SUCTION BREAK TO CONTROL SLOPE-INDUCED MOISTURE VARIATION IN LAYERED COVERS

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ABSTRACT
Covers with capillary barrier effects (CCBE) can be used to limit gas flux into or out of waste disposal sites. Numerical modeling and field test results showed that the hydraulic behaviour of such type of cover is influenced by slope inclination, which can induce a local desaturation that is detrimental to its efficiency. This negative effect can be minimized by placing a suction break in the moisture-retaining layer of the inclined cover. This concept was applied on a small portion of the South-east dam of the LTA tailings site cover, and tests were conducted under various conditions. The results under natural climatic conditions show the presence of a saturated zone near the suction break, which confirms the validity of this concept in the field. The volumetric water content of this saturated area was not affected even after 78 days without water infiltration. Also, in situ tests with large precipitation lead to a better understanding of the influence of a suction break on the hydraulic behaviour of the inclined CCBE, in terms of water and suction distribution in the different layers and of the ensuing water diversion capacity. This study showed that a suction break could be used to improve the performance of inclined CCBE used to limit gas migration, and that it can also influence the diversion length under particular conditions.

RÉSUMÉ
Les couvertures avec effets de barrières (CEBC) peuvent être utilisées pour limiter le flux des éléments gazeux vers les rejets ou hors des sites d’entreposage. Des résultats de terrain et des modélisations numériques ont montré que le comportement hydrique de CEBC est influencé par la pente, qui peut induire une désaturation locale qui nuit à son efficacité. Cet effet de pente peut être réduit en plaçant un bris de succion au sein de la couche de rétention d’eau. Ce concept a été appliqué au niveau de la digue sud-est de la CEBC installée sur le parc à résidus miniers LTA. Des essais ont été réalisés sous différentes conditions. Les résultats des tests sous les conditions climatiques naturelles montrent l’apparition d’une zone saturée autour du bris de succion validant ainsi ce concept sur le terrain. Cette zone saturée n’a subit aucune variation de teneurs en eau volumiques, après 78 jours sans infiltrations d’eau. Les essais d’infiltration avec des taux de précipitations élevés ont aussi permis de mieux comprendre l’effet du bris de succion sur le comportement hydrique de la CEBC inclinée, en terme de distribution de l’eau et des suctions au sein des différentes couches, et sur sa capacité de diversion. Cette étude montre que le concept de bris de succion peut être utilisé afin d’améliorer la performance des CEBC inclinées utilisées pour réduire la migration des gaz, et aussi pour influencer la capacité de diversion sous certaines conditions.

1. INTRODUCTION
When mine wastes are considered acid-generating, different waste management options and rehabilitation strategies are available to inhibit acid production. Under the humid climate prevailing in the eastern Canadian provinces, the use of techniques that limit oxygen availability (sometimes called oxygen barriers) is generally considered to be the most viable option (e.g. SRK 1989; MEND 2001). Among these techniques, one of the most practical option is the use of a cover with capillary barrier effects CCBE (e.g. Nicholson et al. 1989; Aubertin et al. 1996a, b; Ricard et al. 1997a, b; Bussière et al. 2003a, b). This type of cover is based on the capillary barrier principle. When a fine-grained material overlies a coarser one, the water retention contrast between the two materials creates capillary barrier effects that limit the vertical flow of water at the interface. Capillary barrier effects then help to maintain the fine-grained material near saturation. Because the conductivity and diffusion of gas is low through a soil with a high moisture content, creating a highly saturated layer reduces the availability of oxygen at the bottom of the cover. By limiting the diffusion of oxygen, the cover reduces the production of acid mine drainage (AMD). The same phenomena can also be used to limit outward gases migration such as radon or biogas from waste disposal site.

In addition to the configuration of the CCBE and the properties of materials, other parameters must be taken into account at the design stage to insure the performance of the cover. One of them is the geometry of the sloping areas. Many studies have shown the effect of the slope on water movement in inclined covers (Frind et al. 1976; Ross 1990; Stormont 1995; Aubertin et al. 1997b; Bussière et al. 2002, 2003a). These studies indicate that when a cover is built on an inclined surface, the water
distribution in the layers is not uniform along the slope. In a CCBE used to limit the oxygen flux to reactive tailings, suction tends to increase upward along the sloping cover. This situation can induce a progressive desaturation by drainage of the moisture-retention layer. The desaturation is generally more significant near the top of the slope than at the bottom (Bussière et al. 2003a, b; Bussière et al. 2005; Maqsoud et al. 2005).

In order to reduce the slope effect in inclined covers, the suction break concept was proposed (Aubertin et al. 1996a, b, 1997a). The objective of the suction break is to create a localized saturated area in the moisture-retention layer, and consequently a near-zero suction zone in the cover (see Figure 1). The influenced zone will have a lower suction, and thus a higher degree of saturation and lower gas diffusion characteristics. To be effective, the suction break must be made out of a low hydraulic conductivity material. For example, one can use silty or clayey materials, GCL or geomembranes.

![Figure 1. Configuration of the suction break cell constructed at the LTA tailings disposal site](image)

Few preliminary studies on the behavior of suction breaks were carried out, mainly by the use of numerical modeling and field tests (Golder Associates 1999; Bussière et al. 2000, 2002 and 2003a). To evaluate the effect of suction break, a new field test was performed on the "Les Terrains Aurifères" (LTA) cover installed on reactive tailings. In this paper, the authors present: i) a description of the constructed suction break cell and its instrumentation, ii) a description of the different field tests, iii) the main test results with a brief discussion. The paper ends with a short conclusion.

2. LTA COVER

The LTA tailings pond is located in the Fournière and Dubuisson Townships, approximately 8.5 km South-east of Malartic, Québec. The LTA tailings site occupies an area of approximately 60 ha and contains about 12 m of sulphide tailings placed over 5 m of non acid-generating tailings (McMullen et al. 1997; Ricard et al. 1997a). The site was rehabilitated in 1995-1996. The rehabilitation scenario for the tailings impoundment consisted in the construction of a multi-layered cover with capillary barrier effect (CCBE) that aims to reduce the oxygen flux to the reactive tailings and consequently, the production of AMD. The LTA cover consists of three layers. From bottom to top (see Figure 2), they are (Ricard et al. 1997b; 1999):

- a 0.5 m layer of sand used as support and a capillary break layer, its saturated hydraulic conductivity \( k_{sat} \) is between \( 8 \times 10^{-2} \) and \( 1 \times 10^{-1} \) cm/s, while its Air Entry Value \( \psi_a \) measured in the lab is between 20 and 40 cm of water.
- a moisture-retaining layer with a thickness of 0.8 m. This layer is made of non acid-generating tailings (MRN tailings) taken from the nearby Malartic Goldfield property (a site which belongs to the Quebec Natural Resources Ministry); the \( \psi_a \) value measured in the lab on the MRN tailings samples is between 136 to 280 cm of water, depending on its grain size and porosity. The \( k_{sat} \) of the MRN tailings, evaluated in rigid wall permeameters for a range of porosity \( n \) of 0.42 to 0.51, is between \( 3.0 \times 10^{-5} \) and \( 1.9 \times 10^{-4} \) cm/s.
- a 0.3 m sand and gravel layer on top to create a drainage and protective layer against erosion, evaporation and bio-intrusions.

![Figure 2. Configuration of the LTA site, with the cover and location of the suction break cell](image)

Various instrumented monitoring stations were installed on the LTA site to evaluate the hydraulic behaviour of the CCBE. The emphasis was placed on assessing the response of the moisture-retaining layer. Some stations were equipped with TDR probes (to measure the volumetric water content \( \theta \)) and Watermark sensors (to measure the matric suction \( \psi \)), while others were only equipped with TDR probes. The details regarding these stations can be found in Golder Associates (1999), and Ricard et al. (1997a, b, 1999).

Results from the monitoring at LTA site show that on the flat area occupying most of the site and at the bottom of sloping areas, the volumetric water content \( \theta \) in the moisture-retaining layer remains stable and is usually greater than 0.37 (with Sr > 87% exceeding the design criteria of Sr \( \geq 85\% \)); the suction \( \psi \) at the same locations is below the \( \psi_a \) of the MRN tailings (Maqsoud et al. 2005, Bussière et al. 2005). Nonetheless, near the top of sloping
areas of the cover placed on the tailings dam, the $\Theta$ measured is lower than that near the bottom. In some cases, and especially near the top of the South-east dam (see Figure 2 for location), the $\psi$ can even become higher than the $\psi_a$ value of the MRN tailings for short periods of time during the year. This localised behaviour clearly confirms that the slope influences the hydraulic response of the CCBE, especially during prolonged dry periods, as predicted by numerical, analytical and physical modeling (e.g. Aubertin et al. 1997a, Bussière et al. 2003a). To reduce this slope effect, the concept of suction break was proposed by Aubertin et al. (1996a, b; 1997a). A preliminary assessment was done on location in 1997 (Golder Associates 1999), but the results were not entirely conclusive. Hence, additional field tests were conducted in 2004. In the next paragraphs, the main steps for the suction break cell construction are presented, followed by the field tests performed.

3. DESCRIPTION OF THE FIELD INVESTIGATIONS

Monitoring results showed that the top of the South-east dam is more affected by the geometry of the slope than the other sections of the dam. For this reason, this dam was chosen to study the influence of a suction break on water movement in an inclined CCBE (see Figure 2 for location of the suction break).

3.1 Suction break construction

The suction break cell was constructed during the month of June of 2004. The length of the slope of the South-east dam is approximately 30 m and the inclination angle is about 33°; the total elevation of the dam is 16 m. For the construction of the suction break cell, a geosynthetic clay liner (GCL) was used to create a saturated zone in the moisture-retaining layer. This material has a low saturated hydraulic conductivity ($k_{sat}$ of about 5x10^{-8} cm/s). The suction break cell was installed 10 m from the base of the slope. The cell is 17.5 m long and 2.5 m wide (see Figure 3).

![Figure 3. Detailed description of the suction break cell (SB) constructed at the LTA site, with its instrumentation](image)

The construction of the suction break cell was conducted in three steps (see Figure 4 for details):

- **Step 1**, materials excavation: The installation of the suction break required the excavation of the protective layer and of the moisture-retaining layer (sand and gravel; MRN tailings). During this operation, the materials used for these two layers were put aside separately.

- **Step 2**, GCL installation: After the excavation of the two layers, the GCL was installed directly on the bottom sand layer which constitutes the capillary break layer (see Figure 4). During this operation, different monitoring stations were also installed (see details below).

- **Step 3**, reinstallation of the cover materials: After the placement of the GCL, the excavated materials were put back in place, respecting the initial configuration of the CCBE and the initial in situ properties of the materials (such as porosity).

![Figure 4. Steps for the construction of the suction break cell in the LTA cover of the South-east dam (Step 1: excavation, Step2: GCL installation and Step 3: material put back in place)](image)
3.2 Monitoring stations

To evaluate the effect of the suction break on moisture distribution in the inclined CCBE constructed on the South-east dam, several monitoring stations were installed. These stations were placed along the slope and were grouped in three lines: A, B, and C (see Figure 3). Lines A and B cross the suction break cell, while Line C was placed out of the suction break cell influence so that it could be used as reference for the evaluation of the suction break influence on water distribution.

For each line, five monitoring stations were installed and these were numbered 1, 2, 3, 4 and 5 going from top to bottom of the slope (see Figure 3). These stations were placed approximately at 6 m intervals. Each station was equipped with three Watermark sensors (W) for suction measurements and with three TDR probes (T) for volumetric water content measurements. The Watermark sensor W3 and the TDR probe T3 are located at the same elevation (15 cm from the base of the moisture-retaining layer), while the Watermark sensor W5 and the TDR probe T5 are installed 15 cm from the interface between the moisture-retaining layer and the top sandy layer. The TDR probe T1 and Watermark sensor W1 were installed in the bottom sandy layer, 15 cm from the interface with the moisture-retaining layer.

3.3 Field tests performed

After the construction of the instrumented suction break cell, θ and ψ measurements were taken under various conditions:

- Natural climatic conditions: For 4 weeks, θ and ψ were measured once a week. The principal objective was to further evaluate the behaviour of this part of the South-east dam under natural climatic variations.
- Zero infiltration boundary conditions: In order to evaluate the behaviour of the studied area under long periods without infiltration, a watertight plastic cover was placed on the studied area (see Figure 5). This period lasted 78 days.
- Extreme precipitation: After the long drainage period, the plastic cover was removed and large scale infiltration tests were performed. The infiltration rate used was equivalent to extreme rain conditions corresponding to a period of return of 1000 years (Aubertin et al. 1997b). The corresponding intensity of sprinkled water applied was 27 mm per hour for six hours.

4. MAIN RESULTS

During the construction of the instrumented suction break, various in situ measurements were carried out including MRN tailings layer thickness, and volumetric water content with sampling of MRN tailings for laboratory characterization. Measurements of gravimetric water content and dry density of the MRN tailings were determined, along with grain size analyses. These results are not shown here, but can be found in Cissokho (2004); the results were in accordance with the design parameters for this cover.

In the following section, the main results of the θ and ψ measurements taken during the field tests are presented, emphasizing the hydraulic behaviour of the sloping area with the suction break cell. For convenience, the time given in all of the figures (under natural climatic conditions and zero infiltration boundary conditions) corresponds to the end of the suction break construction.

4.1 Natural climatic conditions

As previously mentioned, θ and ψ were measured every week under natural climatic conditions (for four weeks). The first objective was to verify the validity of the suction break concept, which consists in creating a water-saturated area in the moisture-retaining layer where suction is near zero. The second objective was to further evaluate the actual hydraulic behaviour of this part of the South-east dam under natural climatic conditions and to determine the effect of the suction break on the hydraulic behaviour of the slope.

The results of ψ measurements for Lines A and C at level four are presented in Figure 6. This figure shows that the ψ values near the suction break cell (Station A4 – see Figure 3 for location) remained close to zero throughout the entire observation period. In comparison, at Station C4, where there was no suction break, the ψ values varied and were greater than zero (30 < ψ <110 cm of water).
Figure 6. Evolution of the suction measured in the moisture-retaining layer at Stations A4'-W3 and C4-W3 under natural climatic variations

The zero suction value in the moisture-retaining layer of the suction break cell, and the corresponding high degree of saturation of this zone are attributed to the GCL, which controls the water flow along the slope and creates an accumulation zone. Based on these results, it was inferred that the installation of the suction break cell produced the desired effect.

The evolution of the volumetric water content measured along Line A is presented in Figure 7. This figure shows that there is a clear differentiation of the volumetric water content along the slope. The highest \( \theta \) value was measured near the suction break cell, at about 0.43, whereas the lowest \( \theta \) value was measured near the top of the slope (\( \theta \) of approximately 0.30).

The \( \theta \) value tends to decrease from the suction break cell (Station A4') toward the top of the slope (Station A1). Also, the \( \theta \) values measured near the lower part of the slope are slightly smaller than those measured near the suction break cell. This phenomenon is attributed to the nearly impervious GCL that limits water movements to the bottom part of the slope.

Figure 7. Volumetric water content evolution measured along Line A under natural climatic variations

4.2 Zero infiltration boundary conditions

The studied area was submitted to an artificial zero infiltration boundary conditions by covering the area with a watertight plastic sheet. This area was 34 m long and 30 m wide. Because of space limitations, only \( \theta \) and \( \psi \) measurement results from Station A2 located (near the top of the slope) and from Station A4' (located at the suction break cell) are presented.

Figure 8 shows the \( \theta \) and \( \psi \) values measured at the base of the moisture-retaining layer (15 cm from the interface with the capillary barrier layers), at Station A2. This figure shows that during the testing period, the water content decreased from 0.34 to 0.30 (see Figure 8). The \( \theta \) value stabilized after 47 days of forced drought (corresponding to 75 days after the construction of the suction break cell).

During the same period, the \( \psi \) values near the top of the slope in the moisture-retaining layer increased gradually from 102 cm of water to a maximum value of 204 cm of water at the end of the test. This increase in suction explains the decrease in volumetric water content. It indicates that the suction became larger than the air entry value (\( \psi_a \)) of the MRN tailings.

Results obtained at Station A4' near the lower part of the slope (see Figure 3 for location) are given in Figure 9. This figure shows that the \( \psi \) values are close to zero (considering the precision of the equipments). This indicates that the moisture-retaining layer remained saturated locally, despite the zero infiltration boundary condition. The \( \theta \) value showed a slight variation, which corresponds to a maximum of 0.02; this variation is close to the TDR measurement precision (0.02; see Whalley, 1993). Consequently, one can consider that the \( \theta \) value in the moisture-retaining layer remained near its saturation value of 0.44 (which corresponds to the \textit{in situ} porosity measured in the field).

Figure 8. Evolution of volumetric water content and suction values measured at Station A2 under zero infiltration condition

Results obtained at Station A4' near the lower part of the slope (see Figure 3 for location) are given in Figure 9. This figure shows that the \( \psi \) values are close to zero (considering the precision of the equipments). This indicates that the moisture-retaining layer remained saturated locally, despite the zero infiltration boundary condition. The \( \theta \) value showed a slight variation, which corresponds to a maximum of 0.02; this variation is close to the TDR measurement precision (0.02; see Whalley, 1993). Consequently, one can consider that the \( \theta \) value in the moisture-retaining layer remained near its saturation value of 0.44 (which corresponds to the \textit{in situ} porosity measured in the field).
To evaluate the effect of the suction break cell on the water distribution along the sloping CCBE, results from Line C were compared with those from Line A at two positions: near the top of the slope (Stations A2 and C2) and at level four where the suction break cell was installed (A4' and C4).

For the stations located near the top of the slope, one can see that the $\theta$ values decreased at both stations (see Figure 10).

At Station A2, the $\theta$ values decreased from 0.34 to 0.30. At Station C2, there is a more significant decrease in the $\theta$ value. It dropped from 0.36 to 0.28. The small difference in the initial $\theta$ measurements is probably due to the instrument precision and may also be to the slight variability in the grain-size distribution and porosity of the MRN tailings. The lower variation of $\theta$ at Station A2 is attributed to the suction break effect.

Figure 11 shows the suction evolution at both stations (A2 and C2). It shows that the $\psi$ value increases from 102 to 204 cm of water and from 20 to 173 cm of water at Stations A2 and C2 respectively. So $\psi$ in the moisture-retaining layer increased by about 102 and 153 cm of water respectively at Stations A2 and C2, showing that the drainage effect is more important in the area without the suction break cell than in the area with the suction break cell. These results are in accordance with $\theta$ measurements.

At Station A4’ and C4, the $\psi$ values are close to zero. These suction measurements are much larger in the area without the suction break. By comparing the results from these Stations (A4’ and C4), one can see the beneficial role of the suction break. It helps to maintain a lower suction value in the moisture-retaining layer during the entire testing period (see Figure 12).

4.3 Infiltration test

An infiltration rate (water added) of about 27 mm per hour was applied on the tested area for approximately six (6) hours. The use of a multiplexer allowed the continuous measurements of volumetric water content at different stations along the slope.

The results from the station located at the top of the slope (Station A1) are presented in Figure 13. This figure shows the evolution of the volumetric water content in the moisture-retaining layer near the base (T3), near the upper interface of the moisture retaining layer (T5), and in the sandy capillary break layer (T1). In the bottom sand
layer, the volumetric water content did not change, remaining at about 0.09 throughout the entire infiltration test. Near the base of the moisture-retaining layer, the volumetric water content remained stable at about 0.27, although a small increase of about 0.02 was seen after 24 hours. Near the top of the moisture-retaining layer, a slight increase in $\theta$ was observed (0.26 to 0.29%). This behaviour is attributed to the slope effect which tends to divert the water along the inclination, toward the bottom of the sloping cover.

The results from stations A2 and A3 show somewhat similar trends (see Figures 14 and 15), but are different than those observed at Station A1. At both stations (A2 and A3), the volumetric water content in the moisture-retaining layer increased significantly after a few hours. However, it took more time at Station A2 than at Station A3. Also, for both stations, the volumetric water content took longer to increase at the base of the moisture-retaining layer than it did near the top. This delay was approximately to 2 hours.

In the capillary break (sand) layer of Station A3, one can observe that the $\theta$ value remained constant for six (6) hours, before increasing rapidly from 0.12 to 0.23. This indicates that the pressure at the interface between the MRN tailings and the sand reached the water entry value of the sandy material, leading to water percolation into the capillary break layer (Steenhuis et al. 1991; Zhan et al. 2001; Bussière et al. 2003b). Consequently, it can be inferred that the Down Dip Limit or DDL (Ross 1990) was above station A3 for these precipitation conditions (DDL <12 m from the top of the slope).

Results from Station A4’ show no evolution of the volumetric water content during the entire infiltration test period (see Figure 16). This phenomenon is attributed to the high degree of saturation of the MRN tailings at this level.

For Line C located besides the suction break cell, the results are almost similar to those obtained along Line A (results not shown here), particularly in regards to the location of the DDL. However, the behaviour is different at Station C4 where $\theta$ increased during the infiltration test.
5. CONCLUSIONS

The main objective of the field test conducted at the LTA tailings disposal site was to evaluate the effect of a suction break on water movement in the layered cover system. The results under natural climatic conditions show that near the suction break cell, the moisture-retaining layer of the CCBE is saturated, as expected. This saturation of the moisture-retaining layer is attributed to the GCL, which stops the water diversion at the interface between the moisture-retaining layer and the capillary break layer, hence creating a saturated zone (where the suction is near zero). These results also show that the slope effect is present in spite of the suction break cell.

Under zero infiltration boundary condition, the drainage of the moisture-retaining layer is more important along the line without the suction break, according to suction and volumetric water content measurements at different levels of the slope. The reduction in the drainage rate of the moisture-retaining layer is attributed to the role of the suction break cell.

During the infiltration test, three behaviours in the volumetric water content of the moisture-retaining layer were observed along the slope: 1) a slight variation at the top of the slope in the MRN tailings; 2) an increase in volumetric water content in the moisture-retaining layer after a certain time in the middle of the slope; 3) No evolution in the volumetric water content at the level of the suction break cell, because of the saturation of the moisture-retaining layer (Station A4'). It was also observed that after a few hours at Station A3, the volumetric water content in the capillary break layer started to increase confirming that the inclined CCBE was no longer able to divert water along the interface for the intensity of precipitations tested. The DDL (Down Dip limit) was estimated to be less than 12 m for the extreme conditions (for the LTA site) applied.

The field test results at the LTA site showed the beneficial effect of the suction break cell on the performance of the inclined CCBE, which aims at limiting oxygen flux.

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