# THE USE OF HYDRAULIC BREAKS TO LIMIT DESATURATION OF INCLINED CAPILLARY BARRIERS[1]

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ABSTRACT Recently, covers that use the capillary barrier effect between different layers have been used to limit gas diffusion on waste dumps and mine tailings stacks containing acid generating residues. These covers with capillary barrier effects (CCBE) can maintain a high degree of saturation in the moisture retaining layer, which reduces the influx of gas. Various factors affect the saturation levels in the moisture retaining layer of a CCBE. Three of the most important factors are the water retention curve of the different layer materials, the thickness of the layers and the geometry of the site. In situations where the slope inclination has the potential to reduce the performance of the CCBE, the placement of a hydraulic break can mitigate the risk of desaturation. The objective of the hydraulic break is to limit lateral drainage in the fine material layer and to create a near-zero suction zone in the cover. In this paper, the authors present results of a numerical study that illustrate how the placement of a hydraulic break can potentially increase saturation in the moisture retaining layer (at least locally), and how this may improve the performance of a CCBE to limit gas diffusion. Some results from an experimental *in situ* study are also shown, and confirm the increased degree of saturation due to the placement of a hydraulic break in an inclined CCBE.

RÉSUMÉ Les couvertures avec effets de barrière capillaire (CEBC) sont régulièrement utilisées depuis quelques années comme technique visant à isoler des sources de contamination, notamment pour les résidus miniers générateurs d'eaux acides. Dans ce dernier cas, on utilise les effets de barrière capillaire afin de maintenir un degré de saturation élevé dans la couche de rétention d'eau, ce qui limite le flux gazeux. Différents paramètres, tel les caractéristiques de rétention d'eau, l'épaisseur des couches et la géométrie, affectent le degré de saturation dans la couverture. Lorsque l'inclinaison de la pente réduit l'efficacité de la couverture à limiter l'infiltration des gaz, certaines actions peuvent être prises pour atténuer ce genre de problème, incluant la mise en place de bris hydrauliques. Ces bris visent à créer une zone d'accumulation d'eau dans la pente qui réduit à cet endroit la succion à une valeur proche de zéro. Les résultats d'une étude numérique présentés ici démontrent que les bris hydrauliques permettent d'augmenter le degré de saturation dans la couche de rétention d'eau, du moins de façon locale, permettant ainsi d'améliorer la performance de la CEBC pour limiter la diffusion des gaz. Des résultats provenant d'une étude expérimentale sur le terrain montrent également une augmentation importante du degré de saturation dans la couche de rétention d'eau suite à la mise en place d'un bris hydraulique.

## 1. INTRODUCTION

Covers are frequently used to limit infiltration of water into waste disposal facilities. The main objective of such covers is to reduce water inflow by having one or more material layers with low saturated hydraulic conductivity. Recently, an interesting alternative to low hydraulic conductivity covers, identified here as covers with capillary barrier effects (CCBE), has been proposed. 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 limits the vertical flow of water at the interface. CCBE can be used to restrict water percolation in arid climates or gas diffusion in humid climates. In the latter case, the objective of the cover is to maintain one (or more) layers near saturation. Because the diffusion of gas through almost saturated soil is low, creating a saturated layer will reduce the availability of gas at the bottom of the cover. In the mining industry, a CCBE can be used to reduce the availability of oxygen to the underlying sulphidic rock wastes or tailings (e.g. Rasmuson and Erikson, 1986; Collin and Rasmuson, 1988; Nicholson et *al.*, 1989). By limiting the migration of oxygen by diffusion, the cover reduces the production of acid mine drainage (AMD). More information about the efficiency of a CCBE to limit the production of AMD can be found in the literature (e.g. Aubertin et al., 1995, 1999; Ricard et al., 1997a, b; Bussière and Aubertin, 1999).

Recent studies have shown that the geometry of a CCBE will affect its performance to limit gas diffusion (Aubertin et al., 1997; Bussière et al., 1998, 2000; Bussière, 1999). In inclined layered systems, the top of the slope drains and the effective diffusion coefficient becomes higher near the top than at the bottom of the slope. The effect of the slope on the performance of a CCBE is a function of the slope angle, the drainage period and the water

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retention curves of the materials used (Bussière et al., 1998, 1999, 2000; Bussière, 1999). Because cover desaturation due to slope angle may seriously affect its efficiency in limiting oxygen diffusion, it may be necessary to modify the design of the inclined cover.

In this paper, the authors present one alternative to limit the desaturation of a sloped CCBE which is to build a hydraulic break into the layered cover. The objective of the hydraulic break is to limit lateral drainage in the fine material and to create a near-zero suction zone in the cover. To study the impact of the hydraulic breaks on the performance of inclined CCBE, a numerical study was done. Relevant data from an experimental field study will be also presented.

## 2. MODEL DESCRIPTION

The numerical model simulates the CCBE placed on the south-east part of the LTA tailings pond located near Malartic, Québec, Canada. The cover is composed of three layers: a 50 cm sand layer at the bottom, a 80 cm layer of silty material in the middle, and a 30 cm sand and gravel layer on the top of the CCBE (see figure 1). The layer made of silty material (i.e. MNR non reactive tailings) is the moisture-retaining layer which aims to limit diffusion of oxygen. The cover was placed over the reactive tailings which generate acid. Details about design, construction, instrumentation and monitoring of the site have been presented by Ricard et *al.* (1997a,b), McMullen et *al.* (1997), Golder Associates (1999)

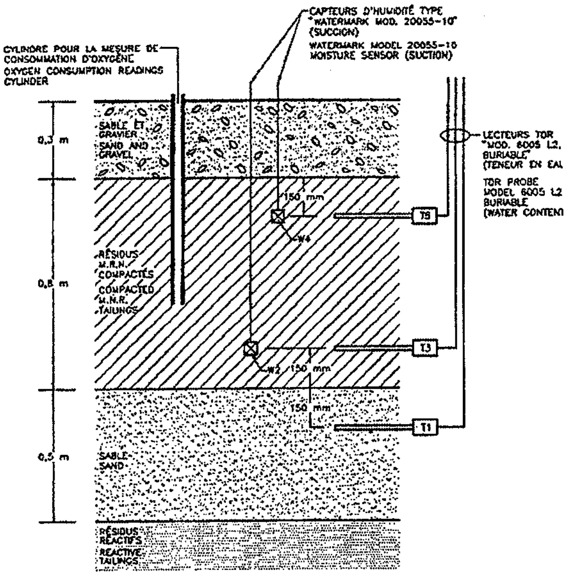

FIGURE 1. Stratigraphy of the CCBE placed on the LTA tailings (from Ricard et *al.*, 1997b)

The length of the simulated slope is about 50 m and the inclination is approximately 18° ( slope of about 3H:1V). The model also includes a 25 m horizontal section of the top of the stack; preliminary numerical modeling results showed that, at this location, the horizontal flow in the cover is negligible, so it has been taken as the external boundary of the mesh. The density of the mesh was increased in the CCBE in order to improve the precision in that critical part of the model. The phreatic surface in the sulphidic tailings was initially located where it had been observed in the field by piezometers. A toe drain is simulated at the bottom of the slope. The hydraulic breaks were made of a relatively impervious material which has a constant hydraulic conductivity ($1x10^{-6}$ cm/s). The location of the different hydraulic breaks varied depending on the simulation: the hydraulic break was placed at the bottom of the slope (about 10 m from the bottom of the slope) for simulation HB2, at about 10 m of the top of the slope for simulation HB3, and two hydraulic breaks were simulated (one at the bottom and one at the top) for simulation HB4. The simulation HB1 was used as the reference configuration, without a hydraulic break. The initial pressure head at each node, required for the transient analyses, was obtained from a steady state analysis of the same model; an infiltration flux of 30 mm/month was used at the top of the cover for steady state calculations. Starting from these initial conditions, a 60 days period was simulated. A schematic representation of the numerical model is shown in Figure 2. It is important to mention that this numerical model allowed the authors to make realistic predictions of the actual (instrumented) hydraulic behavior of the LTA cover (Golder Associates, 1999; Bussière, 1999).

## 3. MATERIALS PROPERTIES AND BOUNDARY CONDITIONS

Unsaturated hydraulic functions for each of the different materials were required to perform unsaturated flow modeling of the sytem. The functions used are the water retention curves (or soil-water characteristic curves) and the permeability functions. Figures 3 and 4 show the unsaturated functions of the different materials and Table 1 presents the main hydraulic parameters of these materials. The water retention curves were obtained from laboratory tests performed on remoulded samples, except for the material identified as «Fondation Silt» for which the curve was selected in the choice offered by the program used (SEEP/W, briefly described below). As can be seen in Figure 3, the water retention contrast between the LTA Sand and the MRN Tailings is significant, and this is key to create the capillary barrier effect between the layers. Permeability functions, presented in Figure 4, were determined from the corresponding water retention curve with the closed form analytical expression of the Mualem (1976) model proposed by van Genuchten (1980).

The main boundary conditions of the numerical model are: an infiltration function at the top, presented in Figure 5 (real data observed from near the LTA site), the toe drain at the bottom of the slope (using a pressure head equal to the elevation at the nodes located at the top of the drain), and a no flux boundary condition at the bottom and the right of the model.

**TABLE 1.** Main hydraulic properties of the materials studied; $\psi_a$ is the Air Entry Value, $\theta_s$ is the volumetric water content at saturation, $k_{sat}$ is the saturated hydraulic conductivity, and $\alpha_v$ and $n_v$ are constants of the van Genuchten (1980) equation.

| Materials | $\psi_a$ (cm of water) | $\theta_s$ | $k_{sat}$ (cm/s) | $\alpha_v$ (cm$^{-1}$) | $n_v$ |
|---|---|---|---|---|---|
| LTA Sand | 20 | 0.36 | $1x10^{-1}$ | 0.0496 | 2.06 |
| MNR Tailings | 284 | 0.44 | $5.0x10^{-5}$ | 0.0034 | 1.63 |
| Sulphidic Tailings | 303 | 0.31 | $7.0x10^{-4}$ | 0.0033 | 3.27 |
| Hydraulic break material | 2000 | 0.44 | $1x10^{-6}$ | --- | --- |
| Fondation Silt | 323 | 0.38 | $2.3x10^{-5}$ | 0.0031 | 3.48 |

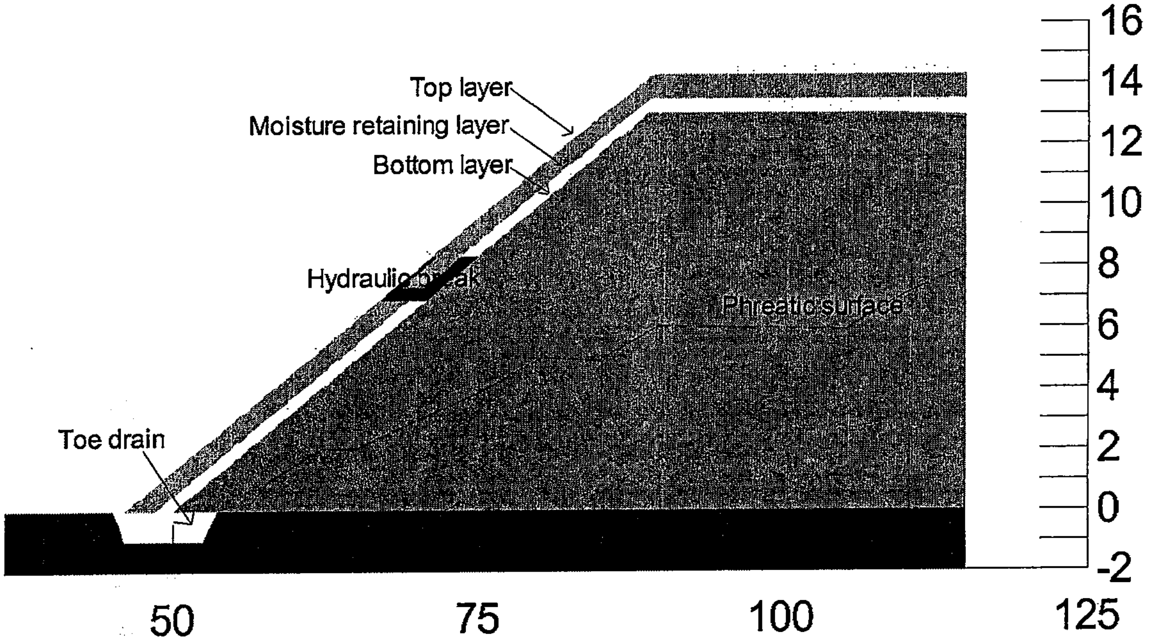

FIGURE 2. Schematic representation of the model used in the numerical simulations

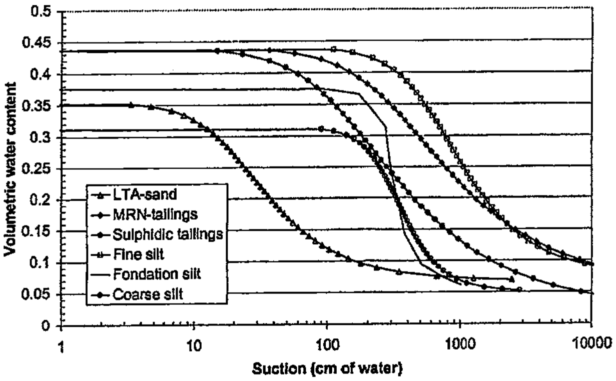

Figure 3. Water retention curves of the different materials used in the numerical simulations.

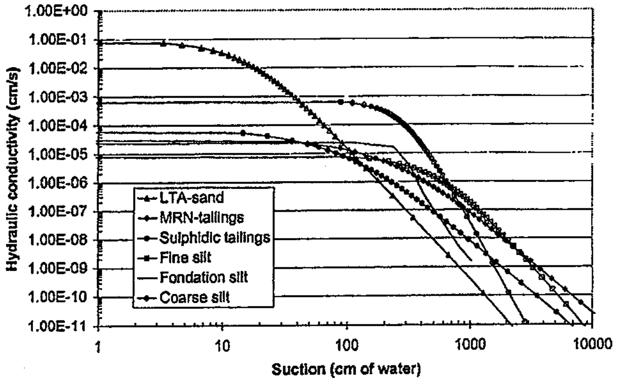

Figure 4. Permeability functions of the different materials used in the numerical simulations.

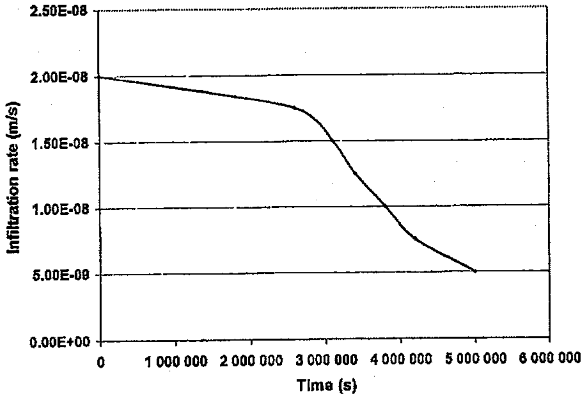

Figure 5. Boundary condition applied at the top of the CCBE.

## 4. MODELING RESULTS

To evaluate the influence of the hydraulic breaks on the desaturation phenomenon of an inclined CCBE, a numerical modeling program was used. The program selected is SEEP/W developed by GEOSLOPE International (1994). This program is able to simulate various situations in two dimensions including variably saturated flow, for steady state and transient conditions. This program has been tested and used by the authors for numerous other calculations (Aubertin et *al.*, 1995, 1996, 1997; Bussière et *al.*, 1995, 2000; Bussière, 1999).

### 4.1 Simulation HB1

The first simulation was done on the model without the hydraulic break. Figure 6 presents the degree of saturation (or saturation ratio) evolution at the centre of the moisture retaining layer made of MNR Tailings. One can observe that saturation decreases from bottom to top. After 60 days with the infiltration flux applied at the top of the cover (see Figure 5), the degree of saturation decreased from 100% at the bottom to values between 80% and 85% at 12 m (from the toe). These results clearly show that the position along the slope affects the performance of the cover; as the distance from the bottom of the slope increases the saturation decreases and the ability of the CCBE to reduce gas diffusion also decreases.

### 4.2 Simulation HB2

The objective of the second simulation was to evaluate the impact of placing a hydraulic break 10 m from the toe of the cover on the hydraulic behaviour of the moisture retaining layer. As can be observed from Figure 7, the hydraulic break has a significant local effect on the degree of saturation, especially close to its location (i.e. at approximately 10 m on the X-axis). The saturation increases at the hydraulic break to values near 100%, and decreases slowly to values similar to the one without a hydraulic break at a distance of about 10 m from the hydraulic break.

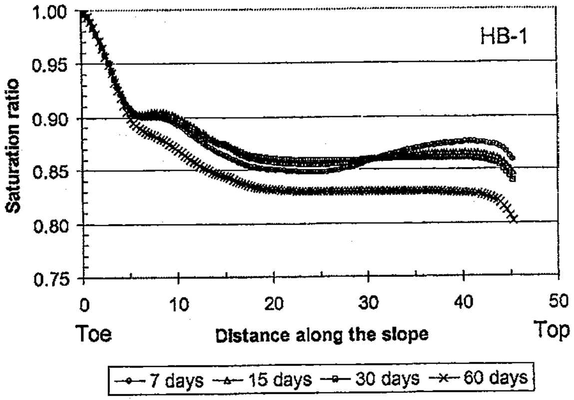

Figure 6. Degree of saturation evolution in the centre of the moisture retaining layer as a function of time and position along the slope (0 = bottom of the slope); Simulation HB1 without hydraulic break.

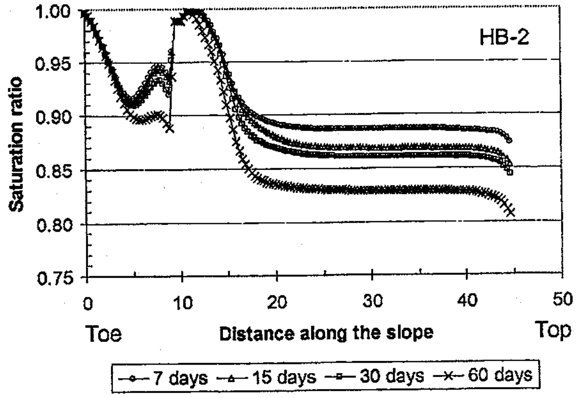

Figure 7. Degree of saturation evolution in the centre of the moisture retaining layer as a function of time and position along the slope (0 = bottom of the slope); Simulation HB2 with a hydraulic break at 10 m of the toe.

### 4.3 Simulation HB3

The third simulation was done to evaluate the influence of the hydraulic break location on the performance of the CCBE. As shown in Figure 8, saturation in the centre of the moisture retaining layer is locally affected by the hydraulic break. In this simulation, the degree of saturation increases close to the hydraulic break to 100% and then decreases slowly to values similar to those observed without a hydraulic break (the length affected by the hydraulic break is about 10 m).

### 4.4 Simulation HB4

The objective of this simulation is to quantify the effect of placing two hydraulic breaks on the hydraulic behavior of the moisture retaining layer. The hydraulic breaks have been placed at 10 m and 30 m from the bottom of the cover. Figure 9 shows that the results nearly correspond to a juxtaposition of the results obtained in simulations BH2 and BH3. The saturation increases locally at the hydraulic break and the impact disappears at a distance of approximately 10 m away from their location.

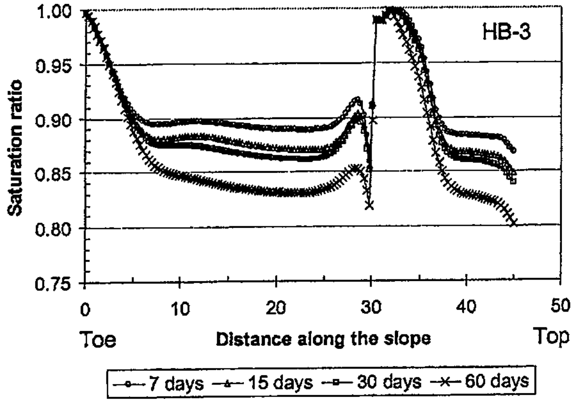

Figure 8. Degree of saturation evolution in the centre of the moisture retaining layer as a function of time and position along the slope (0 = bottom of the slope); Simulation HB3 with a hydraulic break at 30 m of the toe.

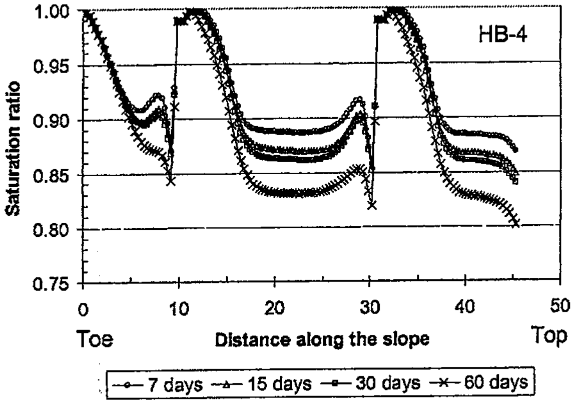

Figure 9. Degree of saturation evolution in the centre of the moisture retaining layer as a function of time and position along the slope (0 = bottom of the slope); Simulation HB4 with 2 hydraulic breaks: one at 10 m and one at 30 m of the toe.

## 5. RESULTS ANALYSIS

The main objective of a CCBE placed on sulphidic tailings is to limit the diffusion of oxygen. To do so, capillary barrier effects are used to create a moisture-retaining layer. As saturation increases in a porous medium, the effective diffusion coefficient $D_e$, which controls the oxygen flux, decreases. To reduce the desaturation phenomena in sloping CCBE, the installation of hydraulic breaks was suggested (Aubertin et al. 1997). The four numerical simulations presented in the previous section show that a hydraulic break locally increases the degree of saturation in the moisture retaining layer.

To quantify this impact in terms of a reduction in gas diffusion flux through the cover, a new indicative parameter is proposed: the slope effective diffusion coefficient ($D_{e\_Slope}$). This parameter is evaluated by determining the values of the degree of saturation $S_r$ for each node in the middle of the moisture-retaining layer. From each $S_r$ value, it is possible to estimate the equivalent effective diffusion coefficient using simple empirical models (e.g. Millington and Shearer, 1971; Collin and Rasmuson, 1988). In this study, the model proposed by Eberling et *al.* (1994) is used; this equation can be written as follows:

$$[1]\ D_e = \tau D_a^0 (1 - S_r)^\alpha + \tau S_r D_w^0 / H$$

where $D_a^0$ is the diffusion coefficient for a pure air phase ($1.8 \times 10^{-5}$ m$^2$/s), $D_w^0$ is the diffusion coefficient for a pure water phase ($2.2 \times 10^{-9}$ m$^2$/s), H is the dimensionless modified Henry's law constant (33.9 @ 25°C), $\alpha$ and $\tau$ are fitting parameters ($\tau = 0.273$ and $\alpha = 3.28$ as proposed by Eberling and Nicholson, 1996). The average value of $D_e$ (for the centre of the moisture-retaining layer) is taken as the slope effective diffusion coefficient ($D_{e\_Slope}$).

The $D_{e\_Slope}$ values calculated for the different simulations are presented in Table 2. As observed, the effect of the hydraulic break is important for the first seven days ($3.86\text{x}10^{-9}$ and $3.48\text{x}10^{-9}$ m$^2$/s with one hydraulic break, versus $7.80\text{x}10^{-9}$ m$^2$/s without a hydraulic break) but the positive effect is reduced with time (after 60 days: $1.27\text{x}10^{-9}$ and $1.12\text{x}10^{-9}$ m$^2$/s with one hydraulic break and $1.51\text{x}10^{-9}$ m$^2$/s without hydraulic break) when the infiltration rate is lower (see Figure 5). By comparing the results from simulations HB2 and HB3, one can see that the location of the hydraulic break along the slope is not critical. Placement of a second hydraulic break increases the performance of the CCBE by a factor varying from approximately 2.5 to 1.7 depending on time.

**TABLE 2.** Slope effective diffusion coefficient for the different simulations: HB1 is the simulation without a hydraulic break; HB2 is the simulation with a hydraulic break at 10 m from the bottom; HB3 is the simulation with the hydraulic break at 30 m from the bottom and HB4 is the simulation with 2 hydraulic breaks.

| | $D_{e\_Slope}$ (m$^2$/s) 7 days | $D_{e\_Slope}$ (m$^2$/s) 15 days | $D_{e\_Slope}$ (m$^2$/s) 30 days | $D_{e\_Slope}$ (m$^2$/s) 60 days |
|---|---|---|---|---|
| HB1 | $7.80\text{x}10^{-9}$ | $7.48\text{x}10^{-9}$ | $7.58\text{x}10^{-9}$ | $1.51\text{x}10^{-8}$ |
| HB2 | $3.86\text{x}10^{-9}$ | $5.62\text{x}10^{-9}$ | $6.32\text{x}10^{-9}$ | $1.27\text{x}10^{-8}$ |
| HB3 | $3.48\text{x}10^{-9}$ | $5.03\text{x}10^{-9}$ | $6.13\text{x}10^{-9}$ | $1.12\text{x}10^{-8}$ |
| HB4 | $3.08\text{x}10^{-9}$ | $4.07\text{x}10^{-9}$ | $4.95\text{x}10^{-9}$ | $9.00\text{x}10^{-9}$ |

The numerical results presented above have been partly confirmed by an experimental hydraulic break that was build in the sloping CCBE of the south-east part of the LTA site in 1997 (Golder Associates, 1999). The configuration of the hydraulic break is presented in Figure 9. The length of the hydraulic break, made of a fine silt less pervious than the MNR Tailings, was 20 m. The CCBE was instrumented with TDR probes and Watermark sensors which measure, respectively, the volumetric water content and the matric suction.

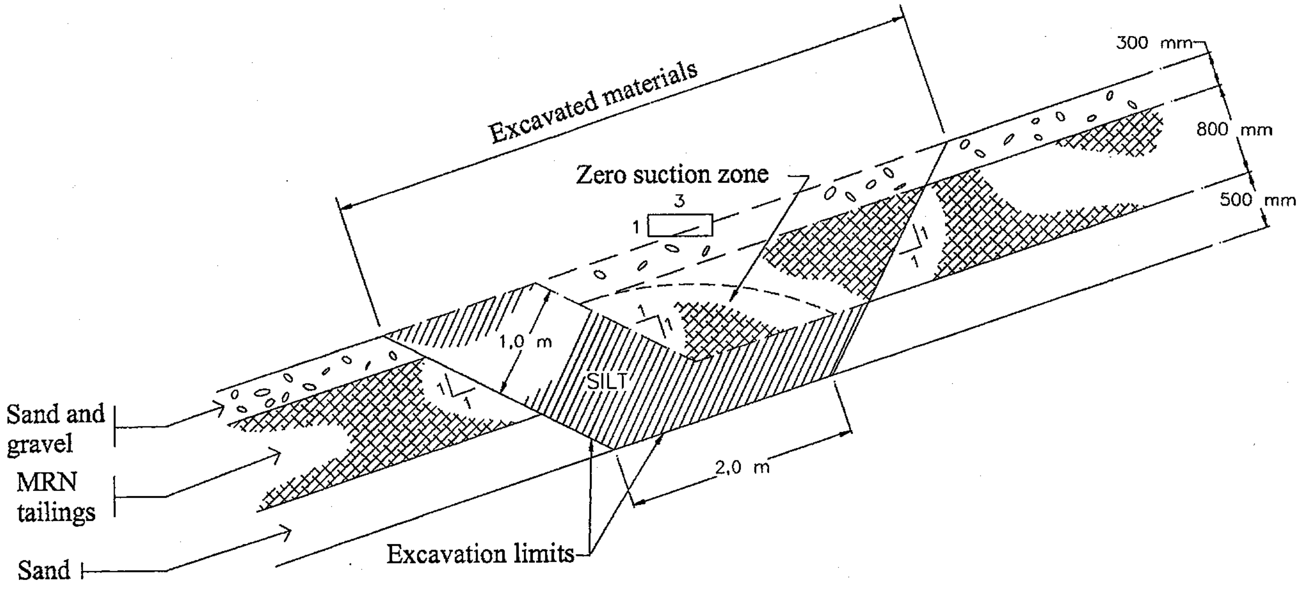

Figure 10. Configuration of the experimental hydraulic break installed in the sloping CCBE of the LTA site (from Golder Associates, 1999).

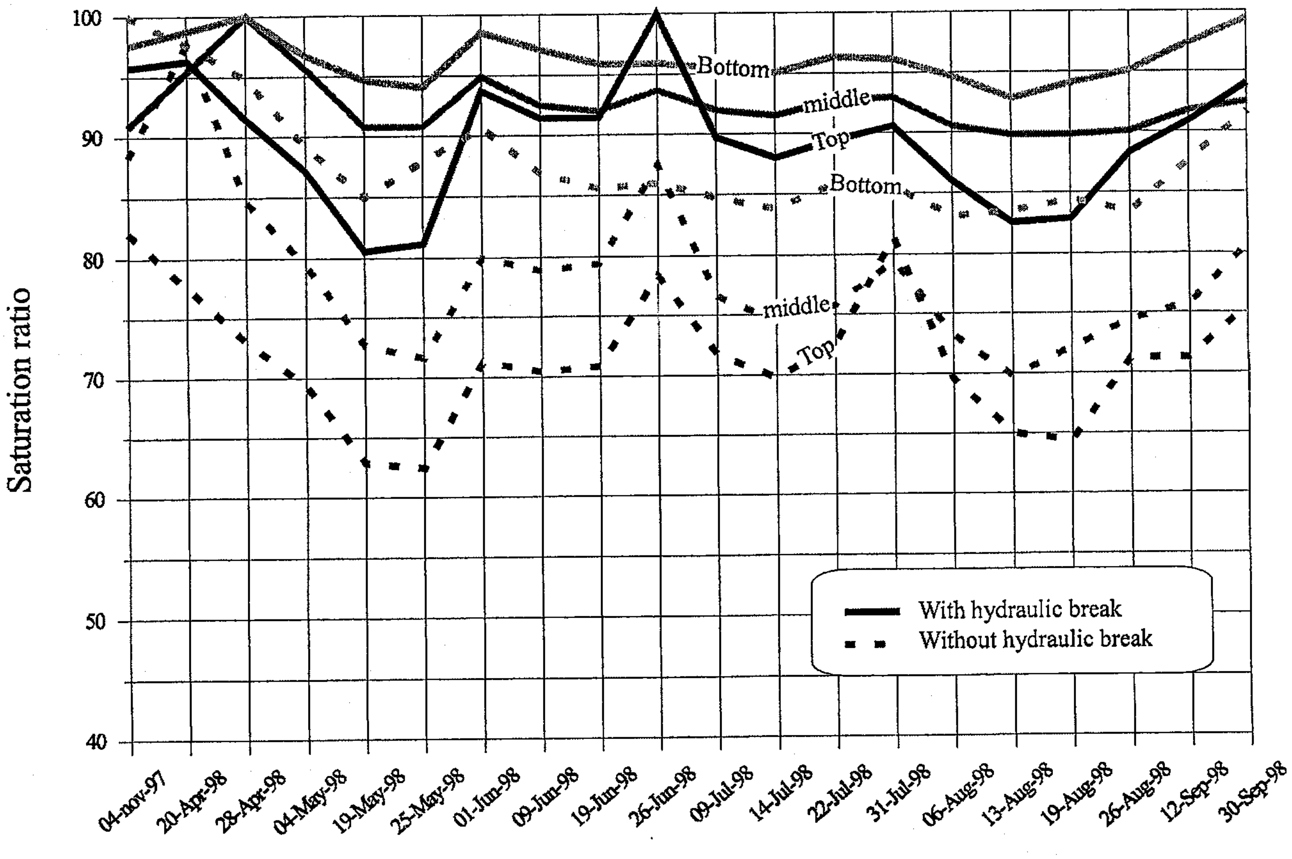

Figure 11. Evolution of the saturation ratio in the moisture retaining layer (at the top, in the middle and at the bottom of the slope) with or without hydraulic break during the year 1998 (from Golder Associates, 1999).

The results presented in Figure 11 show that the hydraulic break have significantly increased the performance of the cover by increasing saturation of the moisture retaining layer. In general, the degree of saturation with the hydraulic break was more than 10% higher than the one without hydraulic break. This confirms that the hydraulic break could help to maintain an higher saturation in the moisture retaining layer of an inclined CCBE. The observed performance of the hydraulic break in the field is somewhat better than the one predicted by numerical modeling. This could be due to the difference between the infiltration conditions applied in the numerical study and the real one in the field. More details about this *in situ* experimental study can be found in Golder Associates (1999).

## 6. CONCLUSIONS

The unidimensional hydraulic behavior of CCBE is well known, and it has served as a design basis for covers installed on reactive tailings and rock waste. To date, the effects of cover geometry on gas barrier performance have been largely neglected, even when systems were placed on the side of stacks and piles which can have relatively high slope angles. Recent studies show that the inclination of the slope has a significant effect on the hydraulic behavior of a CCBE and on its overall ability to reduce oxygen diffusion. It is thus necessary to take into account this particular aspect in the design process to avoid misleading conclusions and unsafe configurations. To avoid the desaturation of the slope, the installation of hydraulic breaks could be a solution. This study shows, using numerical modeling results, the effect of hydraulic breaks on the performance of an inclined CCBE. Generally, average effective diffusion coefficient of the slope could be reduced by a factor of between 1.2 to 2.5, depending on the infiltration rate applied at the top of the slope. The improvement of the CCBE performance was also demonstrated by an *in situ* study done at the LTA site.

## 7. AKNOWLEDGMENTS

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