ANALYSES OF THE WATER DIVERSION LENGTH OF INCLINED, LAYERED SOIL COVERS

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ABSTRACT
Various types of cover systems can be used to control water infiltration into waste disposal sites. For instance, when designing a layered cover, different soils can be combined to create a capillary barrier effect in order to limit percolation. Such an effect is created under unsaturated conditions when a fine-grained soil is placed over a coarser material. The difference in hydraulic properties between the two soils can then serve to impede water flux along the interface. The finer soil layer stores moisture from precipitation, which can later be released by evaporation. In sloping areas, the cover may also act as a lateral water diversion system. The behaviour of an inclined cover system is, however, fairly complex, as it is influenced by many factors. In this paper, the authors present some results from a numerical investigation into the response of steeply inclined covers with capillary barrier effects (CCBEs) under a relatively humid climate. After a brief recall of the physical processes involved, the presentation focuses on calculation results that aim at assessing the effect of various influence factors, including layer thickness, material properties and precipitation rate. A discussion on the implications follows.

RÉSUMÉ
Plusieurs types de systèmes de recouvrement peuvent être utilisés afin de contrôler les infiltrations d’eau dans les sites d’entreposage de rejets. Par exemple, lors de la conception de couvertures multicoches, on peut combiner différents sols afin de créer un effet de barrière capillaire pour limiter la percolation. Cet effet est créé en conditions non saturées lorsqu’un sol fin est placé sur un sol plus grossier. La différence des propriétés hydriques entre les deux sols permet alors de réduire le flux à l’interface. Le sol fin sert ainsi à emmagasiner l’eau des précipitations, qui est ultérieurement relâchée par évaporation. Sur une surface inclinée, la couverture permet aussi de dévier l’eau latéralement. Le comportement d’un recouvrement incliné est toutefois relativement complexe, car il est influencé par plusieurs facteurs. Dans cet article, les auteurs présentent certains résultats d’une étude numérique sur la réponse de couvertures à effets de barrière capillaire (CEBC) très inclinées. Après un bref rappel des processus physiques impliqués, on présente les résultats de calculs visant à évaluer l’effet de divers facteurs tels l’épaisseur des couches, les propriétés des matériaux et le taux de précipitation. Une brève discussion sur les implications suit.

1. INTRODUCTION
Cover systems have been extensively studied over the last two decades or so, as a practical means to control the exchange of fluids (water and gas) at the surface of waste disposal sites. Many different configurations and materials have been evaluated along the way. In this regard, an interesting alternative for cover design is to use a combination of various soils to induce capillary barrier effects into the layered system. A capillary barrier effect can be created under unsaturated conditions when a relatively fine-grained material (typically a silty or clayey soil) overlies a coarser (usually sandy) one (e.g., Rasmussen and Eriksson, 1986; Morel-Seytoux 1992; Morris and Stormont, 1997). The difference in hydraulic properties between the superimposed soils, which is due to their different grain size and porosity, may then serve to limit water flow at the interface. At a sufficiently high suction (negative pore pressure), the coarse material will have a much lower unsaturated hydraulic conductivity $k_u$ than the finer material above it. This creates a barrier that limits the downward motion of water at the contact between the two soils. The capillary barrier phenomenon is important in many situations, including issues related to irrigation and infiltration in natural soil strata (e.g. Iwata et al. 1988; Zaradny, 1993), moisture distribution in man-made layered cover systems (e.g., Collin 1987; Nicholson et al. 1989; Aubertin et al. 1995), and in stratified waste rock dumps (Fala et al. 2005). Under arid and semi-arid climatic conditions, a cover with capillary barrier effects (CCBE) can be quite effective for controlling infiltration (e.g., Benson et al. 2001; see also various papers in Miller et al. 2006). A CCBE can be used to store water in the fine-grained soil, because of its high retention capacity (reflected by a relatively large air entry value AEV), the capillary barrier effect at the interface with the coarse-grained material underneath also favours water accumulation in this fine soil layer. This accumulated moisture can later be released by evaporation (or evapotranspiration). When inclined, the CCBE may also take advantage of the unsaturated soil...
properties to induce lateral drainage during and after wetting periods, to complement humidity evaporation from the cover (e.g., Ross 1990; Stormont 1996; Zhan et al. 2001). However, the fact that moisture is not evenly distributed along the slope length makes inclined CCBEs somewhat more complex to analyse. In this case, one must pay attention to water accumulation in the lower parts of the cover system. This accumulation may reach a critical suction at a certain location down the slope, which may reduce the capillary barrier efficiency. Infiltration of water into the coarse material (and/or into the waste) then becomes possible as the suction reaches its water entry value (WEV). Depending on the intensity and duration of the precipitation, the cover system may have to manage a large amount of water that can then exceed its diversion capacity (Bussière et al. 2003a; Aubertin et al. 2006). This aspect is even more critical for a humid climate.

In this paper, the authors present a study of the hydrogeological behaviour of inclined CCBEs used to reduce water infiltration under a wet climate. The results presented here are based on recent numerical modelling, which is part of a broad investigation into the use of CCBEs to control the production of acid mine drainage.

2. DIVERSION CAPACITY OF INCLINED COVERS

As mentioned above, a fine-grained soil that overlies a coarser material in a relatively dry state tends to retain the infiltrating water by capillary action. The coarse material, which desaturates more easily under suction, acts as a barrier against deep percolation because of its low hydraulic conductivity at a small degree of saturation. Moisture then accumulates above the interface between the two soils until the local negative pressure reaches the water entry value (WEV) of the coarse material. On the water retention curve (WRC), the WEV is equivalent to the residual suction \( \psi_r \) (neglecting hysteresis effects) corresponding to the residual water content. At this point of the WRC along a wetting path, moisture starts to penetrate the material more significantly, provoking a rise of the water content. Once water starts moving across the interface, it increases the degree of saturation and hydraulic conductivity of the coarse material, hence dissipating the capillary barrier effect.

The response of horizontal CCBEs is fairly well understood, but the same cannot be said for dipping layered systems. For an inclined cover, the moisture that builds up above the contact with the coarse material tends to flow along the sloping interface. However, when there is a significant inflow of water, the fine soil may become wet enough so that at a certain point downsip, the pressure at the interface may reach the WEV of the coarse-grained material. At this location, water infiltration into the coarse material becomes significant, and the capillary barrier effect progressively disappears. The location of this “point” along the slope (which is actually a zone) is known as the Down Dip Limit or DDL point (Ross, 1990). The distance between the top of the slope and the DDL point is referred to as the diversion length of the capillary barrier (\( L_d \)), which is shown schematically in Figure 1.

![Figure 1 - Schematic representation of a layered cover (adapted from Bussière 1999), showing water movement in an inclined CCBE made of silt and sand layers, placed on a coarse-grained material (rock waste in this case). Following a precipitation event, the water flows along the cover and breaks through the coarse material where the suction reaches its WEV; this gives the diversion length \( L_d \).]

3. BACKGROUND STUDIES

Various analytical solutions have been proposed to estimate the diversion length of sloping layered systems (e.g., Ross, 1990; Lu and Likos, 2004). However, the simplifying assumptions seriously limit their applicability to practical situations (Bussière et al. 1998). In most instances, numerical tools represent a more convenient approach to define the response of inclined SDR covers.

The authors and collaborators have studied CCBEs fairly extensively over the last fifteen years or so, emphasizing their possible role as an oxygen barrier for controlling the production of acid mine drainage (e.g. Aubertin et al. 1995, Bussière et al. 2003b; Dagenais et al. 2005). The investigations have included the evaluation of layered covers under controlled laboratory conditions in instrumented columns. Additional tests were also performed in a specially developed set-up to study water diversion along a layered system, for different slope angles and precipitation rates (Bussière et al., 2002, 2003a). The latter tests showed that the capillary barrier effect along the interface between two different soils with contrasting texture tends to disappear progressively along the slope (rather than at a pin-point location). The data obtained from these experiments were also well correlated to unsaturated flow modelling results (as were the column tests). The laboratory studies and corresponding numerical simulations were complemented by field investigations on an instrumented experimental site (Aubertin et al. 1999; Bussière, 1999). The field work also included investigations of inclined CCBEs under semi-arid (Zhan et al. 2001) and humid (Maqsoud et al. 2005) climatic conditions. The field data confirmed the slope effect on cover behaviour. The data also indicated that properly conducted numerical simulations could provide a good representation of the actual field observations.
The results were complemented by additional modelling of inclined cover systems that aim at reducing water infiltration under semi-arid conditions, after large (but relatively short) precipitation events. Results have shown how the diversion length is influenced by the layer thickness(es), material properties, slope length and inclination, as well as the duration and rate of precipitation (e.g., Apithy, 2003; Bussière et al. 2003a; Martin et al. 2005; Aubertin et al. 2006). Some methods for increasing the diversion length have also been investigated. More recently, additional work has focussed on humid climates, to assess the conditions that could make a SDR layered cover a viable option to control infiltration into steeply inclined waste rock dumps. In this case, the simulations must address the longer term response. Some of the main results are presented below.

4. SIMULATIONS OF THE YEARLY RESPONSE UNDER HUMID CONDITIONS

The program used for the simulations is the commercial finite element code SEEP/W developed by GÉOSLOPE International (2002). This program uses the Richards’ (1931) equation to simulate problems in two dimensions, including variably saturated flow for steady-state and transient conditions. SEEP/W has been previously used for several unsaturated studies on layered covers (e.g., Bussière et al. 2003a, 2003b; Martin et al. 2005; Aubertin et al. 2006).

The calculations have been conducted for an inclined CCBE used to prevent water infiltration into mine waste, considering an annual regime of precipitation and evaporation. Various cover systems have been analysed for the climatic conditions of western Quebec as input parameters. The annual distribution of precipitation and evaporation used in the calculations are shown in Figure 2; these include alternate days of positive (infiltration) and negative (moisture losses) surface fluxes based on mean monthly climatic data. Note that there is no surface flux during the winter months (November to March), because the cover is frozen. Somewhat similar data have been used in other modelling calculations (e.g., Fala et al. 2005). The case shown here loosely represents a waste rock pile, which would be covered by a layered system upon closure. The study focussed mainly on defining the diversion length for various conditions (see details in Cifuentes, 2006).

Figure 2 - Distribution of precipitation and evaporation during the modelled year.

The basic model represents a circular waste rock pile with a height of 25 m, and a base diameter of 110 m (Fig. 3). The top surface of the pile is slightly inclined outward, at an angle of about 5°, while the main external slope angle is 37°. The waste rock in the dump is considered homogeneous; its hydraulic properties have been defined from in situ and laboratory tests on a reference site. The waste rock hydraulic conductivity $k_{sat}$ is $4.3 \times 10^{-4}$ cm/s, its AEV is about 10 cm of water, and its WEV is about 60 cm of water (for a porosity of 0.23). The cover is made of a layer of silt (placed on the waste rock) on which a layer of coarse sandy soil is added to control runoff and erosion. The properties of the silt and the coarse sand (with variable thickness in both cases) are respectively: $k_{sat}$ of $5.0 \times 10^{-5}$ cm/s and $9.9 \times 10^{-5}$ cm/s; an AEV of about 200 cm and 10 cm of water (porosity of 0.44 and 0.36 respectively); a WEV of 7000 cm and 100 cm of water. Figure 4 shows the hydraulic conductivity functions for these three materials (based on the van Genuchten 1980 model, adjusted with a minimum conductivity value – see Ebrahimi et al. 2004).

Figure 3 - Representation of the base model used for the numerical simulations; different silt and sand layer thicknesses were considered in the calculations. The position of the water table corresponds to the top of the toe drain.
The simulations represent various cover scenarios, and assess the effect of changing cover characteristics on the diversion length. The results shown in Figure 5 illustrate the observed trends. This figure shows how suction just below the cover (for the base case shown in Fig. 3) evolves over time. These calculated suction values are used to identify the DDL location (as an idealised point) as shown in Figure 5. Figure 6 shows, for the same base case, how the diversion length changes during the year; the results clearly show that $L_d$ is progressively reduced as water from precipitation accumulates in the cover layers.

Figure 7 illustrates how the evolution of suction below the cover and the corresponding diversion length as a function of the silt layer thickness (for a sand layer thickness of 1 m), based on the calculation results at the end of the one-year climatic cycle (i.e. in December, at the onset of winter when infiltration stops for about 4 months due to freezing). This figure shows that a minimum thickness (of about 0.6 m in this case) is required to divert water along the inclined CCBE. The diversion length increases with the silt layer thickness in a non linear manner. A quasi-plateau is reached at a thickness of about 2 m and beyond that, $L_d$ is little influenced by the silt layer thickness. Other calculations have been conducted to assess the effect of the sand layer thickness (for a constant silt layer thickness of 1 m); the results are shown in Figure 8. As can be seen, there is an increase of the diversion length up to a thickness of about 1.5 m. Other cover characteristics have also been evaluated in the parametric study including the material properties, cover geometry and climatic regimes. The overall results are presented in Cifuentes (2006).
b) Figure 7 - Effect of the silt layer thickness on the diversion length of a sand-on-silt cover placed on the slope of the waste rock pile (at the end of the year); a) suction distribution below the cover; b) value of the diversion length $L_d$, for a DDL point location determined according to the tangent method (Fig. 7a) and based on suction that reach predetermined values (of 10 and 15 kPa in this case).

Figure 8 Effect of the sand layer thickness on the diversion length of a sand-on-silt cover placed on the slope of the waste rock pile (at the end of the year); the DDL point is determined according to the tangent method (Fig. 4) and also for suction that reach predetermined values of 10 and 15 kPa.

5. DISCUSSION AND CONCLUSION

The results presented above illustrate how simulations can be used to investigate the response of inclined covers with capillary barrier effects (CCBEs) designed to limit water infiltration under the climatic conditions of western Quebec. For this purpose, the authors have used the location of the DDL point to determine the diversion length of the layered covers. This point is identified from the calculation results, as the location where the suction in the coarse grained material, acting as the capillary break, reaches its water entry value $WEV$ at the interface with the water retention layer placed on top of it. The results presented here, and others presented in companion studies (e.g., Apithy, 2003; Bussière et al. 2003a; Martin et al. 2005; Aubertin et al. 2006; Cifuentes, 2006), show how the diversion length of a Store-Divert-and-Release (SDR) type of layered cover is influenced by factors such as layer thickness, climatic conditions, soil properties, and slope geometry. This type of parametric study can be quite useful to evaluate the possible use of a CCBE to prevent water infiltration into a waste disposal site. This paper recalls the main physical principles which govern the behaviour of sloping CCBEs and indicates how covers can be optimised with the help of numerical simulations.

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