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Use of Dual Capillary Barrier as Cover System for a Sanitary Landfill in Singapore

H. Rahardjo, A. Satyanaga, F.R. Harnas and E.C. Leong

Abstract

Construction and demolition of buildings together with the reconstruction of roads and pavements produce a lot of solid wastes every year. These wastes create problems related to cost and space for disposal, especially for countries with limited land area like Singapore. Therefore, it is important to choose suitable landfill management system (i.e. cover system) for optimization of landfill area in Singapore. Landfill cover offers many geo-environmental benefits, including reducing water infiltration, isolating waste and controlling landfill gases. In Singapore the cover system is located within the unsaturated zone above the groundwater table. Therefore, it is necessary to incorporate unsaturated soil mechanics principles in designing the cover system for the landfill. Soil properties in the unsaturated soil zone affect the rate of wetting front movement from the ground surface. As a result, the rates of changes in pore-water pressures during and after rainfall will vary in accordance with the characteristics of unsaturated soil properties.

In this study, the performance of dual capillary barrier (DCB) in minimizing rainwater infiltration into a sanitary landfill in Singapore was investigated. The DCB consists of fine recycled asphalt pavement (RAP) and coarse RAP as the materials for the fine- and coarse-grained layers, respectively. The recycled materials were used in the DCB to reduce the cost associated with the construction of a cover system in the field and to maintain environmental sustainability. Laboratory tests were conducted to characterize the index properties and hydraulic properties (i.e. soil-water characteristic curve (SWCC) and permeability function) of the RAP for the cover system under saturated and unsaturated conditions. The SWCC and permeability function were used in the finite element seepage analyses to study the effect of climate change on the soil cover system. The results from the seepage analyses show that the DCB was effective in minimizing rainwater infiltration into the sanitary landfill.

Keywords: unsaturated soil; landfill; dual capillary barrier; recycled asphalt pavement; SWCC; permeability function

1. INTRODUCTION

Landfill is the most common form of waste disposal. Old landfills are present or in close proximity to most communities. Substantial amount of waste from household, industry, and construction are produced everyday around the world including Singapore. The safe and reliable long-term disposal of waste residues is an important component of an integrated waste management. Waste residues that are not incinerated and recycled need to be stored in waste containment systems or landfills. Controlled placement of waste in sanitary landfill greatly reduces the number of rodents and insects, dramatically reduces public health risks, prevents the contamination of waste to the surrounding groundwater and generally contributes to major aesthetic improvements in waste disposal (Tchobanologlous et al., 1993). There are various approaches in the design and management of a landfill (Rowe et al., 1995), among which the role of cover system should be considered.

Landfill cover system is a containment technology that forms a barrier between the waste (contaminated media) and environment. The cover system must restrict surface water infiltration into the contaminated waste to reduce the potential for contaminants to leach from the site. Previous studies indicated that compacted clay liner (CCL), geosynthetic clay liner (GCL) and evapotranspiration cover (ET) system are commonly used as a cover system. Each cover system has advantages and disadvantages. Research works by Suter et al. (1993) showed that CCL system meet the permeability criteria for a cover system. However, the permeability of CCL material increases with time due to desiccation cracking, wet-dry and freeze-thaw effects, root penetration and differential settlement. Daniel and Koerner (1995) recommended the use of GCL system instead of CCL system since the permeability of GCL material is much lower than that of CCL system and the permeability of GCL material will not change with time. However, they also observed that the thin barrier layers within GCL system are more vulnerable to construction damage or post construction puncture, material of GCL is expensive and geosynthetic material within GCL system has low hydrated shear strength. Anderson et al. (1999) suggested to use ET system as an alternative cover system for landfill since this system is cheap and the permeability of material for this system will not change with time. However, this system depends on the health of the plant and is only applicable for area with a dry climate.

Singapore is located in a tropical climate that is characterized by uniform temperature, high humidity and abundant rainfall throughout the year. The average daily temperature ranges between 24^{o}C to 31^{o}C and the humidity ranges from 80% to 98%. A typical rainfall amount of 100 mm/month is observed in Singapore with the highest monthly rainfall being observed during the rainy period in December and January (Rahardjo et al., 2013a). A typical potential evaporation of 5 to 7 mm/day is observed in Singapore (Rahardjo et al., 2013a). A frequent and heavy rainfall resulted in many slope failures with shallow slides in Singapore (Rahardjo et al., 2007; Rahardjo et al., 2010a; Rahardjo et al., 2012a). Rainfall and evaporation also affect the design of landfill cover. The rainfall intensity is much higher than the potential evaporation rate in Singapore. Therefore, the current landfill cover system which was developed in arid or semi-arid regions may not be applicable to Singapore.

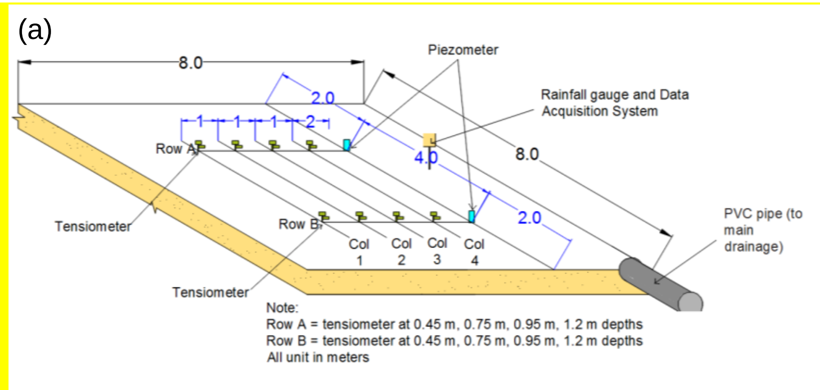
In this study, dual capillary barrier system was used to minimize generation of leachate in Lorong Halus landfill, the largest closed sanitary landfill in Singapore during rainfall. This new system utilized capillary barrier concept that has been proven to work effectively to reduce the rainwater infiltration into soil layers (Harnas et al., 2014) and to maintain the stability of the slope against rainfall-induced slope failure (Rahardjo et al., 2010b; Rahardjo et al., 2012b; 2013b; Rahardjo et al., 2014). Recycled materials (recycled asphalt pavement) were used to reduce the cost of the cover system construction and to maintain environmental sustainability.

2. LANDFILL AT LORONG HALUS

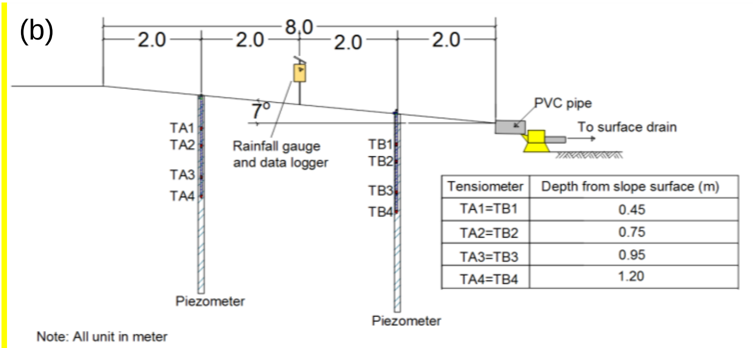
The investigated landfill is located at Lorong Halus in Singapore which covers an area of 44 hectares. Despite its main designation for municipal waste, it has received a wide range of waste materials including construction debris, incineration ash and inert stabilized hazardous wastes. The landfill is bounded by Buangkok East Drive on its western edge, Sungei Serangoon River running along its northern and western perimeter and has an extensive network of landfill gas collection pipes connected to a flare system. It is heavily vegetated with trees and shrubbery with dirt tracks in place to allow for access to each gas collection well/trench point. Lorong Halus landfill was targeted for potential redevelopment into commercial, industrial, or even residential use in the future. Therefore, the development of good cover system becomes necessary to avoid contamination or pollution from leachate to the surrounding environment in the future.

The Lorong Halus landfill is currently covered by residual soil from Old Alluvium, the deposit in which the landfill was located. Old Alluvium is a semi-consolidated deposit consisting mainly of coarse sand and fine pebbles and it is composed of mainly granitic and low grade metamorphic rocks (PWD, 196). The material is very heterogeneous in both vertical and horizontal directions. The soil is a mixture of sand, gravel, silt, and clay. The majority of Old Alluvium is found to be uncemented clay and sand mixtures.

The analyses in this paper focused on the landfill with 64 m^2 area (8 m length and 8 width) and 7^o inclination (Figure 1). Eight (8) tensiometers and 2 piezometers were installed to monitor the pore-water pressure and groundwater table variations, respectively during the dry and rainy periods within the investigated landfill. Four (4) tensiometers (at 0.45 m, 0.75 m, 0.95 and 1.2 m depths) and one (1) piezometer (at 10 m depth) were installed within 2 m from the crest of the investigated landfill (Figure 1). Similar arrangements of tensiometers and piezometer were also provided within 2 m from the toe of the investigated landfill. A rainfall gauge was installed within the proximity of the investigated landfill to observe the variations of rainfall with time. All transducers were linked to the same power supply and data logger to obtain the readings in real-time and were accessible on-line. The variations of groundwater tables and pore-water pressures near the crest and toe of the slope due to climate change during the period of 1 October 2013 until 31 December 2013 are presented in Figures 2, 3 and 4, respectively.



a. Layout of field instrumentation at Lorong Halus



b. Cross section of field instrumentation at Lorong Halus

Figure 1. (a) Layout and (b) cross section of field instrumentation at Lorong Halus

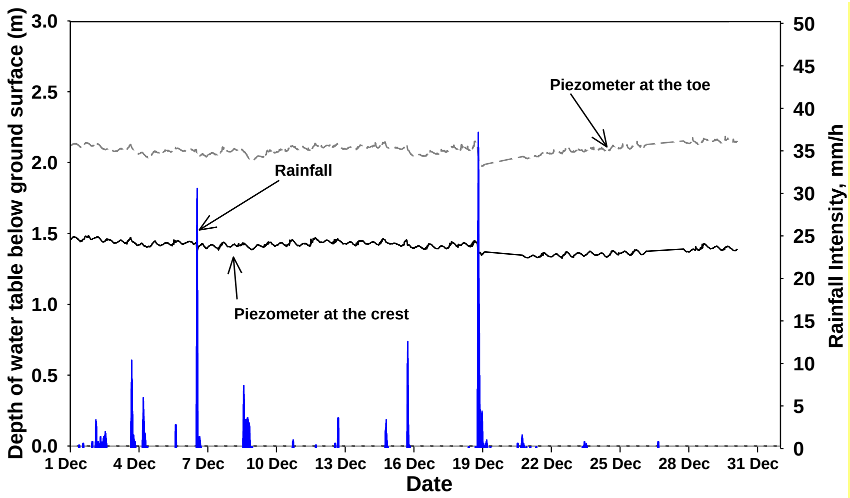


Figure 2. Daily variation of groundwater table

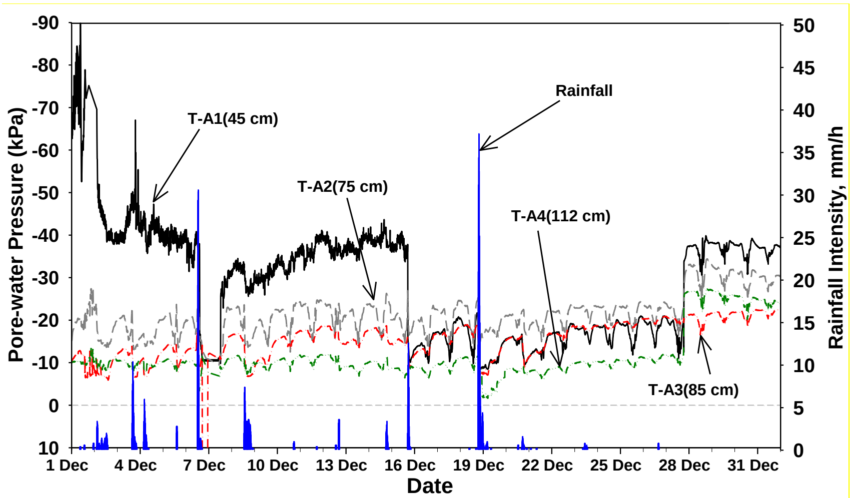


Figure 3. Pore-water pressure measurements with depth at the crest of the slope

During the three (3) months of field monitoring using field instruments at Lorong Halus landfill, the maximum rainfall intensity of 38 mm/h was observed on 18 December 2013 (Figure 2). Figures 3 and 4 showed that pore-water pressures at all depths increased significantly during rainy events on 18 December 2013. This indicated that the residual soil from Old Alluvium was not sufficiently able to reduce the rainwater infiltration into the landfill and to maintain the negative pore-water pressures (the unsaturated condition) at the greater depths.

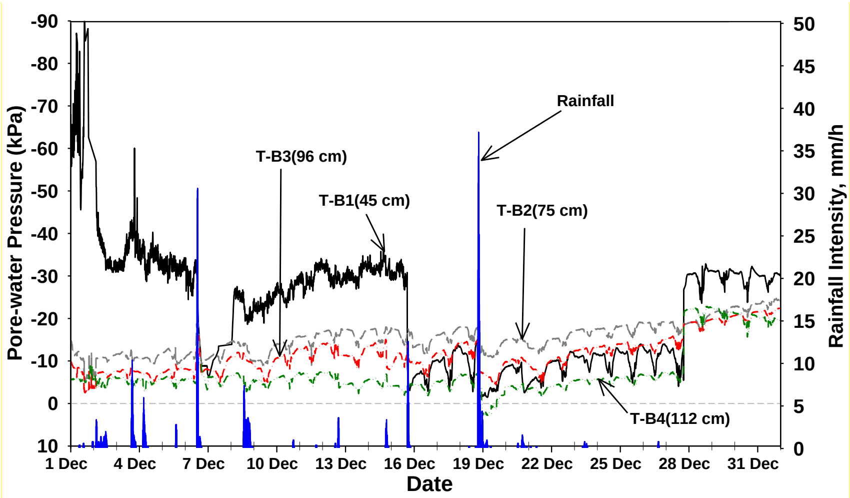
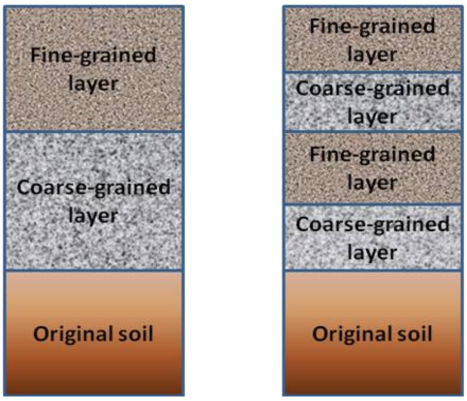


Figure 4. Pore-water pressure measurement with depth at the toe of the slope

3. DUAL CAPILLARY BARRIER

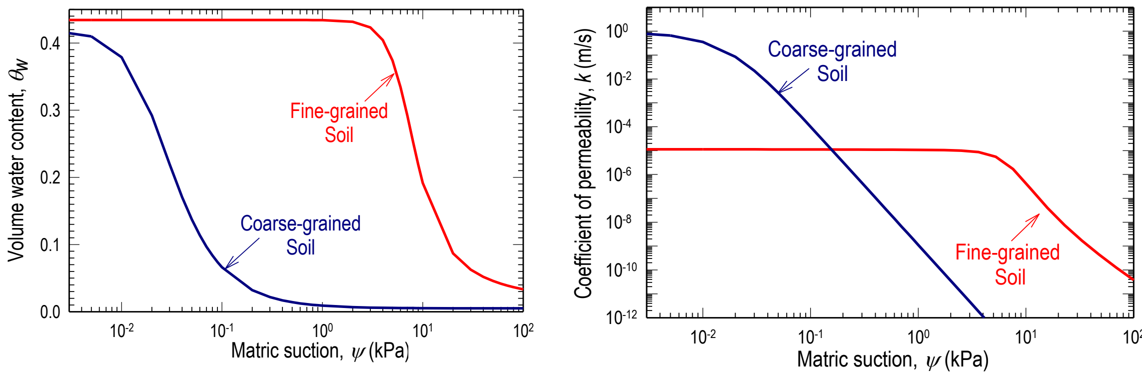
Dual capillary barrier (DCB) comprises two sets of single capillary barrier (SCB) overlying the other (Figure 5). The SCB system is a two layer cover system designed as an unsaturated system using distinctly different hydraulic properties between a fine-grained layer and a coarse-grained layer of soil (Figure 6). The contrast in unsaturated hydraulic properties, which are soil-water characteristic curves and permeability functions, serves to minimize water infiltration into the underlying soil. The infiltrated water is then stored in the fine-grained layer and ultimately removed by evaporation, transpiration and lateral drainage through the slope and percolation into the underlying layer. Previous research works by Rahardjo et al. (2006) showed that there are three controlling parameters that must be considered in selecting the SCB materials, which are: the ratio between the water-entry value of the fine-grained layers and the coarse-grained layers (ψ_w-ratio), the water-entry value of the coarse-grained layer and the saturated coefficient permeability of the fine-grained layer.

Several laboratory tests have been carried out to study the water flow through soil layers in SCB system. The experimental results showed that SCB has high potential application as a slope stabilization measure against rainfall-induced slope failures (Yang et al., 2004; Tami et al., 2004; Krisdani et al., 2006; Indrawan et al., 2006). Harnas et al. (2014) compared the performance of SCB and DCB through laboratory studies and numerical analyses. The results indicated that DCB system has a higher water storage as compared to SCB system with similar total thickness. Therefore, DCB was used as the cover system for the investigated landfill. In this paper, the study focused on the performance of DCB in minimizing rainwater infiltration into landfill. Therefore, the design of gas collection system from waste materials was not included in this paper.



a. b.

Figure 5. Schematic diagram of a. SCB and b. DCB



a. b.

Figure 6. a. Soil-water characteristic curve and b. permeability function of dual capillary barrier materials

4. LABORATORY TESTS

Laboratory tests were carried out to determine saturated and unsaturated properties of the residual soil from Old Alluvium, the fine and coarse recycled asphalt pavement (RAP). The RAP is derived from asphalt pavement wastes which are generated from pavement undergoing reconstruction or resurfacing. The RAP consists of high-quality, well-graded aggregates coated by asphalt cement (BCA-SIA, 2008). In this study, the RAP was obtained from a recycling plant in Singapore whereas the investigated residual soil from Old Alluvium was obtained from Lorong Halus landfill. The fine and coarse RAP were produced by feeding large pieces of asphalt pavement wastes into a jaw crusher which was able to sieve the crushed asphalt wastes into different gradations. The grain size analyses and classification of residual soil and RAP were carried out according to ASTM D6913-04 (2009) and ASTM

D2487-10 (2010), respectively. The grain-size distribution of the investigated residual soil and RAP are presented in Figure 7.

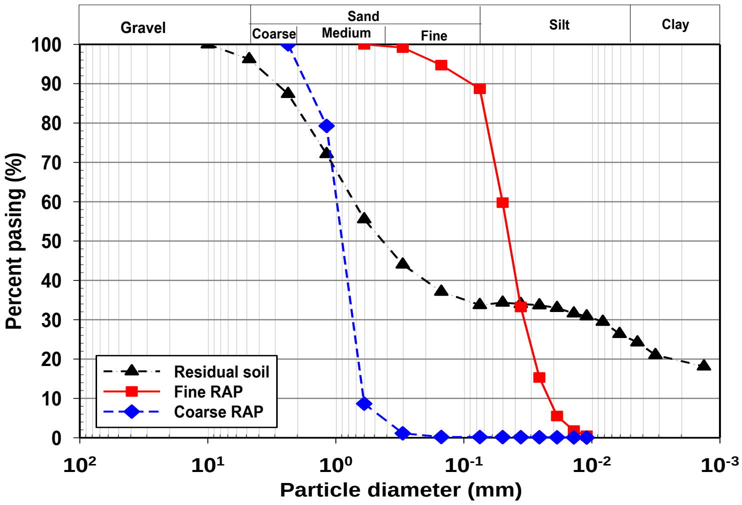


Figure 7. Grain-size distribution of the investigated residual soils and RAP

Relative density tests were conducted to determine the minimum and the maximum dry densities of RAP according to ASTM D4253-00 (2006). The saturated permeability tests of residual soil and RAP were performed using triaxial cell with two back pressure systems (Head, 1986). The index properties of the investigated residual soil and RAP are presented in Table 1. The results of the index properties tests show a bimodal grain-size distribution curve for the residual soil which has a high percentage of coarse particles (65 %). The residual soil is classified as clayey sand (SC) with a low saturated permeability (k_s = 4.8 x 10^{-7} m/s). The grain-size distribution curves of fine RAP and coarse RAP showed similarity with well-graded sand (SW) and poorly-graded gravel (GP), respectively.

The SWCC tests for the residual soil and RAP were conducted using Tempe cell apparatus following the procedure described in ASTM D6838-02 (2008). The details of the SWCC tests for RAP are similar to those explained in Rahardjo et al. (2013c). Various equations have been proposed to represent soil-water characteristic curve (SWCC). In this study, Satyanaga et al. (2013) equation (Equation 1) was used to best fit the drying and wetting SWCCs. Figure 8 shows the SWCCs of the residual soil and RAP. It was observed that the fine RAP on the drying path has a higher water content than that on the wetting path at a given matric suction (hysteresis). This indicates that the SWCC of RAP are similar to that of natural aggregates. The fitting parameters for the SWCC of the investigated residual soil and RAP are presented in Table 2. The residual soil was found to have a high air-entry value (70 kPa) in conjunction with the high percentage of clay content in the soil (25 %). The air-entry value of the fine RAP (0.4 kPa) is higher than that of the coarse RAP (0.02 kPa) indicating a smaller dominant pore size within the fine RAP as compared to that within the coarse RAP.

Table 1 Basic properties of soils

Description	Soils		
	Residual soil	Fine RAP	Coarse RAP
USCS*	SC	SW	GP
Specific gravity, G_s	2.66	2.43	2.41
Gravel content (>4.75mm; %)	3.3	9.3	99.2
Sand (%)	62.2	86.1	0.8
Fines (<0.075mm; %)	34.5	4.6	0.0
Coefficient of uniformity, C_u	123	2.38	1.67
Coefficient of curvature, C_c	0.019	1.17	0.94
Dry density, ρ_d (Mg/m^3)	1.61	1.62	1.53
Void ratio, e	0.45	0.48	0.62
Saturated coefficient of permeability, k_s (m/s)	4.8×10^{-7}	5×10^{-3}	5×10^{-1}

*Unified Soil Classification System (USCS) is described in ASTM D2487 (2000).

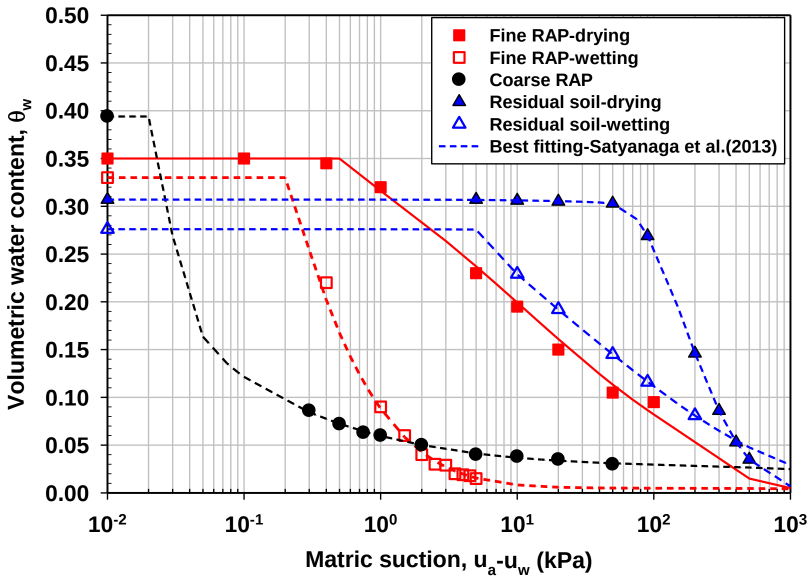


Figure 8. SWCC of soils used in the analyses

$$\theta_w = \left(1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right)\left[\theta_r + \left\{(\theta_s - \theta_r)\left(1 - (\beta)erfc\left(\frac{\ln\left(\frac{\psi_a - \psi}{\psi_a - \psi_m}\right)}{s}\right)\right)\right\}\right] \quad (1)$$

where:

β = 0 when $\psi \le \psi_a$; β = 1 when $\psi > \psi_a$

θ_w = calculated volumetric water content

θ_s = saturated volumetric water content

ψ = matric suction under consideration (kPa)

ψ_a = parameter represents the air-entry value of soil (kPa)

ψ_m = parameter represents the matric suction at the inflection point of SWCC (kPa)

s = parameter represents the geometric standard deviation of SWCC

θ_r = parameter represents the residual volumetric water content

ψ_r = parameter represents the matric suction corresponding to residual volumetric water content (kPa)

erfc = the complimentary error function = $\int_{-\infty}^{X} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) dx$ (2)

Table 2 Parameters for SWCC equation

Parameters	**Residual soil**	**Fine RAP**		**Coarse RAP**
		Drying	**Wetting**	
θ_s	0.307	0.350	0.330	0.394
ψ_a (kPa)	70	0.50	0.20	0.03
ψ_m (kPa)	200	15	0.50	0.04
s	0.92	2.6	1.5	3.7
θ_r	0.00	0.005	0.005	0.029
ψ_r (kPa)	500	500	500	500

The determination of unsaturated coefficient of permeability by experiment is a tedious and time-consuming process. Therefore, a statistical model (an indirect method suggested by Childs and Collis-George, 1950) was used to determine the permeability function from the saturated coefficient of permeability (k_s) and the SWCCs of the residual soil and the RAP. Figure 9 shows the permeability functions of the investigated residual soil and RAP. It was observed that the saturated permeability of the coarse RAP is higher than that of the fine RAP since the particle sizes of the coarse RAP are larger than those of the fine RAP. As a result, the pore sizes of the coarse RAP are larger than those of the fine RAP. The permeability of the coarse RAP is lower than that of the fine RAP at matric suctions beyond 0.1 kPa, indicating that the coarse RAP can be used as a barrier layer in this range of matric suctions.

In other words, breakthrough will occur if matric suction within the coarse RAP decreases to less than 0.1 kPa.

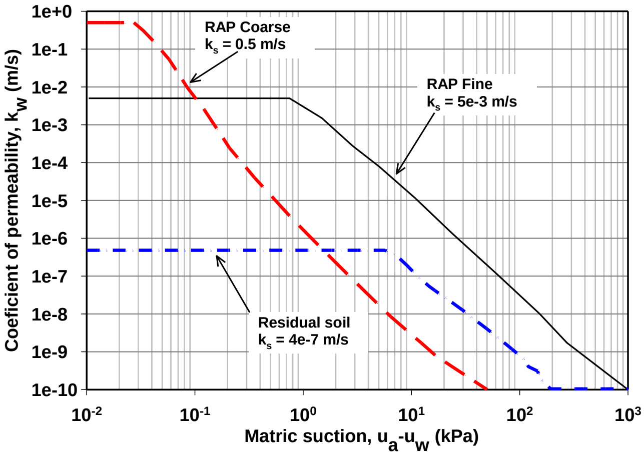


Figure 9. Permeability function of soils used in the analyses

5. FINITE ELEMENT ANALYSES

Two-dimensional seepage analyses were performed using the finite element software Seep/W (GEO-SLOPE International Pte Ltd., 2007). The SWCC and permeability functions of the investigated residual soil and RAP were incorporated in the analyses. The boundary conditions applied to the finite element model are illustrated in Figure 10. The distance between the slope and the side of the slope model was set to three times the height of the slope to avoid the influence of the side boundary conditions. No flow boundaries were simulated by assigning a nodal flux, Q, equal to zero at the bottom and along the sides of the slope model above the groundwater table. The constant total head, h_w, on each side was applied as the boundary along the sides of the numerical model below the groundwater table. The actual rainfall was applied to the slope as a flux boundary, q. Ponding was not allowed to occur at the slope surface. As a result, the seepage model would not allow pore-water pressures greater than 0 kPa to build up at the ground surface when a flux applied to the top boundary was greater than the permeability of the soil. This would simulate the actual field conditions where the excess rainfall at the slope surface was removed as runoff.

Three cases of transient seepage analyses were carried out in this study. In the first case (case 1), the residual soil from Old Alluvium was used as a landfill cover system according to the original condition of the site. A natural rainfall, based on rain gauge readings on 18 December 2013, was applied to the slope surface for the seepage analysis. The total amount of rainfall was 407 mm and the maximum rainfall intensity was 37 mm/h. The rainfall pattern on 18 December 2015 at Lorong Halus landfill is presented in Figure 11. Case 1 was performed in order to evaluate the finite element model by comparing the analysis results with the field data obtained from the instrumentation readings at Lorong Halus landfill. The initial condition for the numerical model in case 1 was generated using a spatial function based on the initial pore-water pressures from tensiometer readings at the beginning of the rainfall at 18.30 h on 18 December 2013 on Lorong Halus landfill.

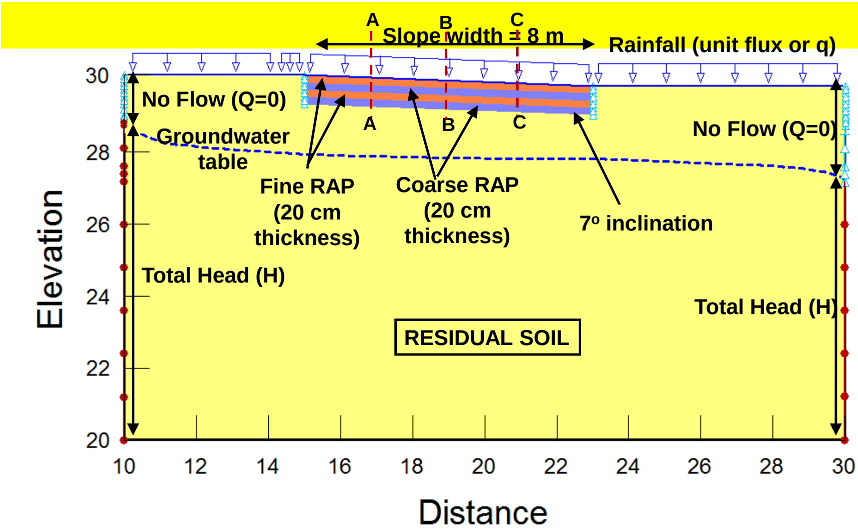


Figure 10. Slope model for seepage analyses

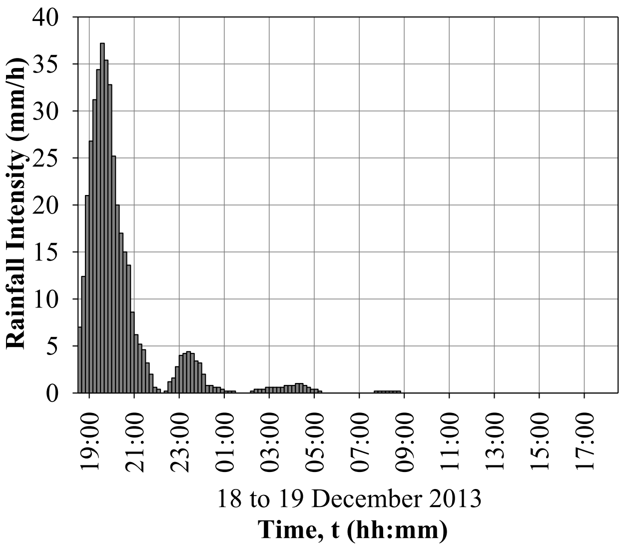


Figure 11. Rainfall event on 18 December 2013 for seepage analysis

In the second and third cases (cases 2 and 3), a dual capillary barrier (DCB) system was modelled as the cover system for the landfill. The natural rainfall in case 1 was also applied to the slope surface for the seepage analysis in case 2. The maximum rainfall intensity of 18 mm/h was applied to the slope surface for 10 hours period for the seepage analysis in case 3. Cases 2 and 3 were analysed in order to assess the performance of DCB under the natural rainfall and maximum rainfall conditions, respectively. The initial condition for numerical model in case 2 was generated using a spatial function based on the initial pore-water pressures in case 1. The initial condition for numerical model in case 3 was taken based on the groundwater table position in the field. The finite element mesh within the DCB and residual soil layer down to 5 m below the slope surface had element sizes of approximately 0.25 m, smaller than elements in other parts of the slope, in order to obtain accurate results within the infiltration zone.

Figures 12 and 13 present pore-water pressure distributions at sections A and C (Figure 10), respectively during 6 h of rainfall on 18 December 2013 as obtained from the seepage analysis in case 1. Section A was located at 2 m from the crest of the slope whereas section C was located at 2 m from the toe of the slope. The pore-water pressures, obtained from both the numerical analyses and field measurements, appeared to increase rapidly during rainfall (Figure 11). However, the increase in pore-water pressures only occurred within 1 m depth during the rainfall event. This condition could be attributed to the low permeability of the soil that resulted in the slow infiltration process of rainwater into greater depths. In general, the pore-water pressure profiles from the numerical analyses show a reasonably good agreement with those obtained from the field measurements at the crest and the toe of the slope. This indicated that numerical model, boundary conditions and soil properties in the finite element analysis in case 1 was correct and can be used for cases 2 and 3.

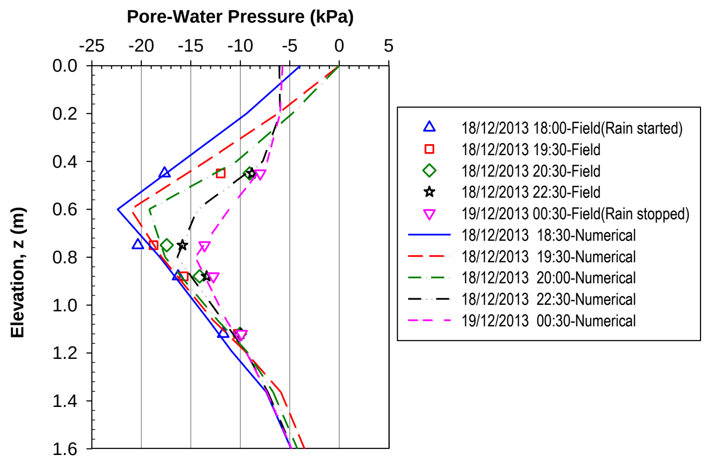


Figure 12. Pore-water pressure profile at section A (crest) of landfill without cover system during rainfall events: 18-19 December 2013

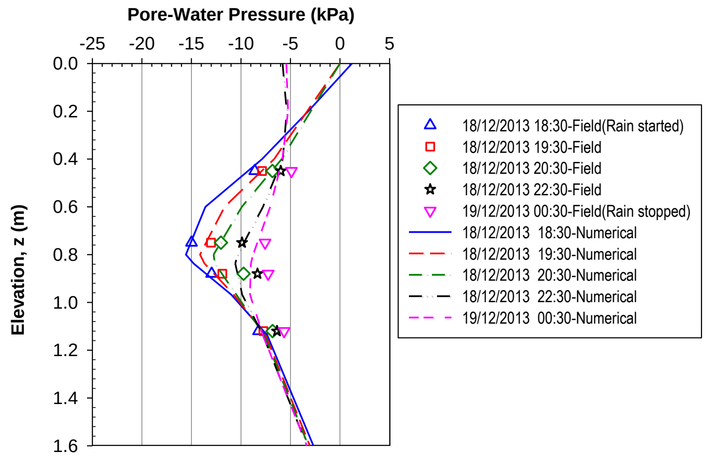


Figure 13. Pore-water pressure profile at section C (toe) of landfill without cover system during rainfall events: 18-19 December 2013

Figure 14 presents the pore-water pressure profiles obtained from the seepage analyses in case 2. The pore-water pressures at the crest, middle and the toe of the slope increased significantly after the rain started. The pore-water pressure at the depth of 0.4 m on the crest of the slope increased from -10 kPa to +2 kPa after 10 h of rainfall. The increment of pore-water pressures in case 2 was higher than that in case 1 since the applied rainfall intensity in case 2 was much higher than that in case 1. Figure 14 also shows that the groundwater table increased after 10 h of rainfall.

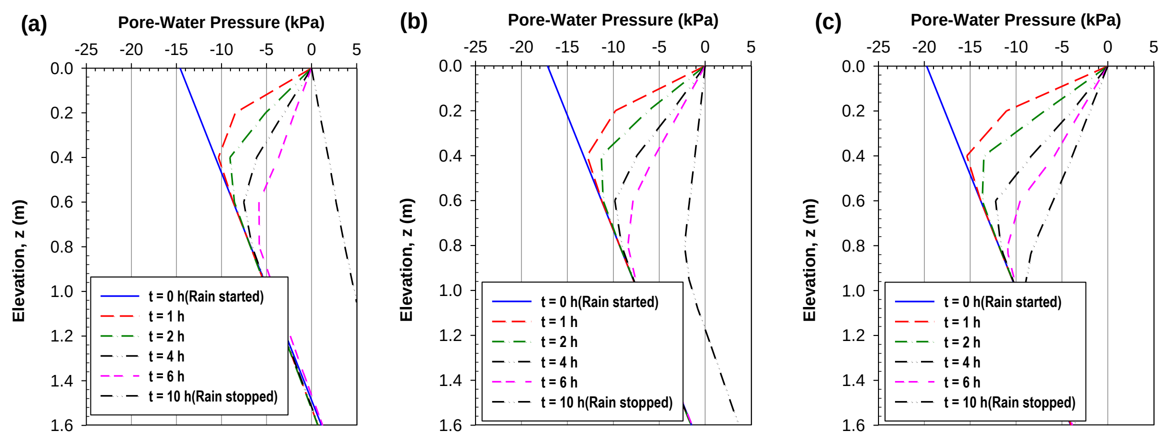


Figure 14. Pore-water pressure profiles at the (a) crest (section A), (b) middle (section B) and (c) toe (Section C) of landfill without cover system during rainfall events 18 mm/h for 10 hours

Figure 15 presents the pore-water pressure profiles obtained from the seepage analyses in case 3. The increment of pore-water pressures only occurred within 0.6 m depth from the slope surface at the crest, middle and the toe of the slope. The pore-water pressures within the second coarse-grained layer of the DCB system and at the greater depths remained negative in all sections after the rain started. Figure 15 also shows that the groundwater table did not change after 10 h of rainfall. This indicated that the infiltrated rainwater was not able to percolate down into the soil layer below the DCB system and only drained laterally within the DCB system. No breakthrough was observed into the second coarse-grained layer of the DCB system, indicating that the thickness length of the DCB layers is sufficient to provide barrier for preventing rainwater infiltration into the landfill. As a result, the leachate of waste materials from landfill into surrounding area can be avoided.

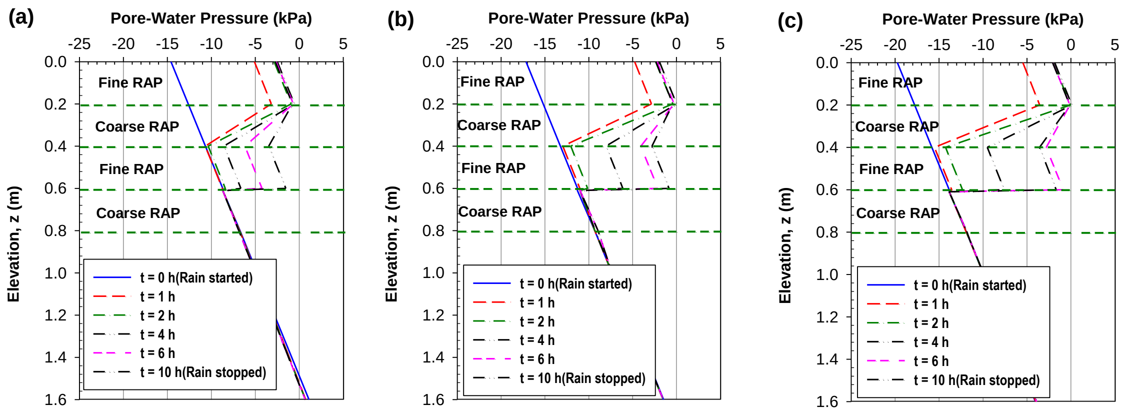


Figure 15. Pore-water pressure profiles at the (a) crest (section A), (b) middle (section B) and (c) toe (Section C) of landfill with DCB during rainfall events 18 mm/h for 10 hours

6. CONCLUSIONS

Unsaturated soil mechanics principles are required in order to design a proper landfill cover system. The capillary barrier effect in DCB exists due to the contrast in the coefficients of unsaturated permeability between the fine- and coarse-grained soil layers. Under unsaturated conditions, the coefficient of permeability of the coarse-grained layer is lower than that of the fine-grained layer. The contrast in the hydraulic properties of the fine- and coarse-grained layers is reflected by the difference in their water-entry values. In this study, a dual capillary barrier has been shown to be effective in providing barrier for preventing rainwater infiltration into the landfill and therefore, avoiding leachate of waste materials into the surrounding area. Recycled asphalt pavements were found to be a suitable alternative to natural aggregates in a dual capillary barrier system.

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