PROCEDURE FOR THE DESIGN OF INCLINED COVERS WITH CAPILLARY BARRIER EFFECT

Serge-Étienne Parent, Dept. Civil Eng., Univ. de Sherbrooke, Quebec, Canada
Alexandre Cabral, Dept. Civil Eng., Univ. de Sherbrooke, Quebec, Canada

ABSTRACT
The capillary effect is created by superposing a relatively fine pore material on a coarser one. The upper material retains water into its fine pores, while the bottom is kept dry. An inclined cover with capillary barrier effect (CCBE) results in the drainage of infiltrating water into the upper layer. CCBEs are widely used for the final top cover of landfills in order to limit water infiltrations through municipal wastes disposals. A design procedure is proposed to select materials and optimizing layer thickness of inclined CCBEs.

RÉSUMÉ
L'effet de barrière capillaire est créé en plaçant un matériau aux pores relativement fins sur un matériau dont les pores sont plus grossiers. Le matériau de la couche supérieure retient l'eau à l'intérieur de ses pores fins, tandis que le matériau de la couche inférieure reste sec. Lorsqu'une couverture avec effet de barrière capillaire (CEBC) est inclinée, l'eau est drainée à travers la couche supérieure. Les CEBC sont largement utilisées comme recouvrements finaux sur les dépôts de déchets municipaux afin de limiter les infiltrations. Une procédure de conception est proposée pour sélectionner les matériaux et optimiser les épaisseurs des couches des CEBC inclinées.

1. INTRODUCTION

Leachate production after the closure of municipal waste facilities can be limited by the use of final capping systems with low permeability covers. For this purpose, covers with capillary barrier effect (CCBE) were used for their low cost, long term stability and effective alternatives (Barth and Wohnlich 1999, Stormont and Anderson 1999, von Der Hude et al. 1999). The capillary barrier effect is created when a relatively fine pore material overlies a coarser one. The textural contrast between the upper layer material (called moisture retention layer, MRL) and the bottom layer material (called capillary break layer, CBL) controls vertical infiltration through the barrier by capillary forces.

Khire et al. (2000) proposed a simple design procedure to optimize layer thickness for nearly flat evapotranspirative covers in dry climates. In humid regions, evapotranspiration may not be sufficient to remove moisture stored into the capping system, which results in a reduction of capillary forces and in water infiltration through the cover system. To avoid percolations to happen, the capillary barrier can be dipped to a sufficient angle in order to drain water laterally into the MRL. In this case, when water infiltrates from the top of the MRL, moisture is retained and drained downside into the MRL; water accumulates until capillary forces can longer take anymore water, and, down this point, called the breakthrough, any additional infiltration is transmitted to the CBL. The distance between the top of the slope and the breakthrough, called the diversion length, can be calculated using the Ross (1990) model.

The design procedure proposed in this paper aims at selecting materials and optimizing layer thicknesses using common computer applications, such as a spreadsheet and an appropriate compiler. The approach leads to a simple integrated model and a comprehensive procedure that allows the development of new capillary barrier concepts.

2. MATERIALS AND METHODS

The three materials used in this paper are the Saint-Rosaire sand (SR-sand), the Clinton gravel (C-gravel) and the well-graded loam (WG-loam). The SR-sand and the C-gravel are coarse-grained materials employed as capillary barrier components at the Saint-Rosaire (Canada) MSW facility (Parent 2003) and the Clinton mine waste site (Cabral et al. 1999), respectively. The water retention curve (WRC) and the hydraulic conductivity function (*k*-function) of SR-sand and C-Gravel were determined by Parent (2003). The WG-loam is a hypothetic loam taken from the soil databank of Geo-slope (2002). The water retention curve (WRC) and the hydraulic conductivity function (*k*-function) of the three materials are presented in Figure 1 and 2.

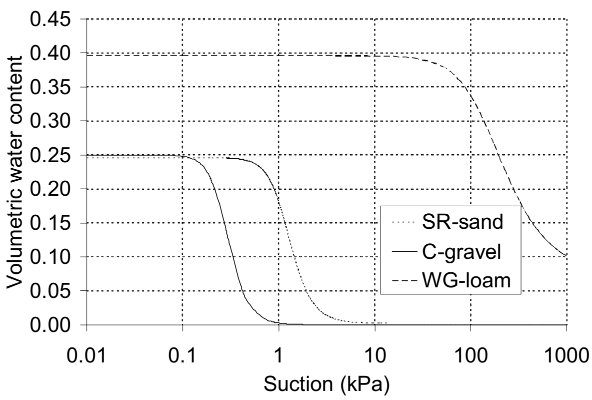

Figure 1. Water retention curves of the three materials used in this paper

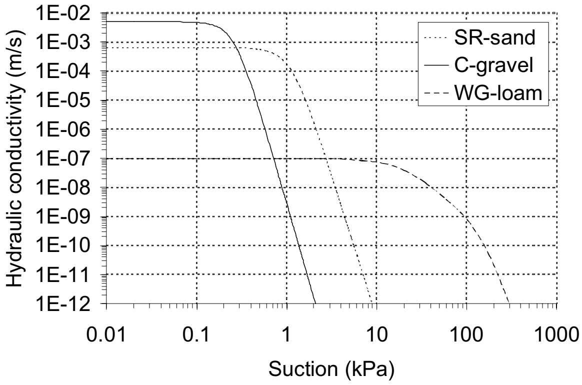

Figure 2. Hydraulic conductivity functions of the three materials used in this paper

The finite element software SEEP/W (Geo-slope 2002) was used to model unsaturated water seepage across capillary barriers. This software has been used in many cover projects and the results obtained often show good agreement with field data (e.g. Choo and Yanful 2000). Hysteresis was not taken into account in any simulation. Numerical computations needed to solve the Ross (1990) and the Kisch (1959) models were performed using Matlab.

3. COVERS WITH CAPILLARY BARRIER EFFECT

In porous materials, water is attracted downward due mainly to gravitational forces and is retained by capillary forces. In a capillary barrier, in addition to gravitational forces, water can be pulled down from the MRL into the CBL by the suction induced at the interface of the two layers. However, this will only occur when the suction level at the interface drops below the water entry value (suction corresponding to the residual water content in the WRC) of the CBL. Before this to occur, water will continue to accumulate in the MRL.

If the CCBE is inclined, water can be drained downsides in the MRL. An infiltration rate applied uniformly on the top of an inclined CCBE will cause accumulation downslope. The more the MRL saturates, the greater the part of the infiltration rate is transmitted into the CBL. At a specific distance from the top of the slope called the diversion length, capillary forces no longer retain the accumulated water and the infiltration rate is entirely transmitted into the CBL. This phenomenon is schematically illustrated in Figure 3. Oldenburg and Pruess (1993) and Webb (1997), using numerical simulations, proposed that infiltration into the CBL might occur progressively and introduced the concept of partial breakthrough, which is coherent with the shape of the WRC.

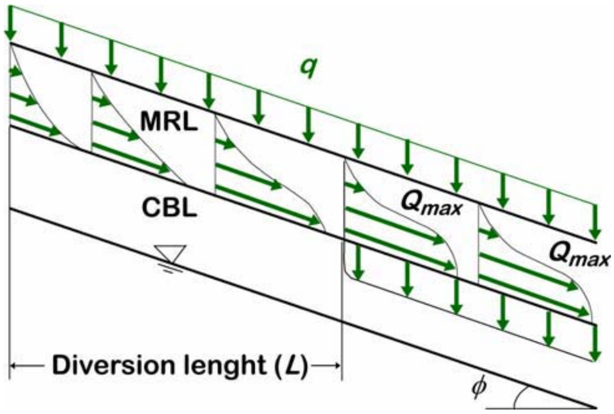

Figure 3. Schematic representation of water flow vectors in an inclined CCBE.

Ross (1990) proposed a model to estimate the diversion length, applying the following assumptions: (1) the water table lies far below the MRL-CBL interface; (2) both layers are very thick; (3) the interface is inclined and much longer than the diversion length; (4) a vertical infiltration rate is applied uniformly to the top of the MRL. Based on these assumptions, six steps are described hereafter to calculate the diversion length. Each computation step considers that the capillary barrier is at equilibrium in terms of pressure and hydraulic gradient profiles, i.e. that the diversion length has been completely overpass. The variables considered are the infiltration rate (q), the slope of the interface (ϕ) and the k-function of the two materials.

Step 1. Estimate the suction profile in the MRL using the linear method. The linear method consists in assuming that suction increases linearly with elevation from the suction at its lower elevation, until it reaches the suction value that is found into the porous material for the given q, with a unit gradient (ψ_c). This suction value can be found using the k-function. The suction at the lowest point of the MRL is equal to the value of ψ_c found in the CBL (ψ_{c_CBL}) for the same q. The height from the base of the CBL where ψ_{c_CBL} is reached is z_{c_CBL}. The maximal suction that can be found in the MRL is ψ_{c_MRL} and the height from the base of the CBL where ψ_{c_MRL} is reached is z_{c_MRL}.

Step 2. Obtain the hydraulic conductivity profile in the MRL using the suction profile via the k-function.

Step 3. Estimate the horizontal hydraulic gradient profile in the MRL. From the interface to z_{c_MRL}, the horizontal hydraulic gradient is equal to the tangent of the capillary interface dip. The horizontal hydraulic gradient is, in the scope of the current model, null above z_{c_MRL}.

Step 4. Obtain Darcy's horizontal velocity profile in the MRL by applying Darcy's law, i.e. by multiplying the hydraulic conductivities by the horizontal hydraulic gradients along the profile.

Step 5. Calculate the horizontal flow in the MRL. The horizontal flow is the area under the curve defined by the horizontal velocity profile, given by Equation 1.

$$Q_{\max} = \int_{z_{c\_CBL}}^{z_{c\_MRL}} v_h(z)dz \qquad [1]$$

where Q_{max} is the diversion capacity (m²/s), $v_h(z)$ is the velocity profile as a function of elevation. According to step 1, elevation can be directly transformed into suction (Equation 2).

$$Q_{\max} = \int_{\psi_{c\_CBL}}^{\psi_{c\_MRL}} v_h(\psi)d\psi \qquad [2]$$

Equation 3 can be deducted via Darcy's law.

$$Q_{\max} = \int_{\psi_{c\_CBL}}^{\psi_{c\_MRL}} i_h\ k(\psi)d\psi \qquad [3]$$

where i_h is the horizontal hydraulic gradient and $k(\psi)$ is the k-function (m/s). The k-function $k(\psi)$ can be split into the product of a relative k-function and a constant and, in this case, i_h is equal to the tangent of the slope. Accordingly, Equation 4 is obtained, which is the general equation of the diversion capacity that constitutes the Ross (1990) model.

$$Q_{\max} = k_{sat} \tan\phi \int_{\psi_{c\_CBL}}^{\psi_{c\_MRL}} k_r(\psi)d\psi \qquad [4]$$

where k_{sat} is the saturated hydraulic conductivity of the porous medium (m/s) and $k_r(\psi)$ is the relative permeability function.

Step 6. Calculate the diversion length (L) using Equation 5.

$$L = \frac{Q_{\max}}{q} \qquad [5]$$

4. MATERIAL SELECTION FOR AN OPTIMAL DESIGN

Equations [4] and [5] show that the diversion length is proportional to the area under the k-function of the material constituting the MRL, between the limits ψ_{c_CBL} and ψ_{c_MRL}. This renders the k-function, hence material selection, an important input in capillary barrier design. As shown in Figure 4, the area under the MRL k-function can be maximized by selecting the most appropriate materials for the construction of a capillary barrier, using the following four criteria (numbered 1 to 4 in Figure 4): (1) for an infiltration rate q, the maximal suction existing in the CBL (ψ_{c_CBL}) should be as low as possible; (2) for the infiltration rate q, the maximal suction existing in the MRL (ψ_{c_MRL}) should be as high as possible; (3) and (4) the hydraulic conductivities in the MRL corresponding to ψ_{c_CBL} and to ψ_{c_MRL} should be as high as possible. All in all, an ideal inclined capillary barrier should include a CBL within which capillarity forces are as weak as possible for the infiltration rate q, and a MRL capable to develop capillarity forces as strong as possible, for the same infiltration rate. In addition, the MRL must be as permeable as possible for suctions between ψ_{c_CBL} and ψ_{c_MRL}, so that water is efficiently drained downslope.

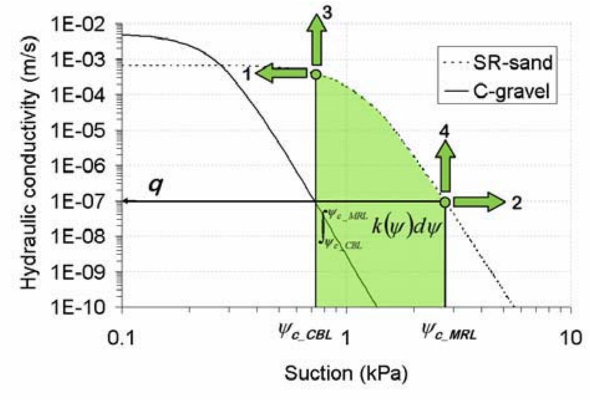

Figure 4. Hydraulic conductivity functions showing how to choose the best materials to constitute the CCBE for a given infiltration rate.

As shown in Figure 5, different material combinations will give different outputs from the Ross (1990) model, in terms of diversion length. It is shown that combination of coarse materials is more efficient than finer-grained capillary barriers. For an infiltration rate of 1×10^{-8} m/s, water will be diverted over 15 m if the CCBE is a WG-loam over SR-sand, and over 178 m if the CCBE is a SR-sand over C-gravel.

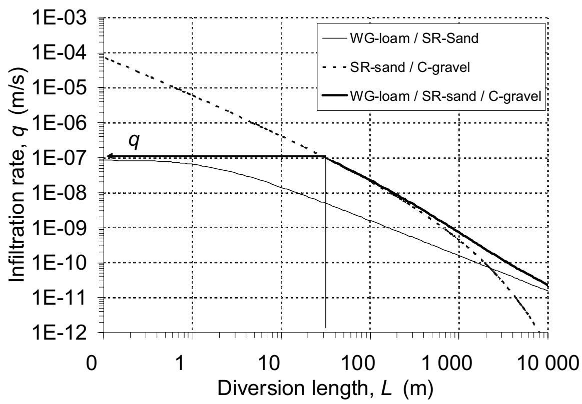

Figure 5. Diversion length for different infiltration rates, using different material combinations.

5. LAYER THICKNESS OPTIMISATION

5.1 Capillary break layer optimization

To maximise the effect of textural contrast between the materials in the CBL and the MRL, suction at the interface must be maximised, i.e. it must be equal to ψ_{c_CBL}. The suction profile into a soil column submitted to a constant infiltration rate can be estimated using the Kisch (1959) method. The linear method may also be used, but it does not model the asymptotic behaviour that is observed at elevations below z_c, when suctions converge towards ψ_c (Akindunni *et al.* 1991). Kisch (1959) combined Darcy's law ($q = k\, dh/dz$), the Buckingham (1907) equation ($h = p + z$) and the k-function to describe the suction profile for a given q, as follows:

$$z(\psi) = -\int_0^{\psi} \left[\frac{q}{k(Y)} - 1 \right]^{-1} dY \qquad [6]$$

where z is the elevation (m), ψ is suction (m), $k(Y)$ is the k-function (m/s) and Y is a dummy variable representing ψ. The Kisch (1959) model can be solved using a finite element unsaturated seepage software or by means of any appropriate compiler.

Given that suction converges towards ψ_c with an asymptotic manner, Kao et al. (2001) suggested that z_c is the height where suction equals 99% of its asymptotic value. The elevation at which z_c will be reached into the CBL depends on the suction at the base of the CBL. The optimal thickness of the CBL can be calculated by subtracting the suction at the base of the CBL from z_{c_CBL}. For a conservative approach, it can be consider that the suction value at the base of the CBL is null.

5.2 Moisture retention layer

The attainment of the suction value ψ_{c_CBL} at the interface is a condition to apply the Ross (1990) model. In the Ross (1990) model, the suction profile in the MRL is obtained using the linear method. However, the Kisch (1959) model, which gives a more accurate suction profile, could be used to describe the suction profile in step 1. Given that the Kisch (1959) model gives a convergence of suction towards ψ_{c_MRL} without reaching it, the upper limit of the integral will not be set at the value of ψ_{c_MRL}, which would give an infinite elevation (infinite thickness), but at the suction value that is obtained on the top of the MRL. According to the Kisch (1959) model. The suction at the top of the MRL depends on its thickness. As a result, for specific slope, infiltration rate and CCBE materials, it is possible to plot the diversion as a function of MRL thickness.

6. CASE STUDY

A 25 m, 4H:1V slope (25%) cover must be installed on the sides of a municipal solid waste disposal. The flow through the interface of the barrier must not exceed 1×10^{-7} m/s. Materials selected are a C-gravel as CBL and a SR-sand as MRL.

The Kisch (1959) model is used to estimate the suction profile in the CBL. For an infiltration rate of 1×10^{-7} m/s into a C-gravel column, results in Figure 6 show that 99% of the value of ψ_{c_CBL} is obtained at a height of 9 cm above a water table. Supposing that the design is based on the worst case scenario, i.e. a water table at the base of the CBL (null pressure), the optimal CBL is 9 cm thick.

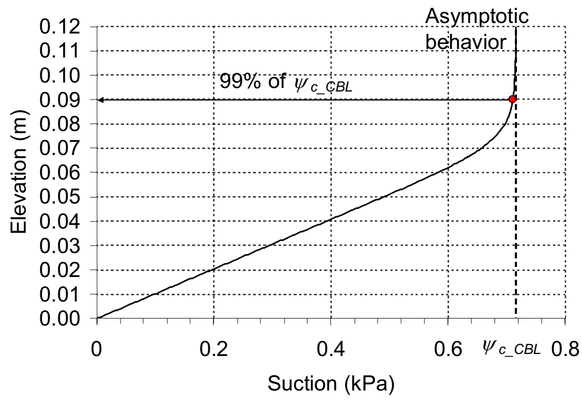

Figure 6. CBL optimization using the Kish (1959) method

The condition that the suction at the interface is ψ_{c_CBL} is met makes the Ross (1990) model applicable to optimize the MRL thickness. Diversion length versus thickness was plotted for q = 1×10^{-7} m/s in Figure 7. In order to obtain a diversion length of 25 m, a MRL thickness of 4 cm is needed.

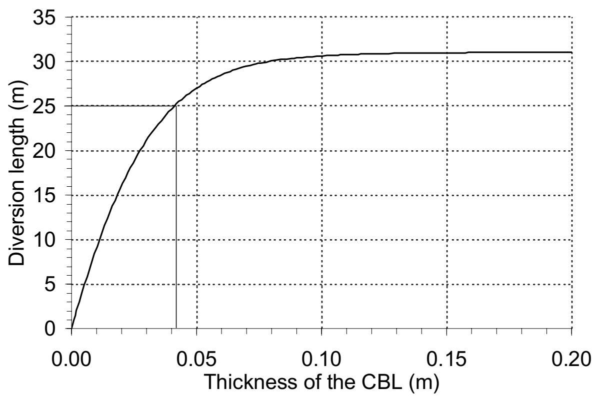

Figure 7. MRL optimisation: results from the adaptation of the Ross (1990) model.

The designed capillary barrier, constituted with a C-gravel layer of 9 cm thick overlaid by a 4 cm thick SR-sand layer, was modelled using SEEP/W. The boundary conditions are a water table at the base of the CBL and a unit flow of 1×10^{-7} m/s at the top of the MRL. Slope length is 25 m and dip is 4H:1V. Given that the materials modelled are coarse, a high density mesh of 8 000 element/m² was used.

Figure 8 shows results obtained from SEEP/W in terms of flow through the interface of the capillary barrier as a function of the horizontal length from the top of the slope. The points obtained from SEEP/W are quite unstable for horizontal distance greater than 10 m, but the trendline, a sigmoïdal model, shows that the targeted infiltration rate of 1×10^{-7} m/s is reached at a horizontal distance of 25 m.

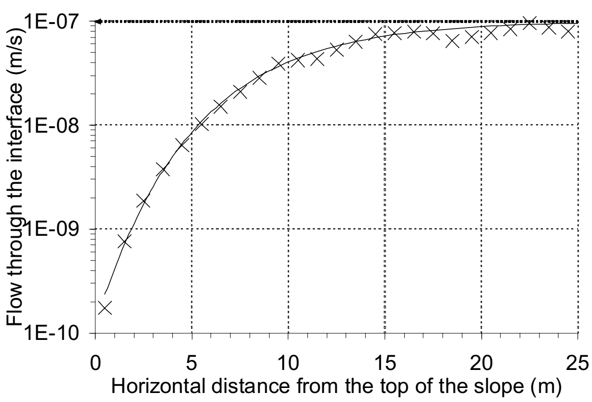

Figure 8. Numerical simulation results of the infiltration through the interface along the slope of the designed capillary barrier, applying the proposed procedure.

The latter proposed CCBE design will work if the flow on the top of the MRL does not overtake 1×10^{-7} m/s. Simulations performed using the HELP model with Montréal (Canada) climatic data (Parent 2003) showed that the infiltration rate could rise up to 2×10^{-7} m/s when snow melts and in the intense rainfalls of November. In this case, the inclined CCBE will not be efficient and a hydraulic barrier layer (HBL), such as the WG-loam, could be placed over the CCBE. Figure 5 shows that the WG-loam will limit the infiltration rate into a capillary barrier made of SR-sand over C-gravel to a value of 1×10^{-7} m/s, for a diversion length of 31 m. Moreover, it would lead to a double capillary barrier effect, but the influence of the latter is negligible. The HBL will act as the limitation layer and, under, the CCBE will diminish percolations by draining water downslope.

7. MODEL LIMITATIONS

The procedure presented above allows for the optimization capillary barriers in terms of material selection and layer thicknesses in order to limit water infiltrations. The procedure does not require the use of numerical simulations. However, four limitations have to be pointed out: (1) The design procedure proposed in this paper is based on limiting the influx to a maximum target value. A more accurate design would be based on a cumulative flux crossing the CCBE interface. Such cumulative flux can be obtained using 2D unsaturated seepage software. (2) As proposed by Khire et al. (2000) for evapotranspirative capillary barriers, a water balance simulation software coupled with an unsaturated flow model - such as UNSAT-H or VADOSE/W - should be used to quantify layer thicknesses, particularly in the case where the lower boundary condition in the CBL is different from the one adopted in this study (pressure head = 0). Khire et al. (2000) also suggested taking into account other factors, such as climatic data, runoff, evapotranspiration, water and wind erosion or desiccation cracking. (3) Kämpf and Holfelder (1999) suggested that a proper design should be tested in flumes, because coarse materials are susceptible to fingering (preferential flow) over a large range of infiltration rates, especially for coarse materials. (4) The proposed approach for designing capillary barriers does not take into account geotechnical aspects, such as slope stability analysis, filtering of MRL material to prevent clogging of the CBL interface, as well as layering effects (due to heterogeneities associated with barrier construction), and constructional aspects.

8. CONCLUSION

A design procedure was proposed to select material and optimize layer thicknesses of inclined covers with capillary barrier effect in order to obtain a proper diversion length. Material selection is based on maximizing the area under the *k*-function of the moisture retaining layer between the suction values found in the two materials under unit gradient for a specific infiltration rate. It was shown that coarse materials are more efficient than fine materials in the constitution of capillary barriers.

The thickness of the CBL is optimise by means of the Kisch (1959) method, that is used to predict the suction profile in a porous material column submitted to an infiltration rate. The optimal CBL thickness equals the height where the convergence suction (ψ_{c_CBL}) is attained. This height depends on the suction imposed at the base of the CBL. For a conservative approach, a null pressure is proposed.

The thickness of the MRL is based on the ability of the material to drain water over the required distance (diversion length). This is done by applying the Ross (1990) model with a modification to the upper limit of the integral, which is set as a variable. In this way, a relationship between diversion length and MRL thickness can be defined. Thus, for a given diversion length, the thickness of the MRL can be obtained.

The procedure was applied for the design of an hypothetic cover. The design was then simulated using the finite element unsaturated seepage software SEEP/W. It was shown that the objective to reach the maximum infiltration rate at the toe of the slope was attained. However, a sand-over-gravel combination may not prevent intense rainfall from infiltrating into the landfill. In this case, a hydraulic barrier constituted of WG-loam can be placed over the CCBE in order to limit infiltration to a maximum equal to the saturated hydraulic conductivity of the WG-loam (1×10^{-7} m/s).

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