Combination of soil materials for granular capillary barriers for minimising rainfall infiltration and gas emission

<table>
<thead>
<tr>
<th>Journal</th>
<th>Canadian Geotechnical Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>cgj-2016-0334.R2</td>
</tr>
<tr>
<td>Manuscript Type</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author</td>
<td>30-Jun-2017</td>
</tr>
<tr>
<td>Complete List of Authors</td>
<td>Zhang, L.M.; Hong Kong University of Science and Technology, Ke, Yanqing; Hong Kong University of Science and Technology</td>
</tr>
<tr>
<td>Keyword</td>
<td>capillary barrier, multiple phase flow, unsaturated soil, rainfall infiltration, Landfill</td>
</tr>
</tbody>
</table>
Combinations of soil materials for granular capillary barriers for minimising rainfall infiltration and gas emission

L.M. Zhang (Corresponding author). Professor, Dept. of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong. E-mail: cezhangl@ust.hk

Y.Q. Ke. Research Assistant, Dept. of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong. E-mail: hfzhao@ust.hk
Abstract: This paper presents a coupled air-water flow analysis to evaluate the performance of a three-layer capillary barrier for controlling water infiltration into and gas emission from a waste containment system in a high precipitation environment, and to optimise combinations of local soil layers for barrier construction. A multiphase flow model is proposed considering the movements of the gas-phase and the water-phase simultaneously. The governing partial differential equations are solved in COMSOL Multiphysics. Several combinations of lean clay with sand (CL), clayed sand with gravel (SC), silty sand with gravel (SM), sandy silt (ML) and well-graded gravel with silt (GW-GM) are examined. The rates of percolation water and gas emission are used as indicators to compare the performance of different combinations. A fine grained surface soil layer reduces both water infiltration and gas emission due to its low desaturation rate and high water retention capacity. The coarse middle layer plays a critical role, promoting capillary effects and hindering water infiltration during rainfall, and draining any infiltrated water or percolated gas.

Key words: Landfill, capillary barrier, rainfall infiltration, multiple phase flow, unsaturated soil.
Introduction

Covers are widely used to control water infiltration into waste containments and tailings (Li et al. 2013). Traditional covers use materials with low permeability, such as compacted clays and geomembrane, to limit rainwater infiltration. A capillary barrier that consists of multiple layers of granular materials is an alternative due to its lower costs and longer durability than those of the traditional covers (Suter et al. 1993). A simple cover with capillary barrier effects (CCBE) is a two-layer system consisting of a fine texture soil layer overlying a coarse texture soil layer (e.g. Harnas et al. 2014; Rahardjo et al. 2013; Yan et al. 2017).

The working mechanisms of capillary barriers have been described by Khire et al. (1999), Shackelford and Benson (2006), Harnas et al. (2014) and others. A capillary cover utilizes the contrast in hydraulic properties between a finer grained soil layer and a coarser grained layer under unsaturated conditions to limit the rainfall penetration into the waste. The difference in the particle sizes of the fine texture soil and the coarse texture soil results in different soil-water characteristic curves (SWCCs) and permeability functions. Before the suction at the interface reaches a breakthrough suction value, rainwater hardly infiltrates into the coarse texture soil layer. The rainwater water is stored temporarily in the fine texture soil layer and removed by evapotranspiration and lateral drainage afterwards. The capillary barrier is considered effective when the combined amount of evapotranspiration, lateral diversion, and water storage capacity is significantly higher than the amount of rainfall infiltration (Harnas et al. 2014). During a rain event, the suction at the interface between the fine texture soil and its underlying coarse soil layer will decrease to a value that permits water to enter and form a continuous network. The hydraulic conductivity of the coarse texture soil layer will increase rapidly, which will result in the disappearance of capillary effect (Stormont and Anderson 1999). Under relatively long time heavy rainfall, the rainfall...
intensity may be greater than the saturated hydraulic conductivity of the fine texture soil. Once capillary barrier effect disappears, water will finally penetrate into waste disposal. Breakthrough occurred several times a year in a two-layer capillary barrier system in a high precipitation and medium evaporation environment (Morris and Stormont 1997). Therefore, two-layer CCBEs may not be robust in areas of high annual precipitation such as Hong Kong where the annual rainfall is more than 2200 mm. Hence two types of three-layer CCBEs have been proposed by Morris and Stormont (1999), Zhan et al. (2014) and Ng et al. (2015a), respectively as alternative final covers for controlling water infiltration and gas emission. Conventional approaches to evaluating the performance of granular covers focus on limiting water percolation (Li et al. 2013). Most infiltration analyses ignore the influence of the gases entrapped in soil pores during infiltration. In reality, a landfill cover is often unsaturated and two-phase flows occur in the capillary zone during water infiltration or gas emission. During a period without rainfall, the evaporation and transpiration process will uptake water from the landfill cover, which will reduce the resistance of the cover to impede the release of the gases generated in the burial waste. As the release of odious landfill gases is a public concern, both water infiltration and gas emission should be controlled and simulated in numerical analyses. The objectives of this paper are (1) to develop a coupled water-gas flow analysis method for evaluating the performance of a three-layer capillary barrier to limit rainfall infiltration under high precipitation conditions and to minimize gas emission considering the influence of evapotranspiration; (2) to optimise combinations of local soil materials for the three-layer capillary barrier; and (3) to investigate the influence of layer thickness on the effectiveness of the three-layer capillary barrier. A multiphase flow model is proposed considering the concurrent movements of the gas phase and the water phase. The governing partial differential equations are solved in COMSOL Multiphysics (COMSOL Inc. 2016).
Desiccation cracking is, however, not considered in this paper.

**Theoretical formulations**

In this paper, an unsaturated soil is assumed to be a three-phase porous medium comprising liquid, gas and solid soil particles. The liquid phase is water and assumed incompressible. The gas phase is assumed to be an idealised gas ignoring the gravitational effect. The soil skeleton is assumed to be rigid. Water and gas transfer is formulated incorporating the effects of advection, but soil deformation and thermal influences are ignored. Based on the mass conservation, the governing equations can be derived for the gas and water phase respectively:

\[
\frac{\partial (\rho_w S_w)}{\partial t} + \nabla \cdot (\rho_w \mathbf{q}_w) = 0
\]

\[
\frac{\partial (\rho_g S_g)}{\partial t} + \nabla \cdot (\rho_g \mathbf{q}_g) = 0
\]

where \( S_w \) and \( S_g \) are the degrees of saturation of the water phase and the gas phase, respectively; \( \phi \) is the porosity of soil; \( \rho_w \) and \( \rho_g \) are the water density and gas density (ML\(^{-3}\)), respectively; \( \mathbf{q}_w \) and \( \mathbf{q}_g \) are the water and gas flux velocity vectors (L/T), respectively.

The movements of water and gas are governed by Darcy’s law and Fick’s law, respectively:

\[
\mathbf{q}_w = -\frac{k_w}{\mu_w} [\nabla P_w + \rho_w g \nabla z]
\]

\[
\mathbf{q}_g = -\frac{k_g}{\mu_g} [\nabla P_g]
\]

where \( P_w \) and \( P_g \) are water pressure and gas pressure (M L\(^{-1}\)T\(^{-2}\)), respectively, which can also be expressed as functions of water pressure head \( h_w \) and gas pressure head \( h_g \), \( P_w = h_w \rho_w g \) and \( P_g = h_g \rho_w g \); \( g \) is the gravitational acceleration (ML\(^{-2}\)); \( h_g \) and \( h_w \) are the gas pressure and
water pressure normalized by the unit weight of water; \( \mu_w \) and \( \mu_g \) are the dynamic viscosities of water and gas, respectively (M L\(^{-1}\)T\(^{-1}\)); \( k_w \) and \( k_g \) are respectively the effective permeabilities of water and gas (L\(^2\)), which are functions of the degree of saturation, among other factors. The coefficients of permeability of water \( (k_w) \) and gas \( (k_g) \) can be expressed as \( \text{LT}^{-1} \)

\[ [5] \quad k_w = \frac{k_w \rho_w g}{\mu_w} \]

\[ [6] \quad k_g = \frac{k_g \rho_g g}{\mu_g} \]

The assumption of rigid soil skeletons implies that

\[ [7] \quad S_w + S_g = 1 \text{ and } \theta_w + \theta_g = \phi \]

The matric suction head \( h_c \) is defined as

\[ [8] \quad h_c = h_g - h_w \]

Ignoring the compressibility of the water phase, the two-dimensional transient flow of the wetting fluid can be described as

\[ [9] \quad C_w \left( \frac{\partial h_g}{\partial t} - \frac{\partial h_w}{\partial t} \right) = \nabla \cdot [k_w (\nabla h_w + \nabla z)] \]

where the capillary capacity can be defined as \( C_w = d\theta/dh_c \) (Touma and Vauclin 1986).

For the compressible gas phase, the gas density can be expressed as a function of reference density and pressure head by introducing a compressible ratio, \( \lambda \) (Chen et al. 1999),

\[ [10] \quad \rho_g = \rho_{o,g} + \lambda h_g \]

where \( \rho_{o,g} \) is the reference density at the atmospheric pressure. The differential equation for gas movement in the soil can be written as

\[ [11] \quad \{ (\phi - \theta_w) \lambda - \rho_g C_w \} \frac{\partial h_g}{\partial t} + \rho_g C_w \frac{\partial h_w}{\partial t} = \nabla \cdot [\rho_g k_g \nabla h_g] \]
Equations (9) and (11) can be solved simultaneously for the unknown pressure heads $h_g$ and $h_w$. The implementation of the two-phase model in COMSOL Multiphysics (COMSOL Inc. 2016) can be divided into three steps:

1. The water and gas pressure heads, normalized by the unit weight of water, are set as two variables to be solved.
2. The two equations describing the movements of water and gas are specified in COMSOL by replacing the corresponding coefficients of partial differential equations.
3. Neumann or Dirichlet boundary conditions are applied in COMSOL.

**Verification of the multiphase movement model**

To verify the multiphase model implemented in COMSOL, a soil column infiltration test was simulated. Touma and Vauclin (1986) reported an infiltration test in a soil column 935 mm in height and 60 mm in inside diameter (Fig. 1). The test soil was a coarse sand. A flux boundary with an intensity of 83 mm/h was applied at the top boundary and lasted for 1.2 hours. The pore water pressure and pore air pressure at six depths (70, 220, 370, 520, 670 and 820 mm) were measured using tensiometers during the experiments. The hydraulic properties and gas conductivity parameters of the test soil are shown in Table 1. As shown in Fig. 1, the bottom of the column is set impermeable for both water and air. Therefore, the air only escapes from the top of the soil column, and water will be stored in the column. In addition to the two-phase flow analysis, a single-phase flow analysis was also conducted to simulate the infiltration test using Seep/W (Geo-Slope International Ltd. 2012) and the results from the two-phase and single-phase analyses are compared with the experimental data.

The measured time evolution of the volumetric water content in the coarse sand column at six snapshots, as well as those calculated using the multiphase model and Seep/W are shown in Fig. 2. The measured volumetric water contents are consistent with the results.
calculated using the multiphase model in COMSOL. The wetting front advancement is accurately captured using the multiphase model. However, the wetting front at each time interval calculated using Seep/W is slightly deeper than both the experimental data and the results from the multiphase model. The volumetric water content in the multiphase model appears to be high in the surface soil when it is nearly saturated, because the infiltration rate is affected by the air outflow. The advance of wetting front will be delayed if air cannot freely escape from the soil column. The results obtained from the multiphase model and the experimental results are indeed consistent.

The air pressure during the infiltration process using the multiphase model increases during the infiltration process. This is consistent with the findings by Wang et al. (1998) that the air pressure ahead of the wetting front in an air-confining condition increases with time, instead of reaching a constant level.

**CCBE materials and combinations**

Figure 3 shows a CCBE model with a width of 25 m and a slope of 1:3. The depths of the left and right boundaries are 17.8 m and 9.5 m, respectively. The model consists of four components: a fine texture soil layer as the surface layer, a coarse texture middle soil layer, a fine texture soil layer as the bottom layer, and the underlying waste material. Completely decomposed granite (CDG) is the most available soil in Hong Kong and its hydraulic and mechanical properties have been widely investigated (e.g. Zhao and Zhang 2014; Zhao et al. 2013). In this study, five types of materials were mixed from a CDG as candidate capillary barrier cover materials. The grain size distributions and basic properties of these five soils are shown in Table 2, referring to Li et al. (2009). According to ASTM D2487 (ASTM 2006), these five materials can be classified as lean clay with sand (CL), sandy silt (ML), clayey sand with gravel (SC), silty sand with gravel (SM), and well graded gravel with silt (GW-
Many combinations of layer materials are evaluated, taking CL, ML and SC for the fine soil layer, and SM and GW-GM for the coarse soil layer.

The soil-water characteristic functions and permeability functions for these soils are shown in Table 3. The SWCCs were measured by Li et al. (2009) and Li et al. (2014) and the SWCC parameters for these soils are summarised in Table 4. The soil water characteristic curves for these materials are shown in Fig. 4. The hydraulic conductivity parameters are shown in Table 5 and the permeability curves are shown in Fig. 5. The waste material underlying the cover is also simulated. The hydraulic properties of the waste material are taken as those for the Qizishan landfill in China (Zhang et al. 2007). The hydraulic conductivity curves are along the wetting branch, which helps avoid the hydraulic hysteresis problem in unsaturated soils (Yang et al. 2012). Water in the soil can move either in liquid form or vapor form. A lower limit of $10^{-13}$ to $10^{-14}$ m/s of the permeability function should be imposed when the predominant flow is in a vapor form based on water vapour flow theory (Ebrahimi-Birang et al. 2004; Fredlund et al. 2012).

In deriving the SWCCs and water permeability functions, the hydraulic and mechanical behaviours are decoupled for simplicity. Sheng and Zhou (2011) and Cai et al. (2014) introduced coupling mechanisms between the hydraulic and mechanical behaviours of unsaturated soils.

The intrinsic permeability is used to predict the gas permeability of each material. Assuming that the soil skeleton is not affected by suction changes and ignoring the Klinkenberg effect, the permeability of either the water phase or the gas phase only depends on the ratio of the phase in the porosity of the material. Based on the concept of intrinsic permeability, the effective permeabilities in Eqs. [5] and [6] for calculating the saturated water permeability and the maximum gas permeability at the dry state are the same. A relationship exists between the coefficients of water-phase and gas-phase permeability. Hence
the maximum gas coefficient of permeability can be calculated from the saturated water coefficient of permeability following Eqs. [5] and [6].

The gas permeability at a particular suction can be predicted according to the relative gas permeability, \( k_{rg} \), referring to Mualem’s model (1976):

\[
[12] \quad k_{rg} = \left(1 - S_{ew}\right)^{\eta \left(\int_{S_{ew}}^{1} \frac{dS}{\psi} \right)^{2} \int_{0}^{1} \frac{dS}{\psi}}
\]

where \( S_{ew} \) is the effective saturation of water; \( \psi \) is the matric suction; \( \eta \) is a tortuosity parameter. The gas permeability functions for the materials in this study are obtained based on numerical integration using the Mualem model (1976) and shown in Fig. 6.

Soil-water characteristics exhibit hysteresis. The soil undergoes a wetting process during the wetting process, and the wetting SWCC, water permeability function and gas permeability function should be used in the numerical analysis. On the other hand, the soil undergoes a drying process during the gas emission stage, hence the drying SWCC, water permeability function and gas permeability function should be used. In the numerical analyses in this study, the hysteresis of the SWCC and water and gas permeability functions is not considered and the wetting curves are used in all the analysis cases, which will overestimate the gas emission amount. However, this does not affect the comparison of the performances of the CCBEs with different material combinations and the identification of the best combination.

**Boundary and initial conditions**

The CCBE model in Figs. 3 and 7(a) represents an axisymmetric landfill with a width of 25 m and a slope of 1:3. In Fig. 7, the bottom boundary of the waste, EF, is set as a stable groundwater table which is far away from the slope surface. The upstream boundary of the
cover, AC, and that of the waste domain, CE, are assumed to be a zero flux boundary. The
downstream boundary of the waste domain, DF, is also set as a zero-flux boundary. The
downstream boundary of the cover system, BD, is set as a free drainage boundary. The free
drainage condition is simulated using a mixed boundary in COMSOL (Chui and Freyberg
2007). During a rainfall event, the slope surface boundary, AB, corresponding to the rainfall
area in the field, is defined as a flux boundary. Given a specific rainfall event, when the
rainfall rate is smaller than the hydraulic conductivity of the soil exposing to precipitation,
the infiltration rate is equal to the rainfall intensity. Once the rainfall rate exceeds the
maximum infiltration capacity of the soil, the actual amount of rainwater infiltrating into the
soil layer will be equal to its saturated hydraulic conductivity; the remaining portion of
rainfall will appear as surface runoff. This condition can be simulated by setting hydraulic
head equal to the elevation of the node at the surface boundary. This assumption is reasonable
when the slope of the cover is steep and no ponding is likely. Three rainfall scenarios are
considered when examining the performance of the cover during rainfall infiltration (Lam
and Leung 1994): (1) a 1000-year return storm in Hong Kong with a rainfall amount of 759
mm in 24 hours; (2) a 10-year return period storm with a rainfall amount of 371 mm in 24
hours; (3) a 2-year return period rain event with a rainfall amount of 214 mm in 24 hours.
Another 1000-year return period storm with a rainfall amount of 904 mm in 48 hours is also
considered to study the performance of the cover under a smaller intensity, longer period
storm.

Similarly, to simulate the gas emission process (Fig. 7b), a constant gas pressure equal to
5 kPa is applied to the waste material at the bottom of the cover, CD. The surface boundary,
AB, is set to be connected to the atmosphere with a constant gas pressure of 0 kPa. The
upstream boundaries of the cover and waste domain, AC and CE, are both assumed to be
zero-flux boundaries. The downstream boundary of the cover, BD, is defined as a drainage
boundary for both water flow and gas flow. However, the gas pressure inside the middle layer of the cover is not assumed to be zero except at the downstream boundary, BD. Hence the gas in the middle coarse layer can emit from the top surface, or move laterally along the middle layer and exit at BD. The downstream boundary of the waste domain, DF, is set as a zero-flux boundary. To consider the influence of evapotranspiration on the cover performance during gas emission, a flux boundary condition is applied on the surface boundary, AB. The evapotranspiration rate is set as 5 mm/day. The actual evapotranspiration rate will decrease with an increase of matric suction in the affected zone, which satisfies a relationship with field capacity and wilting point (Veihmeyer and Hendrickson 1950).

To consider antecedent rainfall in both rainfall infiltration and gas emission analyses, the initial conditions are set as the steady state condition obtained by applying a small rainfall flux on the top surface. The flux was taken as the average annual precipitation in Hong Kong, 2214.3 mm/y. Due to the high annual rainfall intensity, the corresponding steady state suction values are relatively small, which means the cover will stay at a relatively wet condition. This will therefore serve as a non-conservative initial condition for rainfall infiltration. For gas emission analysis, an evaporation process is assumed to start at this initial condition for a period of 30 days at an evapotranspiration rate of 5 mm/day. This will create a critical dry condition for gas emission.

**Performance of cover during rainfall infiltration**

The criteria for evaluating the performance of the three-layer CCBEs with various soil combinations during rainfall infiltration include the amounts of infiltration, drainage, and percolation through the cover system. Six soil layering combinations using lean clay with sand (CL), clayed sand with gravel (SC), silty sand with gravel (SM), sandy silt (ML) and well-graded gravel with silt (GW-GM) are examined, as summarised in Table 6. Additional
analyses in Table 7 are also performed to examine the influence of layer thickness. The 1000-year, 10-year, and 2-year rainfall conditions with a duration of 24 hours in this paper correspond to unit flux values of $8.78 \times 10^{-6}$ m/s, $4.29 \times 10^{-6}$ m/s, and $2.48 \times 10^{-6}$ m/s, respectively. The rainfall intensities in these three scenarios are greater than the hydraulic conductivity of the top layer material (i.e., ML or SC with permeability of $4 \times 10^{-7}$ m/s and $1 \times 10^{-6}$ m/s, respectively). As a result, similar amounts of rainwater will infiltrate into the top layer in the three rainfall scenarios and most rainwater will become runoff. Therefore, only the results for the 1000-year return period storm are reported in detail in this paper.

The infiltration process is illustrated in a Type 1 three-layer capillary barrier cover system using SC, GW-GM, CL as the surface, middle and bottom soil layer, respectively. The volumetric water content and suction head along the middle cross section (x=12.5 m in Fig. 7) after 24-hour rainfall are shown in Fig. 8. At the initial condition obtained by a steady state analysis at the average rainfall, the suction levels in the soil layers are low and the water contents are relatively high. As the rain starts, the suction in the soil continues to decrease (Fig. 8a), but the increases in the water contents in the soil layers are limited (Fig. 8b).

Figure 9 shows the process of rainwater infiltration and lateral movement of the infiltrated rainwater. At the beginning, the rainwater infiltrates into the top fine soil layer and the infiltration into the middle coarse layer is minimal as the permeability of the coarse layer is smaller than that of the fine layer at small suctions (Fig. 9a). As infiltration proceeds, the water content in the coarse layer increases and hence the coarse layer becomes permeable. After the capillary barrier effect at the interface breaks, more rainfall water enters the coarse layer (Fig. 9b). When the wetting front reaches the top of the bottom soil layer, most of the rainwater that has infiltrated tends to accumulate there due to the relatively low permeability of the bottom layer. As the infiltration goes on, part of the infiltrated rainwater will be hold in the bottom layer but the majority of it will drain laterally through the coarse texture soil layer.
(Fig. 9c) when the pore water pressure reaches a value at which the hydraulic conductivity of the coarse soil layer is greater than that of its underlying fine texture soil layer.

The amounts of the rainwater infiltrating into the surface layer, the lateral drainage through the coarse layer, and the percolated water through a unit cross section beneath the interface between the cover and the waste material are shown in Fig. 10 for the material combinations in Table 6. The smaller the coefficient of permeability of the surface soil is, the smaller the percolation amount of rainwater will penetrate the cover system. A sandy layer (SM), if used in the middle, will not be as effective as a gravel layer (GW-GM) to create the capillary barrier effects. Sand (SC) is too coarse to be used as the top layer. The Type I cover (ML GW-GM CL) has the least percolation and the best performance. The cover comprises of a fine surface layer ML to restrain water infiltration, a high-permeability coarse middle layer to promote the capillary effects and drainage, and a fine bottom layer to prevent escaped water from entering the waste.

Fig. 11 compares the amounts of rainwater infiltration into the surface layer, the lateral drainage through the coarse layer, and the percolated water under a 1000-year return period, 24-hour duration storm and a 1000-year return period, 48-hour duration storm for the Type I cover. As the unit flux values in both storm cases are greater than the saturated permeability of the top layer soil (ML), the infiltration amount is limited by the saturated permeability of ML. As expected, the amounts of rainwater infiltration, drainage and percolation in the 48-hour duration storm are nearly twice those in the 24-hour duration storm. However, the change in rainfall duration does not alter the best combination of the cover soils for the six combinations considered in this paper.

Four combinations of layer thickness for the Type I cover (Table 7) are examined to investigate the influence of layer thickness on the performance of the cover system to prevent rainfall percolation. In a benchmarking case the thicknesses of all the layers are all 0.3 m. In
the other combinations the thickness of the top, middle or bottom layer is increased to 0.6 m while the thickness of the remaining layers is kept at 0.3 m. The rainwater percolation amounts in these combinations after exposed to an extremely heavy rainfall for 24 hours are shown in Fig. 12. Increasing the thickness of each layer will enhance the performance of the cover system slightly compared with that in the benchmark case (combination 1). To increase the thickness of the bottom soil layer (combination 4) is the most effective as this will enhance the water retention capacity of this layer and promote the drainage through the middle layer.

**Performance of cover during gas emission**

Numerical analyses are also performed to optimise the three-layer soil combinations for the best gas emission control. The gas emission process in the cover system is shown in Fig. 13. The gas permeability, among other factors, is primarily controlled by the water content or the degree of saturation. When the bottom layer dries, the gas from the waste will enter the coarse GW-GM layer (Fig. 13a). The coarse layer has the largest gas permeability and the right layer boundary is drained. Hence the middle layer forms a drainage channel for the gas that enters that layer (Fig. 13b). The surface layer, when at a high degree of saturation, has a very low gas permeability and the gas hardly emits to the atmosphere. However, the gas permeability can increase significantly when the degree of saturation becomes low after an extended period of evapotranspiration. As such some gas can emit into the atmosphere (Fig. 13c). This explains why gas emission often occurs after an extended dry period.

Fig. 14 presents the amounts of gas drainage, emission and percolation through a unit cross sectional area for the six types of covers in Table 6 after a dry period of 30 days. The best performance is obtained using Type I (ML GW-GM CL) and Type 2 (SC GW-GM CL) covers. The gas emission is mainly controlled by the coarse texture drainage layer (GW-GM)
given that the surface and bottom soil materials are at high water contents and hence have low gas permeability. This again emphasizes the importance for the top and bottom layers to be of high water retention capacity.

**Optimum design for minimising water infiltration and gas emission**

The above analysis for rainfall infiltration shows that the performance of a capillary barrier to impede rainfall infiltration depends largely on the material combinations in the cover. The influences of each layer material on impeding rainwater percolation are briefly described as follows:

1. The coarse-texture soil material with high saturated conductivity dominates the drainage capacity of the three-layer cover system.

2. The amount of rainwater percolation depends on the potential drainage capacity relevant to the permeability of the coarse-texture soil and the permeability of the bottom fine-texture soil. A lower permeability of the bottom fine-texture soil layer will lead to a lower percolation rate and at the same time enhance the drainage efficiency.

3. The amount of rainwater infiltration depends on the surface soil material. A lower permeability provided by the surface fine-texture soil layer will lead to a lower infiltration rate and help minimize the rainwater percolation.

Among the six material combinations (Table 6), the Type 1 cover is recommended adopting ML, GW-GM and CL as its surface fine-texture, middle coarse-texture and bottom fine-texture soil layers, respectively. Such a cover has small amounts of rainfall infiltration and percolation. Meanwhile, the large saturated hydraulic conductivity of its coarse-texture soil layer provides good drainage under extreme rainfall conditions. Increasing the layer thickness does not significantly enhance the performance of the cover (Fig. 12).

The Type 1 cover also minimises gas percolation and gas emission into the atmosphere.
The high coefficient of desaturation capacity of GW-GM efficiently keeps the moisture content of the bottom CL fine-texture soil layer and hence maintains a very low gas permeability, making gas percolation difficult. Therefore, the Type 1 cover is also recommended for preventing gas emission.

The above recommendations are obtained based on the scenario that the cover remains at a relatively wet condition. The performance of the barrier system may be different if the initial suction is very high such as during the drying season.

Cracking in the fine-texture soil layers is not considered in this study. Particularly cracks in the bottom layer, if occurring, will disable the drainage function of the middle coarse layer and aggravate water percolation into the waste. Cracks in the surface layer will promote water infiltration during rainfall and gas emission in the dry period.

Conclusions

This paper presents a coupled air-water flow analysis method and uses this method to evaluate the effectiveness of three-layer capillary covers in limiting rainfall infiltration under heavy rainfall conditions as well as gas emission under dry conditions. The following conclusions can be drawn:

1. The amounts of percolated water and emitted gas are used to evaluate the performance of the capillary covers with different soil combinations and layer thicknesses. Based on the simulation results, the Type 1 cover is recommended, which adopts ML, GW-GM and CL as its surface fine-texture soil layer, middle coarse-texture soil layer and bottom fine-texture soil layer, respectively. This type of three-layer cover allows only a small amount of rainfall infiltration into the cover and a small amount of percolation through the cover to the waste. The coarse middle layer plays a critical role, promoting capillary effects and hindering water infiltration during rainfall, and draining any infiltrated water or
percolated gas.

(2) The Type 1 cover also ensures a very small amount of gas percolation and a minimal amount of gas emission into the atmosphere. The high coefficient of desaturation capacity of GW-GM efficiently keeps the moisture of the bottom fine-texture soil layer and maintains a very low gas permeability.

(3) The thicknesses of the surface fine-texture layer, the middle coarse-texture layer, and the bottom fine-texture layer are all set as 0.3 m in this study. Increasing the thickness of the bottom fine-texture soil layer slightly enhances the performance of the three-layer granular cover by decreasing both water infiltration and gas emission. Increasing the thickness of the surface fine-texture soil layer also slightly enhances the cover performance by increasing the water storage capacity. Optimising the material combinations is more crucial than increasing the layer thickness.

Acknowledgements

This research is substantially supported by the Research Grants Council of the Hong Kong SAR (Grant No. HKUST6/CRF/12R) and the Natural Science Foundation of China (No. 51379053).

References


COMSOL, Inc. 2016. COMSOL multiphysics. Burlington, Massachusetts, USA.


Lam, C.-C., and Leung, Y.-K. 1994. Extreme rainfall statistics and design rainstorm profiles at selected locations in Hong Kong. Royal Observatory, Hong Kong.

304-315.


List of captions

Table captions
Table 1. Summary of parameters for the verification case reported by Touma and Vauclin (1986).
Table 2. Index properties of five Hong Kong candidate soils for capillary covers.
Table 3. Equations for soil-water characteristic curves and water permeability functions.
Table 4. Soil-water characteristic curve fitting parameters (Adapted from Li et al. 2009).
Table 5. Hydraulic conductivity and gas permeability function parameters (Adapted from Li et al. 2009 and Li et al. 2014).
Table 6. Combinations of soil layer materials.
Table 7. Combinations of soil layer thickness.

Figure captions
Fig. 1. Simulation of a one-dimensional column test.
Fig. 2. Measured and calculated evolution of water content profile during an infiltration process. Horizontal bars correspond to experiments uncertainties.
Fig. 3. (a) Geometry of the analysis domain and (b) the finite element mesh.
Fig. 4. Soil water characteristic curves for CL, ML, SC, SM, GW-GM and waste material.
Fig. 5. Hydraulic conductivity functions for CL, ML, SC, SM, GW-GM and waste material.
Fig. 6. Gas permeability functions for CL, ML, SC, SM, GW-GM and waste material.
Fig. 7. Boundary conditions for (a) rainfall infiltration analysis and (b) gas emission analysis.
Fig. 8. Time evolution of (a) suction and (b) volumetric water content along a cross section (x=12.5 m) for cover Type 1 (ML, GW-GM and CL) during a 1000-year return period rainfall.
Fig. 9. Process of rainwater infiltration into a three layer capillary cover.
Fig. 10. Infiltration, drainage and percolation amounts per unit area under 1000-year return period rainfall.
Fig. 11. Infiltration, drainage and percolation amounts per unit area under 1000-year return period, 24- and 48-hour duration storms.
Fig. 12. Infiltration, drainage and percolation amounts per unit area in a three-layer capillary cover with different layer thickness values under 1000-year return period rainfall.
Fig. 13. Process of gas emission through a three layer capillary cover.
Fig. 14. Gas emission, drainage and percolation amounts per unit area.
Table 1. Summary of parameters for the verification case reported by Touma and Vauclin (1986).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>Porosity</td>
<td>0.37</td>
</tr>
<tr>
<td>$\theta_{ws}$</td>
<td>Saturated volumetric water content</td>
<td>0.312</td>
</tr>
<tr>
<td>$\theta_{wr}$</td>
<td>Residual volumetric water content</td>
<td>0.0265</td>
</tr>
<tr>
<td>$K_{sv}$</td>
<td>Dry air permeability</td>
<td>2800 (cm/h)</td>
</tr>
<tr>
<td>$K_{w}$</td>
<td>Saturated coefficient of permeability</td>
<td>15.40 (cm/h)</td>
</tr>
<tr>
<td>$K_{aw}$</td>
<td>Coefficient of permeability</td>
<td>$K_w = A_w \theta_w^{B_w}$</td>
</tr>
<tr>
<td>$K_a$</td>
<td>Air permeability</td>
<td>$K_a = K_{sv} \frac{A_a}{A_a + h_e^{B_a}}$</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>Volumetric water content</td>
<td>$\theta_w = \frac{\theta_{ws} - \theta_{wr}}{1 + (\alpha h_e)^\beta} + \theta_{wr}$</td>
</tr>
<tr>
<td>$A_w$</td>
<td>Parameter of water permeability function</td>
<td>18130 (cm/h)</td>
</tr>
<tr>
<td>$B_w$</td>
<td>Parameter of water permeability function</td>
<td>6.07</td>
</tr>
<tr>
<td>$A_a$</td>
<td>Parameter of air permeability function</td>
<td>$3.86 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B_a$</td>
<td>Parameter of air permeability function</td>
<td>-2.4</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Parameter of volumetric water content function</td>
<td>0.044 (cm$^{-1}$)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Parameter of volumetric water content function</td>
<td>2.2</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Parameter of volumetric water content function</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Table 2. Index properties of five Hong Kong candidate soils for capillary covers.

<table>
<thead>
<tr>
<th>Group symbols (ASTM D2487)</th>
<th>Maximum dry density (kg/m$^3$)</th>
<th>Optimum water content (%)</th>
<th>Dry density (kg/m$^3$)</th>
<th>Porosity</th>
<th>Fines (%)</th>
<th>Sand (%)</th>
<th>Gravel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW-GM</td>
<td>1950</td>
<td>9</td>
<td>1780</td>
<td>0.33</td>
<td>7</td>
<td>35</td>
<td>58</td>
</tr>
<tr>
<td>SM</td>
<td>1970</td>
<td>11</td>
<td>1810</td>
<td>0.31</td>
<td>24</td>
<td>32</td>
<td>44</td>
</tr>
<tr>
<td>SC</td>
<td>1900</td>
<td>13</td>
<td>1620</td>
<td>0.39</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>ML</td>
<td>1710</td>
<td>18</td>
<td>1450</td>
<td>0.45</td>
<td>60</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>CL</td>
<td>1550</td>
<td>21</td>
<td>1320</td>
<td>0.5</td>
<td>80</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Equations for soil-water characteristic curves and water permeability functions.

<table>
<thead>
<tr>
<th>Model</th>
<th>Function</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fredlund and Xing (1994) SWCC model</td>
<td>$\theta = \theta_s \left{ \frac{1 - \ln[1 + (\psi/\psi_r)]}{\ln[1 + (10^a/\psi_r)]} \right} \frac{1}{\ln[e + (\psi/a)^m]}$</td>
<td>$a, n, m, \psi_r$</td>
</tr>
<tr>
<td>Bimodal SWCC model (Zhang and Chen 2005)</td>
<td>$\theta = \theta_s \left{ [1 + (a, \psi)^n]^{-m} + \theta_s [1 + (a, \psi)^n]^{-m} \right}$</td>
<td>$a_l, \alpha_s, n_s, m_s, m_s, \theta_s$</td>
</tr>
<tr>
<td>Gardner SHCC model (1958)</td>
<td>$k = k_s / \left[ 1 + a (n)^b \right]$</td>
<td>$a, b, k_s$</td>
</tr>
<tr>
<td>Water permeability bimodal (Li et al. 2014)</td>
<td>$k = \left( \frac{k_s}{k_r} \right)^{\psi/\psi_r} \left( \frac{k_s}{k_r} \right)^{\psi/\psi_r} k_r$</td>
<td>$c_1, c_2, h, j, k_s, k_r$</td>
</tr>
</tbody>
</table>
Table 4. Soil-water characteristic curve fitting parameters (adapted from Li et al. 2009).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>SWCC fitting model</th>
<th>Porosity</th>
<th>θ_s</th>
<th>θ_i</th>
<th>θ_ss</th>
<th>ψ_r (kPa)</th>
<th>a (kPa)</th>
<th>a_l (kPa⁻¹)</th>
<th>a_s (kPa⁻¹)</th>
<th>m</th>
<th>m_l</th>
<th>m_s</th>
<th>n</th>
<th>n_l</th>
<th>n_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>Fredlund and Xing</td>
<td>0.50</td>
<td>0.50</td>
<td>-</td>
<td>-</td>
<td>3000</td>
<td>146</td>
<td>-</td>
<td>-</td>
<td>1.281</td>
<td>-</td>
<td>-</td>
<td>1.001</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ML</td>
<td>Fredlund and Xing</td>
<td>0.45</td>
<td>0.45</td>
<td>-</td>
<td>-</td>
<td>1500</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>1.299</td>
<td>-</td>
<td>-</td>
<td>0.632</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SC</td>
<td>Fredlund and Xing</td>
<td>0.39</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
<td>1000</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>0.878</td>
<td>-</td>
<td>-</td>
<td>0.809</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SM</td>
<td>Bimodal SWCC model</td>
<td>0.31</td>
<td>-</td>
<td>0.10</td>
<td>0.21</td>
<td>-</td>
<td>1.52</td>
<td>0.01</td>
<td>-</td>
<td>0.540</td>
<td>0.200</td>
<td>-</td>
<td>1.235</td>
<td>1.733</td>
<td></td>
</tr>
<tr>
<td>GW-GM</td>
<td>Bimodal SWCC model</td>
<td>0.33</td>
<td>-</td>
<td>0.18</td>
<td>0.15</td>
<td>-</td>
<td>16.7</td>
<td>0.067</td>
<td>-</td>
<td>0.393</td>
<td>0.308</td>
<td>-</td>
<td>5.640</td>
<td>0.681</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Hydraulic conductivity and gas permeability function parameters (adapted from Li et al. 2009 and Li et al. 2014).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Water permeability fitting model</th>
<th>k_s (m/s)</th>
<th>a</th>
<th>b</th>
<th>k_r (m/s)</th>
<th>k_r (m/s)</th>
<th>ψ_ε1 (kPa)</th>
<th>ψ_ε2 (kPa)</th>
<th>h</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>Gardner SHCC model</td>
<td>1.00×10⁻⁷</td>
<td>1.06</td>
<td>2.17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ML</td>
<td>Gardner SHCC model</td>
<td>4.00×10⁻⁷</td>
<td>2.93</td>
<td>2.15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SC</td>
<td>Gardner SHCC model</td>
<td>4.00×10⁻⁶</td>
<td>17.5</td>
<td>2.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SM</td>
<td>Li water permeability bimodal</td>
<td>1.00×10⁻⁴</td>
<td>-</td>
<td>-</td>
<td>3.00×10⁻⁸</td>
<td>2.00×10⁻¹³</td>
<td>1.342</td>
<td>164.317</td>
<td>1.21</td>
<td>0.793</td>
</tr>
<tr>
<td>GW-GM</td>
<td>Li water permeability bimodal</td>
<td>1.00×10⁻²</td>
<td>-</td>
<td>-</td>
<td>1.00×10⁻⁸</td>
<td>1.00×10⁻¹³</td>
<td>0.612</td>
<td>67.082</td>
<td>2.57</td>
<td>0.606</td>
</tr>
</tbody>
</table>
### Table 6. Combinations of soil layer materials.

<table>
<thead>
<tr>
<th>Combination No.</th>
<th>Soil material for each layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface fine-texture</td>
</tr>
<tr>
<td>Type 1</td>
<td>ML</td>
</tr>
<tr>
<td>Type 2</td>
<td>SC</td>
</tr>
<tr>
<td>Type 3</td>
<td>SC</td>
</tr>
<tr>
<td>Type 4</td>
<td>ML</td>
</tr>
<tr>
<td>Type 5</td>
<td>SC</td>
</tr>
<tr>
<td>Type 6</td>
<td>SC</td>
</tr>
</tbody>
</table>

### Table 7. Combinations of soil layer thickness.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Soil layer thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface fine-texture</td>
</tr>
<tr>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Fig. 1. Simulation of a one-dimensional column test.
Fig. 2. Measured and calculated evolution of water content profile during an infiltration process. Horizontal bars correspond to experiments uncertainties.
Fig. 3. (a) Geometry of the analysis domain and (b) the finite element mesh.
Fig. 4. Soil water characteristic curves for CL, ML, SC, SM, GW-GM and waste material.
Fig. 5. Hydraulic conductivity functions for CL, ML, SC, SM, GW-GM and waste material.
Fig. 6. Gas permeability functions for CL, ML, SC, SM, GW-GM and waste material.
Fig. 7. Boundary conditions for (a) rainfall infiltration analysis and (b) gas emission analysis.
Fig. 8. Time evolution of (a) suction and (b) volumetric water content along a cross section (x=12.5 m) for cover Type 1 (ML, GW-GM and CL) during a 1000-year return period rainfall.
**Fig. 9.** Process of rainwater infiltration into a three layer capillary cover.

(a) Rainwater begins to infiltrate into the surface soil layer

(b) Rainwater penetrates into the coarse-texture soil layer

(c) Rainwater percolates into the bottom fine-texture soil layer and drainage begins
Fig. 10. Infiltration, drainage and percolation amounts per unit area under 1000-year return period rainfall.
Fig. 11. Infiltration, drainage and percolation amounts per unit area under 1000-year return period, 24- and 48-hour duration storms.
Fig. 12. Infiltration, drainage and percolation amounts per unit area in a three-layer capillary cover with different layer thickness values under 1000-year return period rainfall.
Fig. 13. Process of gas emission through a three layer capillary cover.

Gas begins to penetrate into the bottom fine-texture soil layer

Gas penetrates into the coarse-texture soil layer and drainage begins

Gas percolates into the surface fine-texture soil layer
**Fig. 14.** Gas emission, drainage and percolation amounts per unit area.

<table>
<thead>
<tr>
<th>Cover type</th>
<th>Drainage</th>
<th>Emission</th>
<th>Percolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC_SM_ML</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>SC_GW and GM_ML</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>ML_SM_CL</td>
<td>0.00</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>ML_GW and GM_CL</td>
<td>0.00</td>
<td>0.08</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Legend:**
- **Drainage**
- **Emission**
- **Percolation**