to be maintained if the thickness of this layer is greater than 0.3 m. Secondly, the required contrast between hydrogeological properties of NA materials to create capillary barrier effects and prevent desaturation of the MRL, should be provided. Therefore, NA fine-grained material (silt) should have a greater air entry value (AEV or  $\Psi_a$ ) than the water entry value (WEV or  $\Psi_r$ ) of the coarse-grained materials (sand) below and above the silt and a contrast between  $k_{sat}$  of 2–3 orders of magnitude (Aubertin et al. 2016). Numerous publications on this phenomenon can be found in the literature (e.g. Bussi re et al. 2003; Bussi re & Guittonny 2021; Molson et al. 2008; Morel-Seytoux 1992; Nicholson et al. 1989).

### 3 Method used to obtain a natural analogue of a CCBE

#### 3.1 Potential site selection

Preliminary investigations of potential NA sites were carried out based on regional geological data (Abitibi-T miscamingue, Qu bec, Canada) available for mapping underground water resources (Cloutier et al. 2015). One site showing an ideal alternating sequence of sand and silt layers was identified at the border of esker formations in St-Mathieu d'Harricana, Amos, Qu bec (48  27' 28.21" N, 78  12' 56.06" W; Figure 3). The regional climate is cold and humid (Environnement Canada 1993), with a mean annual precipitation of approximately 889 mm and mean summer temperature of about 17 C (Bussi re et al. 2017).



**Figure 3** The site selected to obtain the natural analogue of a CCBE (St-Mathieu d'Harricana in Abitibi-T miscamingue region, Qu bec, Canada)

The substrate profile of the site is composed of sand layers (coarse-grained materials) placed above and below a silt layer (fine-grained material) (Figure 4a), like the targeted configuration of CCBE cover systems. This site covers a total area of 41 ha and is colonised by mature jack pine (*Pinus banksiana* Lamb.) (i.e. over 60 years old jack pine (Campagna 1996; Morrison et al. 1993)) (Figure 4b). Mature jack pine were selected because the species usually develops a deep tap root (De Silva et al. 1999) up to 3 m (Minist re du D veloppement durable, de l'Environnement et de la Lutte contre les Changements climatiques 2017), which

could pump water and decrease the degree of saturation in the MRL, and therefore influence CCBE performance.



**Figure 4** (a) The substrate profile of the selected site for the natural analogue (NA) of a CCBE, composed of sand layers above and below a silt layer; (b) The selected site for the NA of a CCBE is colonised by mature jack pine vegetation

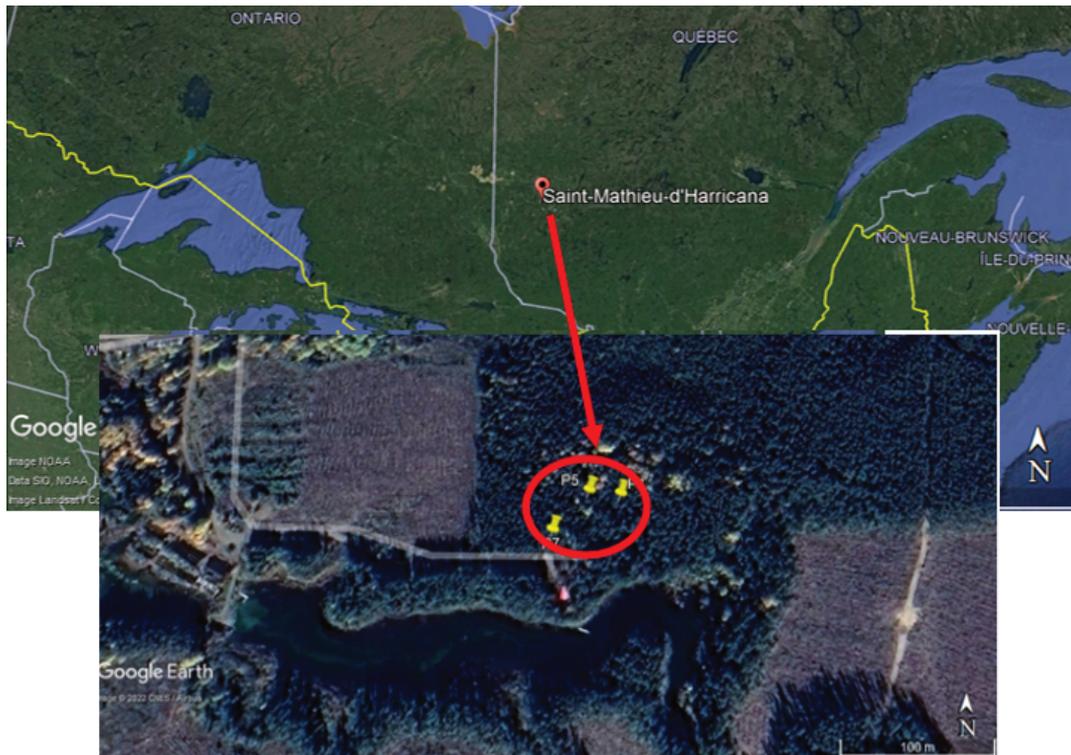
More generally, the site is located in the fir-white birch bioclimatic domain (Viens 2001). The vegetation of the area includes the following species: *Pinus banksiana* Lamb., *Populus tremuloides* Michx., *Picea mariana* (Mill.), *Betula papyrifera* Marsh., *Larix laricina* (Du Roi) K. Koch, *Abies balsamea* (L.) Mill. The growing season begins in May and ends in October.

### 3.2 Sampling, measurements, and analyses

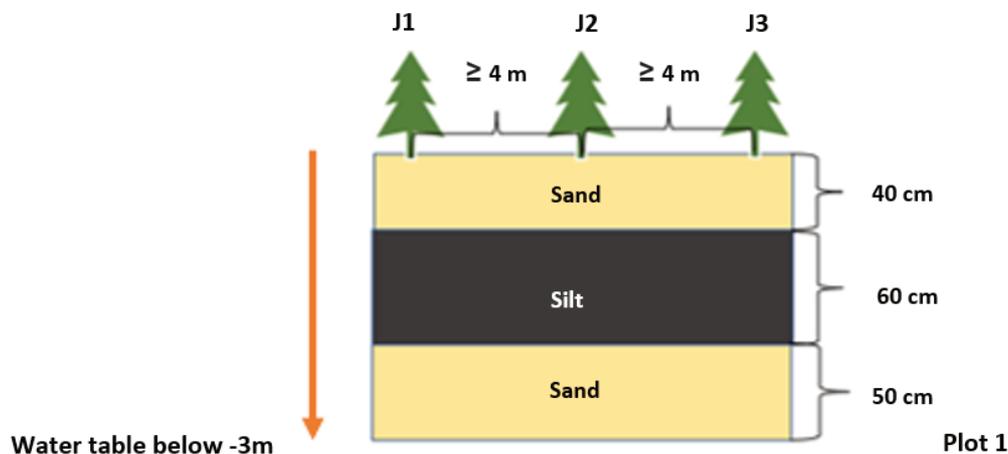
The substrate profile, the water table depth, the substrate geotechnical properties and plant material (age, above-ground size, rooting depth) were characterised in several plots on the selected site. The latter was done to characterise potential plant root colonisation in a CCBE that may influence its performance in the long-term.

#### 3.2.1 Soil coring to check the layered profile and water table depth

In May 2021, one dozen candidate plots were dispersed along a transect perpendicular to the esker. These plots were each validated according to the criteria developed to identify NAs of CCBEs. Thirty cores were dug with a soil auger (3 ¼ Regular auger Bock-1 AMS400.06) across the candidate plots to determine the depth of the water table, as well as the thickness of the sand and silt layers (to a maximum depth of 3 m). Three candidate plots met the two first selection criteria (water table level below -3 m from the surface and coarse-grained materials layers below and above fine-grained material with appropriate thicknesses) and were selected for further study (Figures 5 and 6), while the remaining nine plots were discarded. Then, nine mature jack pine specimens were selected, in a systematic way, from the three plots (i.e. three per plot) to study their root development in the NA profile, as well as check the required hydrogeological properties of materials according to the defined criteria.



**Figure 5** The three experimental plots which met the developed criteria to check the analogy between a constructed CCBE, and a natural equivalent, in St-Mathieu d'Harricana (48° 27' 28.62" N, 78° 12' 56.20" W)



**Figure 6** Example of experimental plot, with the developed criteria to check the analogy between a constructed CCBE and a natural equivalent (water table level, sand below and above silt and materials thicknesses), and targeted plant material (mature jack pine [J])

### 3.2.2 Geotechnical characterisation of each layer material

Firstly, to analyse the particle size distribution, vertical trenches were dug with a mechanical shovel at 50 cm from each jack pine. A total of 18 trenches were dug (six per plot and two per jack pine, perpendicular to each other). Then, material samples were taken on each trench using a core drill. A total of 162 material samples (18 per plot and six per tree) were taken. Three samples were taken per trench (in the sand above the silt, at least at 30 cm from the surface, in the silt, at least at 70 cm from the surface, and in the sand below the silt, at least at 100 cm from the surface). These samples were then dried in the oven at 60°C (for 72 hours, in a laboratory) and then deagglomerated and homogenised. The particle size distribution of each

sample was then obtained by using sieves and a Laser Diffraction Particle Size Analyser (Malvern Mastersizer, Malvern Panalytical Ltd. United Kingdom).

Secondly, undisturbed samples of the sand and the silt were collected in situ with the ring method (CAN/BNQ 2501–058) (known volume) in each of the plots. Then, these samples were dried in an oven at 60°C for 72 hours to determine the dry weight and calculate bulk density. Samples were then deagglomerated and homogenised to determine the relative density (specific gravity [Gs]), using a helium pycnometer (ASTM D5550; Automatic vacuum pycnometer, Qualtech Products Industry, USA). From these results, void ratio (e) and porosity (n) were calculated using well-known mass-volume relationships (Mbonimpa et al. 2020).

Then, the saturated hydraulic conductivity ( $k_{sat}$ ) was predicted using the modified Kozeny-Carman formula (Mbonimpa et al. 2002) (Equation 1):

$$k_{sat} (cm/s) = C_G \frac{\gamma_w e^{3+x}}{\mu_w 1+e} C_u^{1/3} D_{10}^2 \quad (1)$$

where:

$$C_G \approx 0.1.$$

$$\gamma_w = \text{water weight at } 20^\circ\text{C} \approx 10 \text{ kN/m}^3.$$

$$\mu_w = \text{water dynamic viscosity at } 20^\circ\text{C} \approx 10\text{--}3 \text{ Pa}\cdot\text{s}.$$

$$D_{10} = \text{in cm}.$$

$$x \approx 2.$$

The WRC was also predicted using the modified Kovacs (MK) model (Aubertin et al. 2003) (Equation 2), expressed as the volumetric water content as a function of capillary suction:

$$S_r = \frac{\theta}{n} = 1 - \langle 1 - S_a \rangle (1 - S_c) \quad (2)$$

$$\langle y \rangle = 0.5(y + |y|) \text{ (Macaulay brackets)}$$

where:

$$S_c = 1 - [(h_{co}/\Psi)^2 + 1]^m \exp[-m(h_{co}/\Psi)^2] \quad (3)$$

$$S_a = a_c \left(1 - \frac{\ln(1+\Psi/\Psi_r)}{\ln(1+\Psi_o/\Psi_r)}\right) \frac{(h_{co}/\Psi_n)^{2/3}}{e^{1/3} (\Psi/\Psi_n)^{1/6}} \quad (4)$$

$$\Psi_r = 0,86 h_{co,G}^{1,2} \quad (5)$$

$$h_{co,G} = \frac{b}{e D_{10}} \quad (6)$$

$$b = \frac{0,75}{1+1,17 \log(C_u)} \quad (7)$$

$$h_{co} = \text{equivalent capillary height (cm)}.$$

$$m = \text{pore size distribution parameter (1/Cu)}.$$

$$a_c = \text{adhesion coefficient (-) (} a_c = 0.010 \text{ when } \Psi \text{ is expressed in cm of water)}.$$

$$\Psi_n = \text{normalisation parameter introduced for unit consistencies (} \Psi_n = 1 \text{ cm when } \Psi \text{ is given in cm)}.$$

$$\Psi_o = \text{suction (cm) corresponding approximately to complete dryness (} \theta = 0 \text{ at } \Psi = \Psi_o = 107 \text{ cm of water)}.$$

$$\Psi_r = \text{suction at residual water content (cm)}.$$

Finally, the predicted hydraulic properties of the materials were used to validate the contrast between the NA materials for each trench and the presented criteria to check the analogy between a constructed CCBE and a natural equivalent.

### 3.2.3 Root colonisation at each plot and data analyses

The sampled jack pine trunks were cut at the base, their heights measured, and their ages determined by counting tree rings (Mariaux 1967; Peters et al. 2002). Root profiles were then studied. And 4 m × 4 m large and 2 m deep observation trenches were dug with a mechanical shovel at 50 cm from the trunk of each cut tree. Two trenches, perpendicular to each other, were dug by tree. A 90 × 60 cm grid with 5 × 5 cm mesh squares was laid against the vertical trench to study the root distribution along the substrate profile (Guittonny-Larchevêque & Lortie 2017). The root occurrence (number of squares where a root was present/total number of squares × 100) and root density (sum of the number of roots in each grid square/sum of squares' surface in dm<sup>2</sup>) were noted in each trench and were compiled by substrate depth (Guittonny-Larchevêque & Lortie 2017). The maximum depth of root occurrence (cm) from the surface was noted in each trench (Guittonny-Larchevêque & Lortie 2017).

## 4 Results: example of substrate characterisation and vegetation data obtained from a natural CCBE analogue

Example of characterisation results obtained from one NA (plot 1) is summarised in Table 2.

**Table 2 Results obtained from plot 1 material characterisation**

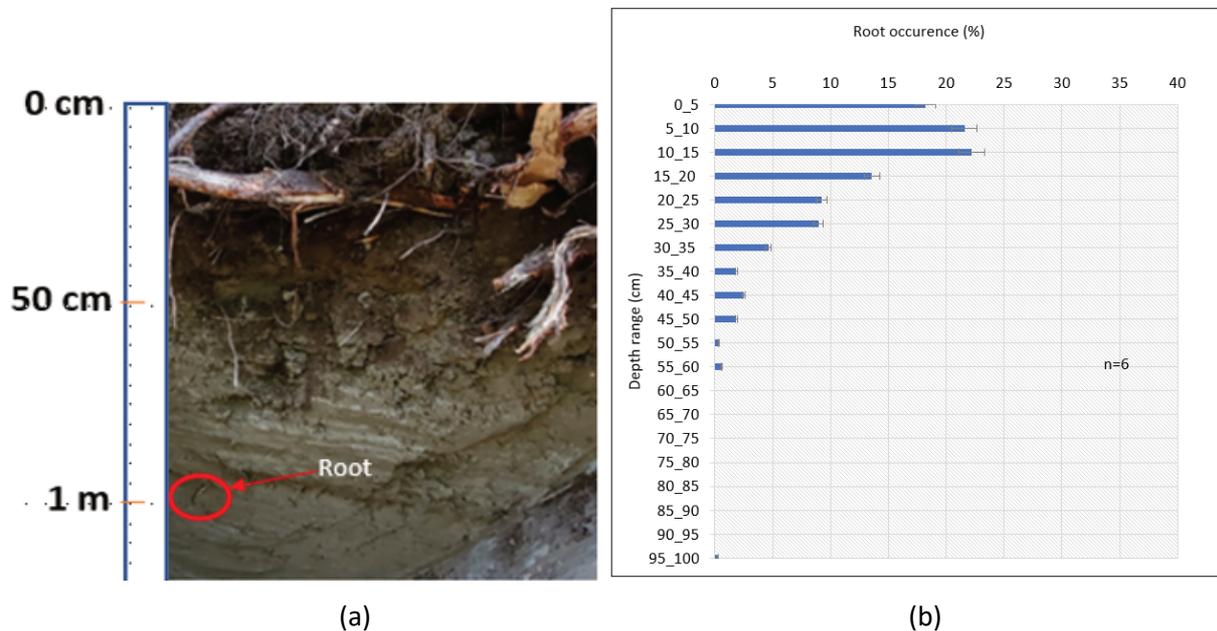
Plot	Plot 1		
<b>Water table level</b>	Below 3 m from the surface		
<b>Materials</b>	Sand	Silt	Sand
<b>Material thickness</b>	40 cm	60 cm	50 cm
<b>Porosity (without unit)</b>	0.424	0.258	0.424*
<b>Void ratio (ratio of void volume to solid volume)</b>	0.737	0.349	0.737
<b>K<sub>sat</sub> (cm/s)</b>	9.98E-2	8.73E-7	6.64E-2
<b>D<sub>10</sub> (µm)</b>	263	1.25	208
<b>D<sub>60</sub> (µm)</b>	466	8.75	385
<b>Ψ<sub>a</sub> (cm)</b>	10	3000	12
<b>Ψ<sub>r</sub> (cm)</b>	50	6 E+05	80
<b>Ψ<sub>a</sub> silt &gt; Ψ<sub>r</sub> sand, contrast between k<sub>sat</sub> of 2–3 orders of magnitude?</b>	Yes	Yes	Yes

\*Assumed to be equal to that of above the silt

Plot 1 substrate characterisation (Table 2) clearly shows that the selected NA meets the developed criteria to obtain a CCBE equivalent. Indeed, the plot water table level is below -3 m from the surface. There is sand below and above the silt and the hydrological properties of materials meet the required contrast between materials (Ψ<sub>a</sub> of the silt > Ψ<sub>r</sub> of the sand and there is a contrast between k<sub>sat</sub> of 2–3 orders of magnitude).

Data of jack pine root development on the NA of a CCBE (root density, root occurrence, and the maximum depth of root occurrence) were obtained. In plot 1, a 77-year-old jack pine with a height of 16 m developed roots up to 1 m deep (in the silt) from the surface (Figure 7a), although most of the roots were concentrated in the first 20 cm in the first sand layer (Figure 7b). The diameter of roots reaching the silt layer ranged from 0.1 to 2 mm. These initial observations showed that, while the deepest roots fell significantly short of

previously reported values from the literature (up to 3 m), they could still reach the silt layer of a CCBE analogue. This could have significant impacts on its hydrogeotechnical properties and ability to control oxygen migration.



**Figure 7** (a) Example of roots (developed by a 77-year-old jack pine) at 1 m depth in the silt of plot 1; (b) Example of mean root occurrence in plot 1 (n = 6 observation trenches around a tree)

## 5 Conclusion: benefits of using NA information for the design of engineered cover systems

In a boreal forest ecosystem, it can take several decades to hundreds of years before natural plant succession establishes mature forests on newly constructed engineered cover systems. However, mine site reclamation is a relatively new practice, with modern reclamation technologies only having begun to be applied over the past 30 years (Bussière & Guittonny 2021). The absence of multidecadal monitoring studies is, therefore, a challenge to understanding the effects of mature forest vegetation on the performance of engineered cover systems. However, the initial results presented in this study suggest that NAs of CCBE do exist in undisturbed ecosystems and can provide data that can help to inform the design of engineered cover systems for long-term resilience. This study proposed the methodology to find a NA of a CCBE. A site at St-Mathieu d’Harricana in Abitibi-Témiscamingue, Québec (Canada) was selected for investigation. The site was primarily forested with mature jack pine, which can develop deep roots capable of pumping groundwater and decreasing the degree of saturation in the MRL of a CCBE. It was hypothesised that this would likely have a negative effect on the long-term performance of a CCBE. Initial data from the site showed that the substrate was comprised of layers of sand and silt that were configured similarly to a CCBE and had the hydrogeological properties necessary to form a capillary break. Observation trenches revealed deep roots (maximum 1 m) that penetrated the silty material. This suggests that NA sites such as this could be useful in studying the impacts of mature ecosystems on the performance of CCBEs.

Future work will include investigations of root development in mature jack pines at additional NA sites to obtain more representative root parameters, as well as the application of these data as inputs in numerical models to predict the long-term performance of CCBEs. Based on a literature review of previous studies (e.g. Albright et al. 2010; Waugh et al. 1994) it was shown that using NA information for the design of engineered cover systems can help to:

- Define future environmental scenarios at reclaimed sites for inputs to numerical models and field tests.

- Provide insights into the possible evolution of covers as a basis for monitoring leading indicators of change.
- Improve our understanding of long-term environmental changes on engineered cover systems.
- Provide complementary and real-world alternatives for stakeholders to visualise the long-term evolution of covers rather than relying solely on the predictions of numerical models.

## References

- Albright, WH, Benson, CH & Waugh, WJ 2010, *Water Balance Covers for Waste Containment: Principles and Practice*, American Society of Civil Engineers, Reston.
- Aubertin, M, Bussière, B & Bernier, L 2002, *Environnement et Gestion des Rejets Miniers*, manual on CD-ROM, Presses Internationales Polytechnique, Montréal.
- Aubertin, M, Bussière, B, Pabst, T, James, M & Mbonimpa, M 2016, 'Review of the reclamation techniques for acid-generating mine wastes upon closure of disposal sites', in D Zekkos, A Farid, A De, KR Reddy & N Yesiller (eds), *Proceedings of Geo-Chicago*, American Society of Civil Engineers, Reston, pp. 343–358.
- Aubertin, M, Mbonimpa, M, Bussière, B & Chapuis, RP 2003, 'A model to predict the water retention curve from basic geotechnical properties', *Canadian Geotechnical Journal*, vol. 40, no. 6, pp. 1104–1122.
- Aubertin, M, Pabst, T, Bussière, B, James, M, Mbonimpa, M, Benzaazoua, M & Maqsoud, A 2015, 'Revue des meilleures pratiques de restauration des sites d'entreposage de rejets miniers générateurs de DMA' (Review of best practices for remediation of AMD-generating mine waste disposal sites), *Proceedings of the 2015 Symposium on Mines and the Environment*, Rouyn-Noranda.
- Aubertin, M, Ricard, JF & Chapuis, RP 1998, 'A predictive model for the water retention curve: Application to tailings from hard-rock mines', *Canadian Geotechnical Journal*, vol. 35, no. 1, pp. 55–69.
- Benson, AJ, McFarlane, GA, Allen, SE & Dower, JF 2002, 'Changes in Pacific hake (*Merluccius productus*) migration patterns and juvenile growth related to the 1989 regime shift', *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 59, no. 12, pp. 1969–1979.
- Bussière, B & Guittonny, M (eds) 2021, *Hard rock mine reclamation: from prediction to management of acid mine drainage*, CRC Press, Boca Raton.
- Bussière, B, Aubertin, M & Chapuis, RP 2003, 'The behavior of inclined covers used as oxygen barriers', *Canadian Geotechnical Journal*, vol. 40, no. 3, pp. 512–535.
- Bussière, B, Aubertin, M, Mbonimpa, M, Molson, JW & Chapuis, RP 2007, 'Field experimental cells to evaluate the hydrogeological behaviour of oxygen barriers made of silty materials', *Canadian Geotechnical Journal*, vol. 44, no. 3, pp. 245–265.
- Bussière, B, Demers, I, Charron, P, Bossé, B, Roy, P, Jébrak, M & Trépanier, S 2017, *Analyse de risque et de vulnérabilité liés aux changements climatiques pour le secteur minier Québécois (Climate change risk and vulnerability analysis for the Quebec mining sector)*, report submitted to MERN, 106 p.
- Campagna, M 1996, *Le cycle du carbone et la forêt: de la photosynthèse aux produits forestiers (The carbon cycle and forests: from photosynthesis to forest products)*, Direction de l'environnement forestier, Service de l'évaluation environnementale, Gouvernement du Québec, Québec.
- Chapuis, RP & Aubertin, M 2003, 'On the use of the Kozeny-Carman equation to predict the hydraulic conductivity of soils', *Canadian Geotechnical Journal*, vol. 40, no. 3, pp. 616–628.
- Cloutier, V, Blanchette, D, Dallaire, PL, Nadeau, S, Rosa, E & Roy, M 2015, *Projet d'acquisition de connaissances sur les eaux souterraines de l'Abitibi-Témiscamingue (partie 2), Rapport déposé au Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques dans le cadre du Programme d'acquisition de connaissances sur les eaux souterraines du Québec (Project to acquire knowledge on groundwater in Abitibi-Témiscamingue [part 2], Report submitted to the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques under the Quebec Groundwater Knowledge Program)*, research report.
- De Silva, HN, Hall, AJ, Justin, DS & Gandar, PW 1999, 'Analysis of distribution of root length density of apple trees on different dwarfing rootstocks', *Annals of Botany*, vol. 83, pp. 335–345.
- DeJong, J, Tibbett, M & Fourie, A 2015, 'Geotechnical systems that evolve with ecological processes', *Environmental Earth Sciences*, vol. 73, no. 3, pp. 1067–1082.
- Demers, I & Pabst, T 2021, 'Covers with capillary barrier effects', in B Bussière & M Guittonny (eds), *Hard Rock Mine Reclamation: From Prediction to Management of Acid Mine Drainage*, CRC Press, Boca Raton.
- Environnement Canada 1993, *Normales climatiques au Canada: 1961–1990*, Québec (*Canadian Climate Normals: 1961–1990, Quebec*), Environnement Canada, Service de l'environnement atmosphérique, Ottawa.
- Guittonny, M, Bussière, B, Maqsoud, A, Proteau, A, Ben Khouya, T & Botula, YD 2019, 'Colonisation racinaire dans les recouvrements miniers et impact sur leur fonctionnement' (Root colonisation in mining covers systems and impact on their functioning), *Proceedings of the Symposium of Mines and the Environment*, Rouyn-Noranda.
- Guittonny-Larchevêque, M & Lortie, S 2017, 'Above- and Belowground development of a fast-growing willow planted in acid-generating mine technosol', *Journal of Environmental Quality*, vol. 46, pp. 1462–1471.
- Mariaux, A 1967, Les cernes dans les bois tropicaux africains: nature et périodicité : peuvent-ils révéler l'âge des arbres? (Tree rings in African tropical woods: nature and periodicity, can they reveal the age of the trees?), *Bois et Forêts*, no. 113.

- Mbonimpa, M, Aubertin, M, Chapuis, RP & Bussière, B 2002, 'Practical pedotransfer functions for estimating the saturated hydraulic conductivity', *Geotechnical & Geological Engineering*, vol. 20, no. 3, pp. 235–259.
- Mbonimpa, M, Boulanger-Martel, V, Bussière, B & Maqsoud, A 2020, 'Water, gas, and heat movement in cover materials', in B Bussière & M Guittonny (eds), *Hard Rock Mine Reclamation: From Prediction to Management Of Acid Mine Drainage*, CRC Press, Boca Raton.
- Ministère du Développement durable, de l'Environnement et de la Lutte contre les Changements climatiques 2017, *Arbres et arbustes à utiliser pour la végétalisation des terrains réhabilités par analyse de risque (Trees and shrubs to be used for revegetation of reclaimed land by risk analysis)*, Ministère du Développement durable, de l'Environnement et de la Lutte contre les Changements climatiques, Québec.
- Molson, J, Aubertin, M, Bussière, B & Benzaazoua, M 2008, 'Geochemical transport modelling of drainage from experimental mine tailings cells covered by capillary barriers', *Applied Geochemistry*, vol. 23, no. 1, pp. 1–24.
- Morel-Seytoux, HJ 1992, L'effet de barrière capillaire à l'interface de deux couches de sol aux propriétés fort contrastées (The capillary barrier effect at the interface of two soil layers with very different properties), *Hydrol. Continent*, vol. 7, no. 2, pp. 117–128.
- Morrison, IK, Foster, NW & Hazlett, PW 1993, 'Carbon reserves, carbon cycling, and harvesting effects in three mature forest types in Canada', *New Zealand Journal of Forestry Science*, vol. 23, no. 3, pp. 402–412.
- Nastev, M & Aubertin, M 2000, 'Hydrogeological modelling for the reclamation work at the Lorraine mine site Québec', *Proceedings of the 1<sup>st</sup> Joint IAH-CNC-CGS Groundwater Specialty Conference*, American Society of Mining and Reclamation, Lexington.
- Nicholson, RV, Gillham, RW, Cherry, JA & Reardon, EJ 1989, 'Reduction of acid generation through the use of moisture-retaining cover layers as oxygen barriers', *Canadian Geotechnical Journal*, vol. 26, pp. 1–8.
- Peters, VS, Macdonald, SE & Dale, MR 2002, 'NOTE Aging discrepancies of white spruce affect the interpretation of static age structure in boreal mixed woods', *Canadian Journal of Forest Research*, vol. 32, no. 8, pp. 1496–1501.
- Proteau, A, Guittonny, M, Bussière, B & Maqsoud, A 2020a, 'Oxygen migration through a cover with capillary barrier effects colonised by roots', *Canadian Geotechnical Journal*, vol. 57, no. 12, pp. 1903–1914.
- Proteau, A, Guittonny, M, Bussière, B & Maqsoud, A 2020b, 'Aboveground and belowground colonisation of vegetation on a 17-year-old cover with capillary barrier effect built on a boreal mine tailings storage facility', *Minerals*, vol. 10, no. 8, p. 704.
- Smirnova, E, Bussière, B, Tremblay, F & Bergeron, Y 2011, 'Vegetation succession and impacts of bioinvasion on covers used to limit acid mine drainage', *Journal of Environmental Quality*, vol. 40, no. 1, pp. 133–143.
- Viens, É 2001, *Effets de l'éclaircie commerciale sur la croissance et la forme de la tige du pin gris (Pinus banksiana Lamb.) en Abitibi, Québec (Effects of commercial thinning on growth and stem shape of jack pine (Pinus banksiana Lamb.) in Abitibi, Québec)*, Université du Québec à Chicoutimi, Québec.
- Waugh, W, Petersen, K, Link, S, Bjornstad, B & Gee, G 1994, 'Natural analogs of the long-term performance of engineered covers', in G Gee & N Wing (eds), *In-Situ Remediation: Scientific Basis For Current And Future Technologies*, Battelle Press, Columbus, pp. 379–409.