Water Infiltration into a New Three-Layer Landfill Cover System

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Abstract: One of the main purposes of a landfill cover system is to minimize the migration of water into waste, known as percolation, and thereby reduce excessive leachate production. One possible way to achieve this goal is to use a two-layer cover with capillary barrier effects (CCBEs) for arid and semi-arid regions. For a humid climate or prolonged rainfall, the two-layer system with CCBEs is expected to lose its effectiveness for minimizing water percolation. A new three-layer landfill cover system is proposed and investigated for humid climates. This new system adds a fine-grained soil (i.e., clay) underneath a two-layer barrier with CCBE (i.e., a silt layer overlying a gravelly sand layer). The study is conducted by carrying out a one-dimensional (1D) water infiltration test in a soil column. The soil column was instrumented with tensiometers, heat dissipation matric potential sensors, and moisture probes to monitor the variations of pore-water pressure and water content with depth. The amount of water volume infiltrated into the soil during ponding was also monitored. In addition, transient seepage simulations were carried out to back-analyze the soil column test and to investigate the influence of saturated permeability of clay on the effectiveness of the three-layer system. Based on the 1D experiment and numerical analysis, no percolation was observed after 48 h of constant water ponding, which is equivalent to a rainfall return period of greater than 1,000 years. This is consistent with the results from the numerical back analysis. However, the upper two-layer capillary barrier is only effective for a rainfall return period of approximately 35 years. This indicates that the proposed bottom clay layer is necessary for a humid climate. Numerical parametric simulations reveal that with an increase of saturated clay permeability by three orders of magnitude (i.e., from 5.7×10^{-9} m/s to 5.7×10^{-6} m/s), the amount of percolation is approximately 0.1 mm after 12 h of constant water ponding, which is equivalent to a rainfall return period of greater than 1,000 years. **DOI: 10.1061/(ASCE)EE.1943-7870.0001074.**

Author keywords: Landfill cover system; Soil column; Water infiltration.

Introduction

With increasing population and a high urbanization rate, the production of municipal solid waste (MSW) also increases and is a global concern. Landfilling is the simplest, cheapest, and most cost-effective method of disposing such MSW. In most developing nations, almost all of the MSW goes to landfill. However, even in developed countries, MSW is also landfilled. For instance, in the European Union, more than half of the member states still dispose more than 50% of their waste to landfill (EEA 2013). In the United States, 50% of the total waste generated is also disposed in landfills (USEPA 2015). The closure standards for MSW landfills require the owner/operators to install a final cover system to minimize the downward migration of water into the waste, known as percolation, so as to prevent substantial leachate generation and groundwater contamination. To satisfy this standard, most modern landfill cover systems use geotextile composites and geomembranes because of their low permeability. Albright et al. (2013) presented field data from seven large-scale test sections, simulating landfill covers with composite hydraulic barriers (a geomembrane over a soil barrier or geosynthetic clay liner), which have climates ranging from cool and humid to warm and arid. The annual percolation through the cover at the wettest site (Cedar Rapids, Iowa; average precipitation = 915 mm/year) ranged between 0.1 and 6.2 mm/year. The recommended equivalent percolation rate for covers with composite barriers is 3 mm/year for humid climates. However, geomembranes are highly susceptible to interface stability and defects/holes, which can compromise their reliability (Daniel 1994; Koerner and Daniel 1997; Amaya et al. 2006).

It is also common to rely on naturally occurring low-permeability materials such as clays. Typically, regulations (USEPA 1993) require a prescribed cover with a saturated permeability of less than 10^{-9} m/s, which is a limit of 30 mm/year of percolation, if the barrier is continuously wetted with a hydraulic gradient of 1.0. However, unprotected clay barriers are prone to desiccation induced cracking, which can compromise their integrity (Melchior 1997; Albright et al. 2006).

Melchior (1997) reported that clay barriers in a cool and wet climate leaked 8 to 9% of precipitation; he noted that at the end of an 8-year experiment, leakage rates were increasing. Albright et al. (2006) evaluated the performance of compacted clay barrier covers at three sites over the course of 2 to 4 years. The climate at the sites was arid in California, humid in Iowa, and subtropical in Georgia. The as-built permeability of the clay barrier layers varied between 1.6×10^{-10} and 4.0×10^{-10} m/s. During the test period,

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permeability of the barriers increased up to 800 times the as-built value. They concluded that large increases in the permeability of clay barriers with time are not uncommon as a result of desiccation cracks. Therefore, some alternative covers are considered and used.

Alternative covers are defined as any cover used in place of prescribed covers (USEPA 1993). Current regulation requires that alternative covers be equivalent to prescribed covers in terms of their effectiveness in minimizing water percolation. For instance, Benson et al. (2001) proposed the equivalency criterion of 30 mm/year, which is currently used for the assessment of an alternative cover. Most alternative covers rely on water-storage principles (i.e., controlling percolation by water storage during periods of high precipitation and evapotranspiration during periods of low precipitation) and are often referred to as evapotranspirative (ET) covers. They are found to be suitable for arid, semi-arid (Hauser et al. 2001; Zornberg and McCartney 2005; Albright et al. 2004; Bohnhoff et al. 2009), and sub-humid climates (Barnswell and Dwyer 2011; Mijares and Khire 2012a, b). A cover with a capillary barrier effect (CCBE), a layer of fine-grained soil (silt, clay) over a coarse geomaterial (sand, gravel, nonwoven geotextile), is sometimes added to increase the water-storage capacity of the cover (Ross 1990; Khire et al. 2000; Iryo and Rowe 2005; Bouazza et al. 2006; McCartney and Zornberg 2010; Siemens and Bathurst 2010; Zornberg et al. 2010; Rahardjo et al. 2012). Several water-infiltration column tests have been conducted to study the behavior of CCBE under controlled laboratory conditions (McCartney et al. 2005; Yang et al. 2006; Bathurst et al. 2007; McCartney and Zornberg 2010; Rahardjo et al. 2012). These experimental studies have clearly shown the development of a capillary break, which minimizes the amount of water that can flow through the interface from the fine-grained soil into the coarse geomaterial, until the overlying soil is nearly saturated. Field studies have also shown that employing capillary barriers can be effective for arid and semi-arid regions in minimizing percolation into underlying waste or contaminated soil (Benson and Khire 1995; Khire et al. 1999, 2000; Zornberg and McCartney 2003). Although more attention has been paid to CCBEs as an alternative cover system in semi-arid and arid regions, the performance of CCBE under humid climates has so far been unsatisfactory (Morris and Stormont 1999; Khire et al. 2000; Albright et al. 2004; Rahardjo et al. 2006). These experimental studies report that there is a significant increase in the moisture contents in the CCBE during periods of high precipitation and low ET, which leads to water breakthrough of the barrier and subsequent production of a large amount of leachate.

In humid climates such as Norway, Singapore, Cardiff city in the United Kingdom, and some states in the United States (namely Hawaii, Louisiana, Alabama, and Florida), where annual rainfall of over 1,200 mm is not uncommon (World Bank 2014), water breakthrough is expected to occur for the traditional two-layer CCBE cover. To address this issue, based on the theory of unsaturated soil mechanics (Ng and Menzies 2007), a new three-layer landfill cover system is proposed and explored to improve a capillary barrier for humid climatic conditions. This new system consists of a fine-grained soil, such as a clay layer, which is added underneath a CCBE. It was intended and anticipated that the bottom clay layer would be protected by the upper two soil layers from desiccation during dry seasons. The feasibility and effectiveness of the proposed three-layer cover system were investigated by theoretical examination and by conducting a one-dimensional (1D) water infiltration test. The experiment was back-analyzed and the computed results were compared with the measured data. Moreover, a numerical parametric study was carried out to investigate the effectiveness of the proposed three-layer system if desiccation cracks formed in the clay layer underneath the CCBE.

Theoretical Considerations of Newly Proposed Landfill Cover

Schematic diagrams of a two-layer CCBE and the proposed landfill cover are compared in Fig. 1. As shown in Fig. 1(a), CCBE contains two soil layers: a fine-grained soil layer overlying a coarse-grained soil layer. It relies on the capillary barrier effect between these two soil layers to prevent water infiltration. The mechanism of this is further explored in the next section. Comparatively, the newly proposed landfill soil cover is a three-layer cover system, which consists of a compacted clay layer, a coarse-grained layer, and a fine-grained layer, compacted successively from the bottom to the top of the system, as shown in Fig. 1(b). According to the water permeability functions illustrated in Fig. 2, by introducing a compacted clay layer beneath a CCBE, infiltrated water through the upper two layers can be intercepted and reduced by the bottom clay layer, which has a lower water permeability at a high degree of saturation (i.e., low suction) in a humid climate. In contrast, the bottom clay layer can be protected by the upper two soil layers from desiccation during dry seasons, because the upper two soil layers have low water permeability at high suctions (i.e., low relative humidity). However, the clay layer of the proposed design may not be completely immune from any desiccation because of vapor flow, which is favored by the overlaying dry coarse layer and root intrusion.

In accordance to regulatory requirements (USEPA 1993) for a traditional three-layer compacted clay cover, the functionalities of

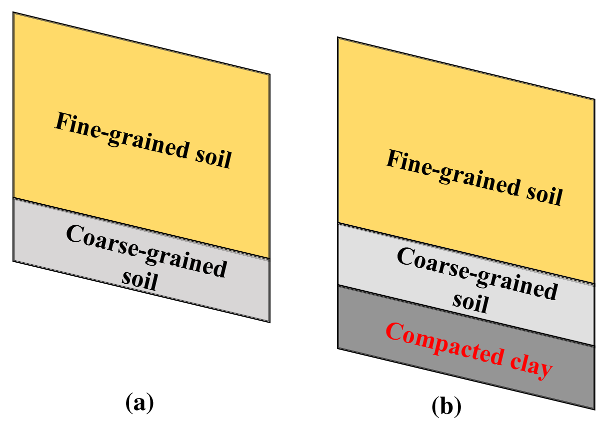

Fig. 1. Conceptual diagrams of landfill covers: (a) conventional capillary barrier landfill cover; (b) newly proposed landfill cover

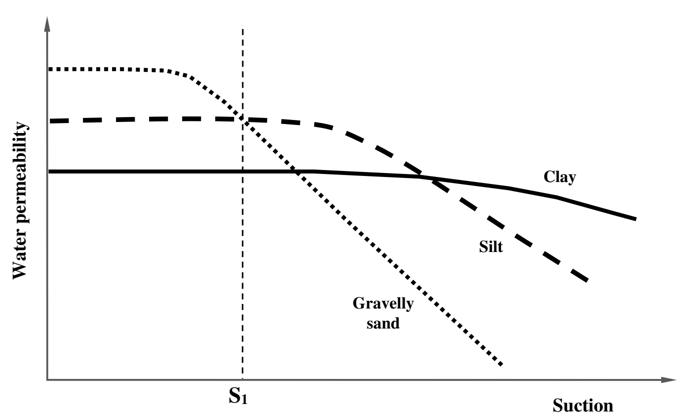

Fig. 2. Schematic diagram showing water permeability functions of silt, gravelly sand, and clay

the upper two layers of this proposed landfill cover are fundamentally different. As mentioned previously, the proposed upper two layers function as a CCBE, whereas the upper and lower layer of a traditional compacted clay system act as a vegetation support layer and a drainage layer, respectively, which may enhance the desiccation through vegetation roots and water drainage. The upper layer of a traditional three-layer compacted clay cover is not necessarily designed as a CCBE. On the contrary, the bottom clay layer of the newly proposed landfill cover system is protected by the upper two layers to minimize desiccation. A comparison between these two types of cover is given in Table 1. Furthermore, this new three-layer landfill cover system has recently been granted a U.S. Patent [C. W. W. Ng et al., "All-weather landfill soil cover system for preventing water infiltration and landfill gas emission," U.S. Patent No. 9, 101, 968 B2 (2015)].

Principle of Reducing Water Infiltration and Percolation

Percolation is the process in which water migrates through a whole soil profile, such as a landfill cover. Percolation is closely related to but not equivalent with infiltration, which relates to the breakthrough of water into the soil through pores and/or cracks in the surface. Fig. 2 shows a schematic diagram illustrating the relationship between water permeability and matric suction of each soil layer. Matric suction is defined as the difference between pore gas pressure and pore-water pressure in a soil. When a soil becomes drier and water content decreases, the suction and water permeability increases and decreases, respectively (Ng and Menzies 2007).

1. When soil suction in the three-layer landfill cover is larger than point S_1 (Fig. 2), i.e., at semi-arid or arid climates, cover soils are relatively dry. Water permeability of the silt layer is much higher than that of the gravelly sand layer. Infiltrated water stores in the silt layer and flows away in this layer, but no water infiltrates into the gravelly sand layer. In other words, the two-layer CCBE works.
2. When soil suction in the landfill soil cover is less than point S_1 (Fig. 2) under heavy or prolonged rainfalls, i.e., at humid climates, cover soils are nearly saturated or saturated. Water permeability of the gravelly sand layer is the highest, whereas that of the clay layer is the lowest. The capillary barrier effect formed by the upper silt layer and underlying gravelly sand layer will lose its function and water infiltrates into the gravelly sand layer, because the water permeability of the gravelly sand layer is higher than that of the silt layer. At this point, the infiltrated water is prevented by the clay layer because of its lowest water permeability, and may be drained away through the gravelly sand layer because of its relatively high saturated permeability. In this way, the head of water on the underlying clay layer is reduced, so the amount of water percolation will be minimized.

The addition of the compacted clay layer underlying the CCBE makes the proposed landfill cover applicable to any weather conditions. The focus of this study is to gain a fundamental understanding of the proposed landfill cover system in terms of water infiltration when water breakthrough occurs on the CCBE.

Experimental Apparatus and Instrumentation

1D Soil Column

To evaluate the performance of the proposed three-layer landfill cover for reducing water infiltration, a soil column including a transparent acrylic cylinder and a constant-head water supply apparatus was developed in this study. A schematic diagram of the soil column is shown in Fig. 3. The height of the cylinder, which contains two parts (upper part 700 mm high and lower part 600 mm high), is 1,300 mm. The inner diameter of the cylinder is 140 mm with a 6-mm wall thickness. The height to diameter ratio of this soil column is designed to be greater than 6. This is to ensure one-dimensional flow conditions when studying the infiltration problems as reported by many researchers (Choo and Yanful 2000; Ng and Leung 2012a).

The soil column is designed to control and measure the top and the bottom boundary flow conditions. At the top boundary upon ponding, constant head infiltration could be achieved by using an electronic weighing scale and a constant-head supply system consisting of a water storage tank, which served as a Mariotte's bottle (McCarthy 1934). A copper tube, 2 mm in diameter, was sealed and

Table 1. Comparison between the Traditional and Proposed Three-Layer Landfill Cover for Preventing Water Infiltration

Layer	Working principle for preventing water infiltration: Traditional three-layer compacted clay cover	Working principle for preventing water infiltration: Proposed three-layer landfill cover
Upper layer	Vegetation support layer is used to retain water for growth of vegetation; the purposes of vegetation are to decrease runoff, increase evapotranspiration, and minimize erosion	Capillary barrier is a fine-grained soil layer overlying a coarse-grained soil layer to minimize the downward movement of water through a capillary barrier effect; the principle is based on the contrast of unsaturated hydraulic properties (soil water retention curves and permeability functions) of each layer as illustrated in Fig. 2; infiltrated water is stored in the upper layer and ultimately removed by evaporation, evapotranspiration, and/or lateral drainage at arid and semi-arid regions The presence of this two-layer capillary layer also protects the bottom clay from shrinkage cracks under arid and semi-arid climates
Intermediate layer	Drainage layer. To prevent ponding of water on the lower layer. Drains by gravity to toe drains	
Lower layer	Clay and/or geomembrane prevents infiltration of water into the waste by using low permeability materials Because the clay layer is not protected by the upper capillary barrier, shrinkage cracks will occur under arid and semi-arid climates; this indicates that for heavy rainfall, the bottom will not be effective to prevent infiltration; a FML is needed to prevent infiltration Geomembranes are highly susceptible to interface instability and defects/holes	Clay layer prevents infiltration of water into the MSW in an event that the upper capillary barrier of the three-layer system fails in humid regions such as Norway, Hong Kong, and Cardiff city in the United Kingdom, where the annual rainfall is over 1,200 mm; clay has an inherently low saturated permeability No geomembrane is likely needed even under humid climates

inserted into the water storage tank. The tail of the copper tube was submerged in water, and the tube head was connected to the atmosphere. The elevation of the tube tail was deliberately adjusted to the same level as that of any ponding head on the surface of the soil column. Because the connection between the copper tube and the storage tank was tightly sealed, the total head at the base of the copper tube was identical to that of the desired ponding head in the soil column and top of the copper tube. Any drop of the ponding head would cause water to flow from the storage tank to the soil column until the total head at the base of the copper tube is the same again with the desired ponding head at the soil column. The water storage tank was placed on the electronic weighing scale. As a result, the infiltrated water volume could be measured by continuously recording changes in water weight in the storage tank. The top of the soil column was covered during the test to prevent evaporation. A valve was installed at the base of soil column to control the drainage condition. Under drained conditions, any percolation during test was collected through an outlet at the base of soil column and periodically weighed.

Instrumentation

The instrumentation consisted of small-tip tensiometers (TMs), heat dissipation matric water potential sensors (HDs), and thetaprobe soil moisture probes (TPs). TMs fitted with pressure transducers were used to measure the soil suctions within the range of 0–90 kPa, whereas HDs were used to measure the higher range of suctions (60–2,500 kPa). Because of the lack of sensitivity of HDs below the air entry value of the porous ceramic, small-tip TMs were installed to measure the soil suctions within the range of 0–90 kPa. TPs were used to measure the volumetric water content (VWC). Each pair of TMs/HDs and TPs was installed at the same elevation of the soil column (Fig. 3). This arrangement aimed to verify the measurements between them. Measurements were made at 75, 225, 375, 525, 675, 825, and 975 mm above the base of the soil column.

Before installation, all transducers were calibrated. To ensure good soil–ceramic contact, a hole with a diameter slightly smaller than that of the ceramic tip of TMs and HDs was predrilled at designated locations of the soil column. TMs, HDs, and TPs were then

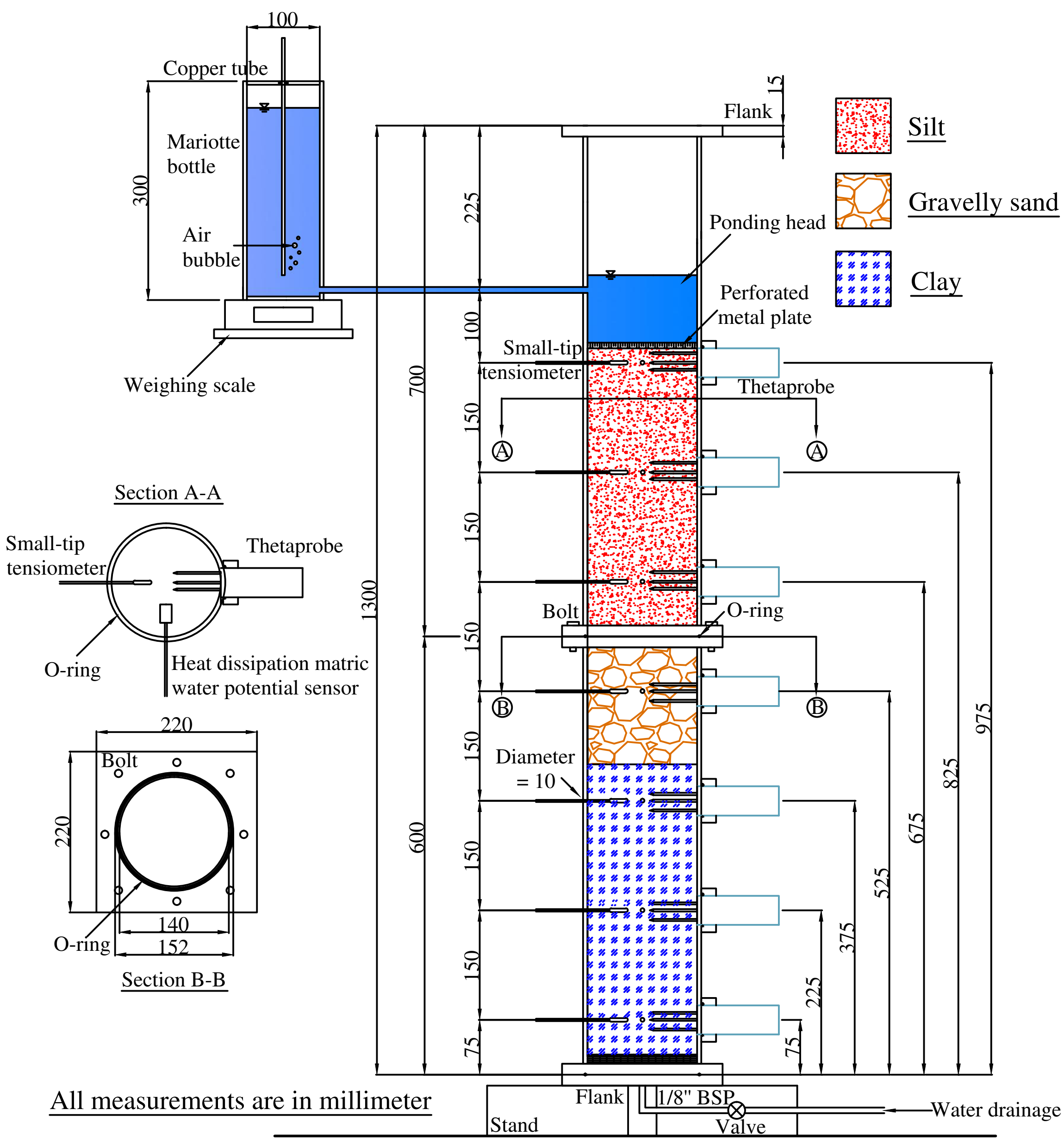

Fig. 3. Schematic diagram of the soil column testing system

installed into the soil column through the predrilled holes. A steel connector was used to fasten them on the wall of the soil column. Rubber O-rings and thread tapes were used on the connector to form a seal in the connection area to prevent leakage. Although it is well known that transducers placed within a soil column may affect the water flow, several column studies with comparable diameter and instrumentation have shown that the error from this effect is not significant as compared with the anticipated experimental outcome (Indrawan et al. 2007; Ng and Leung 2012b; Harnas et al. 2014; Likos 2014).

The data acquisition system used in the study consisted of data loggers, an external power supply, and a personal computer. The TMs and TPs were connected to the Delta-T Dl2e data logger (Cambridge, U.K.), whereas the HDs were connected to the Campbell Scientific CR1000 data logger (Logan, Utah). A program was written to set up communication and data collection between the data loggers and instruments. The data from data logger units were transferred to the personal computer periodically through serial ports. The sampling frequency of the instruments varied from stage to stage and is subsequently described in the test procedure.

Testing Material and Specimen Preparation

Testing Material

Three soils, namely silt, gravelly sand and clay, were used in the study. The whitish silt was silt obtained by a mixture of kaolin clay (12%), quartz powder (75%), and quartz sand (13%). The light-gray gravelly sand, crushed from granite, was obtained commercially. It was essentially a mixture of quartz sand (50%) and gravel (50%). The clay was commercially bought kaolin clay. According to the findings of Benson et al. (1999), the geotechnical properties of the selected clay cover material fall within the typical range of fine-grained soils used as landfill barriers. Additionally, preliminary tests showed that the silt had contrasting hydraulic properties with the gravelly sand; the trial tests revealed that the capillary barrier effect of these two soils was apparent.

The basic properties of the soils are summarized in Table 2. Fig. 4 shows the particle-size analyses, which were obtained from a sieve analysis described in ASTM D422 (ASTM 2007). Specific gravity tests were performed in accordance with the ASTM D854 standard test method (ASTM 2010a). Atterberg limit tests were performed using the standard test method ASTM D4318 (ASTM 2010b). Based on their basic properties, the soils were classified

Table 2. Basic Properties of the Soils Used in the Study

Property	Silt	Gravelly sand	Clay
Unified soil classification system	ML	SP	CH
Specific gravity, G_s	2.61	2.62	2.52
Atterberg limits			
Liquid limit, LL	22	—	59
Plastic limit, PL	16	—	32
Plasticity index, PI	6	—	27
Standard compaction curve			
Maximum dry density, ρ_d (kg/m^3)	1,771	1,494	1,264
Optimum moisture content (%)	13.56	—	36.18
Void ratio, e	0.49	0.58	1.06
Saturated water permeability, k_s (m/s)	1.4×10^{-6}	9.7×10^{-3}	5.7×10^{-9}
Water content at saturation, w (%)	18.78	24.78	42.06

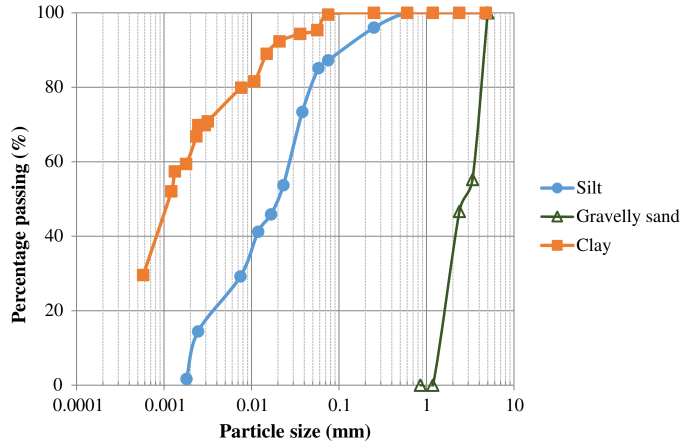

Fig. 4. Particle-size distributions of the silt, gravelly sand, and clay

according to the Unified Soil Classification System (USCS) using the ASTM D2487 standard test method (ASTM 2011). Compaction curves for the silt and clay were determined in accordance with ASTM D698 (ASTM 2012). The saturated permeability (k_s) of the silt and clay was investigated using the flexible wall permeameter, as described in ASTM D5084 (ASTM 2010c), whereas the constant-head method as described in ASTM D2434 (ASTM 2006) was used for the gravelly sand. The dry densities of the soils were controlled to produce consistent soil properties for the saturated permeability tests, soil water characteristic curve (SWCC) tests, and water infiltration test.

The SWCC, which is also known as the water retention curve, describes the relationship between volumetric water content and matric suction of the soil. The drying and wetting SWCCs of the soils were obtained using modified pressure plate apparatus (Ng and Pang 2000) by starting the tests from saturated conditions. Fig. 5 shows the measured and fitted SWCCs of the silt, gravelly sand, and clay. Details of the fitted SWCCs are provided later. As expected, the measurements showed that a considerable hysteresis exists between the drying SWCC and wetting SWCC for silt and clay. However, only a small hysteresis loop is observed for the gravelly sand. This may be because the particle-size distribution (Fig. 4) of gravelly sand is uniform. The *ink-bottle effect* (Hillel et al. 1982), which is one of the key reasons for hydraulic

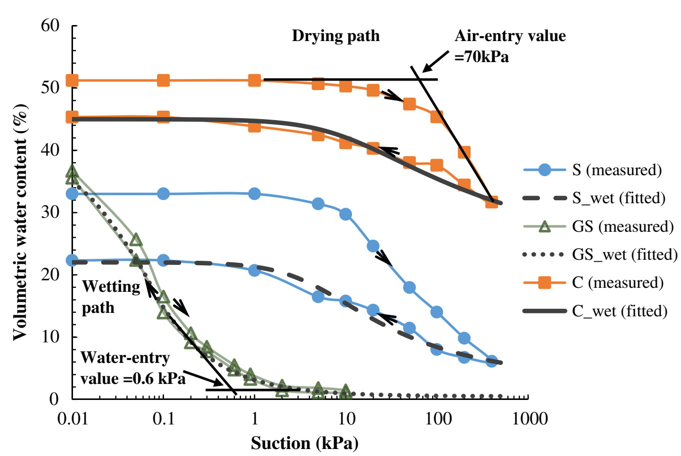

Fig. 5. Measured and fitted SWCCs of silt (S), gravelly sand (GS), and clay (C)

hysteresis, is therefore not significant. Yang et al. (2004) reported a similar result that a uniform, coarse-grained soil had a small total hysteresis. The air-entry value of the compacted clay can be estimated along its drying SWCC to be approximately 70 kPa. The water-entry value of the gravelly soil is 0.6 kPa. This value falls within the typical range (0.3–1 kPa) found by other researchers (Stormont and Anderson 1999; Yang et al. 2004; Abdolahzadeh et al. 2011), and was used as the coarse-grained layer for CCBE.

Specimen Preparation

The three soil layers, namely the clay, gravelly sand and silt layers, were compacted successively from the bottom to the top of the cover system. The thickness of each soil was 0.4, 0.2, and 0.4 m for the clay, gravelly sand and silt layers, respectively. The soils were initially mixed with water to reach the optimum moisture content as given in Table 2. A layer of vacuum grease was applied at the inner surface of the soil column to minimize any occurrence of preferential path of water. The soils were then compacted to their targeted degree of compaction (DOC) or relative density (RD), which is 95 DOC, 95 RD, and 90 DOC for the clay, gravelly sand, and silt layers, respectively. Each soil layer was compacted in 15 lifts, and the required number of hammer drops for each lift was found by carrying out trial compaction tests for each soil. Variation of actual and targeted soil density was found to be within ±3%. The top surface of each lift was scarified before the compaction of the successive lift for better contact.

Testing Procedure

After the sample preparation, a compacted soil column was subjected to an infiltration test under constant head ponding. The testing procedure involved two stages: (1) instrumentation equalization, and (2) ponding, as summarized in the following paragraphs.

An overview of the water infiltration test is shown in Fig. 6. TMs, TPs, and HDs were installed according to the procedures described previously. The sensor readings were then allowed to equalize with the soil for 24 h. Because the soils were initially mixed with water to reach each respective optimum moisture content, initial suctions were expected to be different between each soil layer in accordance to its SWCC (Fig. 5). The average initial suctions for silt, gravelly sand, and clay were found to be 55, 20, and 90 kPa, respectively. After the instrumentation equalization stage, a ponding process was carried out. Approximately 0.1 m of constant head ponding was applied and controlled on the soil column surface by using the constant-head water supply system. The top of the soil column was covered with aluminum foil during the test to prevent evaporation. The bottom valve was opened to allow any percolation to drain out. The free drainage bottom boundary ensured that it was open to the atmosphere, to minimize the possibility of local compression of entrapped air within the soil column. Furthermore, compression of air within the soils during water infiltration may not be significant, as the soil was unsaturated at the initiation of the test. After ponding, any changes in the water level in the constant-head water supply system (i.e., volume of water infiltrated into the soil) and variations of pore-water pressure, volumetric water content, and water outflow rate were recorded every 5 min during the first 24 h and every 15 min thereafter. As a result, the infiltration rate (I) at any time interval dt during ponding could be determined as follows:

$$I(t) = \frac{1}{A}\frac{dV}{dt} \tag{1}$$

where dV = change in volume of water infiltrated within a given dt; and A = ponded surface area inside the inner ring diameter of soil column (i.e., 0.015 m^2).

At the end of the infiltration test, seven soil samples were taken along the height of the soil column to determine the dry density and volumetric water content. These measurements were used to verify any change in soil dry density after the test, and to evaluate the performance of the seven TPs.

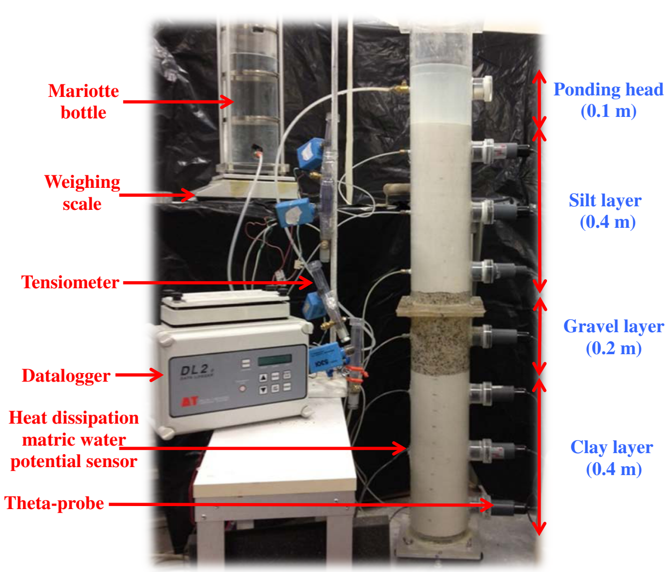

Fig. 6. Overview of water infiltration experiment

Conversion of Water Ponding to Equivalent Rainfall Return Period

Most engineering design guidelines are based on the rainfall return period (GEO 2011). Therefore, to make it more relevant for engineering design, the volume of water infiltrated was converted to an equivalent rainfall return period. Because water infiltration by ponding is similar to water seepage by irrigation used in the hydrology field, a criterion is used in this study to estimate the rainfall return period that is provided by *the Regulation for Hydrologic Computation of Water Resources and Hydropower Projects* [Chinese Ministry of Water Resources (SL278-2002) 2002]. To estimate the rainfall return period caused by ponding, it is required to determine the volume of infiltrated water and a coefficient β, which is the ratio of cumulative volume of infiltrated water to volume of ponded water (extreme rainfall depth), which is the sum of infiltration, surface runoff, and evaporation during this campaign. As suggested by the regulation, a single soil type is used in the estimation process by obtaining an equivalent k_s value of the layered soils used in the experiment. In a layered soil deposit in which the k_s for flow in different directions changes from layer to layer, an equivalent k_s becomes necessary to simplify calculations (Das 2013). With this consideration, a β value of 0.25 is selected as provided by the regulation. Extreme rainfall depth at different ponding duration can then be calculated by multiplying β to the corresponding cumulative infiltration. Rainfall return periods at various ponding durations are back-calculated using the relationship between rainfall depth and duration according to the *Hong Kong Stormwater Drainage Manual* (DSD 2013).

Interpretation of Experimental Results

Observed Infiltration Characteristics

Fig. 7 shows the measured cumulative water infiltration and calculated water infiltration rate with time. The cumulative volume of water infiltrated was found to increase at a decreasing rate, as expected. The water infiltration is one dimensional, and thus no lateral drainage. After the application of ponding, the amount of water infiltrated appeared to increase rapidly with time for up to 12 h. At this duration, the upper two-layer CCBE was nearly saturated, as will be shown at the following sections by the pore-water pressure and volumetric water-content measurements. Nonetheless, the low permeability of clay underneath the two-layer CCBE could be one reason why the cumulative infiltration changes very little for 12 h and onward of ponding duration. Furthermore, no percolation was observed after application of constant water ponding for 48 h. By following the conversion of water ponding to equivalent rainfall return period as described in the previous section, the ponding duration of 4, 6, 8, and 12 h was found to be equivalent to 4, 35, 530, and greater than 1,000-year return period of rainfall, respectively.

To determine the infiltration rate, the measured variation of cumulative water volume infiltrated with time was best fitted by the ordinary least square method; the best-fitted curve was then differentiated with respect to time analytically [Eq. (1)]. The infiltration rate was found to decrease exponentially at a decreasing rate, which is consistent with numerous researchers (Morin and Benyamini 1977; Zhan et al. 2007). This is attributed to a decrease of hydraulic gradient near the ground surface, as the pore-water pressure in deeper depths increases upon downward water flow. The increase in pore-water pressure could also lead to an increase in water permeability at the same time, and this could increase the infiltration rate according to Darcy's law. This effect is, comparatively, minimal, because the resultant infiltration rate shown in the figure decreased throughout the test and reached an almost steady state after 24 h of continuous ponding.

Distribution of Pore-Water Pressure Profile

The measured pore-water pressure distributions along the soil depth for the water infiltration test are shown in Fig. 8. Upon application of 0.1 m constant-ponding head, infiltration occurred primarily in the silt layer but not in the gravelly sand layer in the first 6 h, as

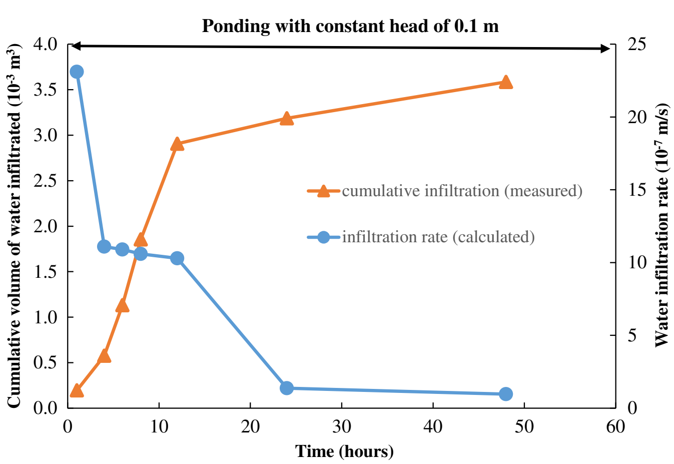

Fig. 7. Measured variations of cumulative volume of water infiltrated and infiltration rate with time

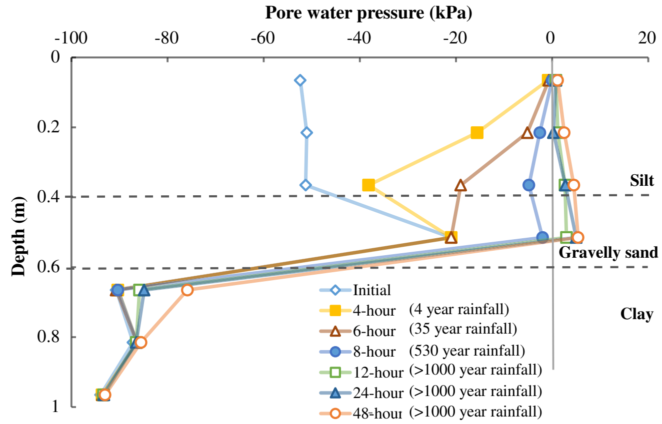

Fig. 8. Measured pore-water pressure distributions in the water infiltration test

reflected by the fact that the pore-water pressure head remained unchanged in the gravelly sand layer. In other words, the gravelly sand layer served as a capillary barrier and impeded the downward flow of water because of its relatively low permeability at higher suction range as shown in Fig. 2. However, the capillary barrier effect was not sustained for a long time when water infiltration continued in the silt layer. As a result, at an elapsed time of 8 h, the pore-water pressure at the gravelly sand layer suddenly increased from −20 to −2 kPa. The sudden increase in pore-water pressure indicated that during the period between 6 and 8 h, water is observed to infiltrate freely into the gravelly sand layer after a total breakthrough of suction value is achieved following continuous water infiltration (Ross 1990; Yang et al. 2006). The two-layer CCBE was no longer effective after this event occurred. This entails that the capillary barrier has a temporary effect in restricting the downward movement of water, as evidenced by the change in pore-water-pressure measurements across the fine-coarse soil interface. When water infiltration was continuously applied to the soil surface, breakthrough at the soil interface would eventually occur under the one-dimensional condition. This phenomenon has been demonstrated by numerous researchers for two-layer CCBEs (Stormont and Anderson 1999; Parent and Cabral 2006; Lee et al. 2011). Because of the continuous application of constant head, it could be observed that after 24 h a hydrostatic condition appeared to develop above the clay layer. This may be the result of clay acting as an impeding layer with its inherently low permeability. Even with the application of 0.1 m of constant head ponding for 48 h, the lower clay layer was still unaffected and no observable percolation was noted. This meets a recommended criterion of 3 mm/year for covers with a composite barrier (Albright et al. 2013) if there is no other occurrence of rainfalls with a return period of greater than 1,000 years within the same year.

Distribution of Volumetric Water-Content Profile

The measured volumetric water-content profiles for the test are shown in Fig. 9. At the start of ponding, the measured VWCs increased primarily in the silt layer. Consistent with the pore-water pressure measurements, the VWC at the gravelly sand layer increased during the period between 6 and 8 h. This could be attributed to the water breakthrough of the upper capillary barrier leading to drainage of water into the gravelly sand layer. This implies that the upper CCBE is only effective in preventing water percolation for rainfall of up to a 35-year return period. At 8 h of ponding,

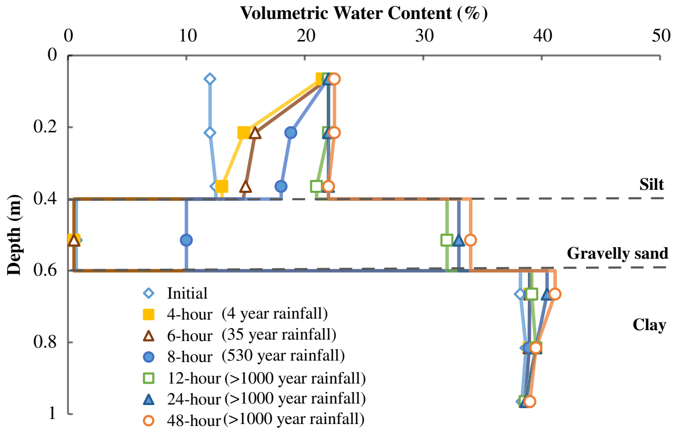

Fig. 9. Measured volumetric water-content distributions in the water infiltration test

which is equivalent to a 530-year rainfall return period, the VWC in the gravelly sand layer increased from 1 to 10%. With continuous ponding, the VWCs of silt and gravelly sand layer reached a value of 22 and 32%, respectively, after 24 h (>1,000-year rainfall return period). The upper two layers are considered to be saturated at this period. At an elapsed time of 48 h (>1,000-year rainfall return period), the upper portion of the clay layer increased only approximately 4% of VWC compared with the initial value as a result of low permeability of the clay layer. No water movement was observed as shown by the absence of change of VWC in the lower portion of the clay layer. The weighing balance did not register any drainage, which indicates that water is retained in the soil layers. Based on these measurements, the proposed landfill cover system functioned properly. When compared with the actual VWC (determined by the soil sampling method) at the end of test, the measured VWCs by the TPs were slightly different at any depth in the soil column. The maximum difference between the actual and measured VWC was ±3%. Assuming the air phase of soil in the experiment is continuous and remains at the atmospheric pressure during an experiment, the magnitude of each measured negative pore-water pressure is equal to matric suction. The measured pore-water pressure and VWC by a 1D column are consistent with the SWCCs (Fig. 5) measured by pressure plate.

Numerical Back Analysis and Parametric Study

Laboratory experimental data were back-analyzed to improve understanding of the experimental results. The initial conditions for the back analysis were obtained by specifying the initial measured pore-water pressure distributions obtained from the 1D experiment.

According to Albright et al. (2006), who carried out in situ and laboratory permeability tests of landfill covers with compacted clays, the k_s value of their compacted clay increased by three orders of magnitude after 4 years of service, attributing to desiccation cracks. Hence, an additional parametric study was carried out to investigate the effect of saturated clay water permeability with the intention of accounting for the influence of desiccation cracks formed in the bottom clay layer of this new cover system. This was just a simple sensitivity study, in which the saturated clay permeability used in the experiment was increased up to three orders of magnitude (i.e., $k_s = 5.7 \times 10^{-9}$ m/s to 5.7×10^{-6} m/s).

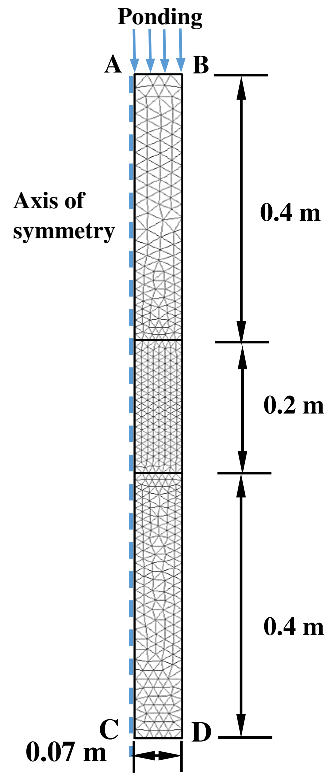

Fig. 10. Finite-element mesh used in the water infiltration analysis

Finite-Element Mesh and Boundary Conditions

Fig. 10 shows the finite-element mesh of the column model. Considering the geometry of the experimental setup (Fig. 3), the axis-symmetric condition was assumed in the finite-element analysis. The computer code used to perform the numerical simulation was coupled deformation brine, gas, and heat transport (CODE_BRIGHT) developed by the Technical University of Catalonia (UPC) (Olivella et al. 1994). This program can be used to model both the saturated and unsaturated flows under transient conditions. The governing equation for simulating transient flows in the three-layer cover system, given as follows:

$$\frac{\partial \theta}{\partial t} = \nabla[k\nabla(H)] \tag{2}$$

where θ = volumetric water content; t = time; ∇ = gradient of a vector field; k = water permeability; and H = total head. Similar boundary conditions as those applied in the actual experimental column test were applied. On the exposed cover surface (AB), a fixed water pressure of 1 kPa is specified to simulate a 0.1-m water ponding. The right boundary (BD) is an impermeable boundary. The left boundary (AC) is the axis of symmetry for the axis-symmetric condition. The bottom boundary (CD) is specified as a potential seepage face to simulate a drainage outlet.

Soil Properties

Because water infiltration into the soil is a wetting process, the measured wetting SWCCs of the silt, gravelly sand, and clay are adopted for the numerical simulation. Fig. 5 shows the best-fit wetting SWCCs by using the van Genuchten (1980) SWCC equation. Fig. 11 shows the computed unsaturated permeability function from wetting SWCC by using in conjunction the

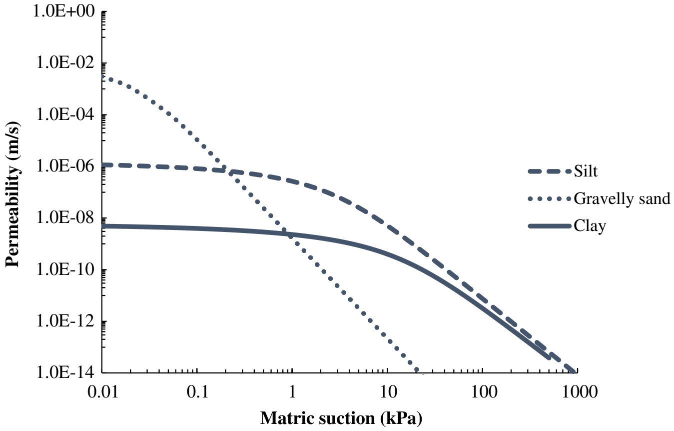

Fig. 11. Fitted wetting permeability functions for silt, gravelly sand, and clay used in the water infiltration analysis

van Genuchten-Mualem equation (van Genuchten 1980; Mualem 1976). For back analysis, the k_s of each soil are similar to those of Table 2. To investigate the effect of clay cracking, five different values of k_s of clay were selected. The actual saturated clay permeability, 5.7×10^{-9} m/s (reference), was increased by 100, 500 and 1,000 times, which are equivalent to 5.7×10^{-7} m/s, 2.9×10^{-6} m/s, and 5.7×10^{-6} m/s, respectively. However, the shape of the permeability function was kept the same.

Computed Results

All results in the following sections are presented in total head against depth. The bottom of the soil column, 1 m below the ground surface, was selected as the datum for the total head calculations.

Comparisons between the Experiment and Numerical Simulation

Fig. 12 shows the comparisons between the total head profiles obtained from the finite-element analysis and the measured experimental results during the test. At the initial condition, both the measured and simulated total head at the gravelly sand layer was higher than that of the silt layer, with the clay layer having the lowest total head. After 4 h of ponding (4-year return period of rainfall), the total head profile in the silt layer obtained from the numerical simulation shifted to the right, consistent with the movement of the total head profile measured from the experimental test. There was no observable total head change in the gravelly sand. After 8 h of ponding (530-year return period of rainfall), the total head at the gravelly sand layer also shifted to the right, whereas the total head at the silt layer shifted farther to the right, nearing the hydrostatic condition. This implies that water had already infiltrated into the gravelly sand layer, and the upper two-layer capillary barrier was no longer effective. After 24 h of ponding (>1,000-year return period of rainfall), a hydrostatic condition appeared to develop above the clay layer with the wetting front approximately 620 mm below the ground surface. After 480 h of further ponding >1,000-year return period of rainfall), the wetting front in clay layer was approximately 930 mm below the ground surface. This implies that the clay layer had yet to be fully saturated. Furthermore, this indicates that because of the addition of clay layer underneath a two-layer CCBE, the infiltrated water required a rather long duration for the wetting front to reach the deeper portion of the clay layer; thus, percolation could be prevented even for rainfall greater than a 1,000-year return period. In comparison, Yang et al. (2006) carried out a soil column infiltration test on a 1-m CCBE, clayey sand over fine sand, subjected to rainfall of 10 mm/h for 72 h (80-year rainfall return period). Their test results revealed that after 36 h of rainfall, steady-state infiltration was reached. This implies that the proposed landfill cover system was more effective than the two-layer CCBE in minimizing percolation from severe rainfall.

A further examination of the total head profiles revealed that results obtained from the numerical simulations had some slight differences than those measured in the experiments. The difference may be attributed to the discrepancies between actual and predicted unsaturated permeability functions of soil, which is caused by the inherent potential problem of predictive methods to rely on an accurate determination of residual water content (Ng and Leung 2012b). Another possibility for the difference may be because of the possibility of local compression of entrapped air between the soil layers. Nonetheless, the trends predicted by the finite-element analysis using wetting permeability function are in good agreement with those observed in the experiment of water infiltration, suggesting that any such effect from air compression may not be apparent.

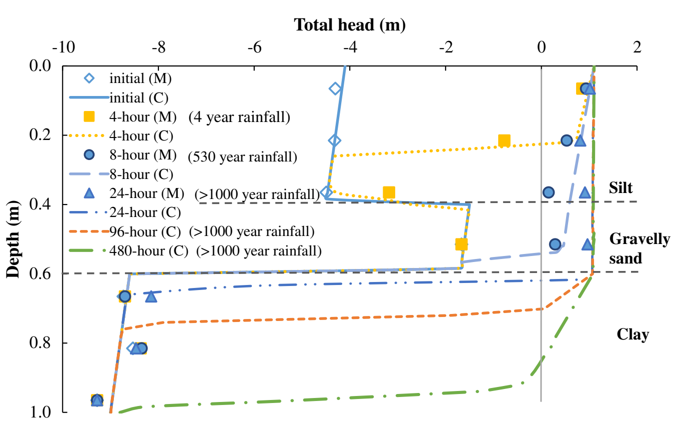

Fig. 12. Comparisons between measured (M) and computed (C) total head profiles in the infiltration test

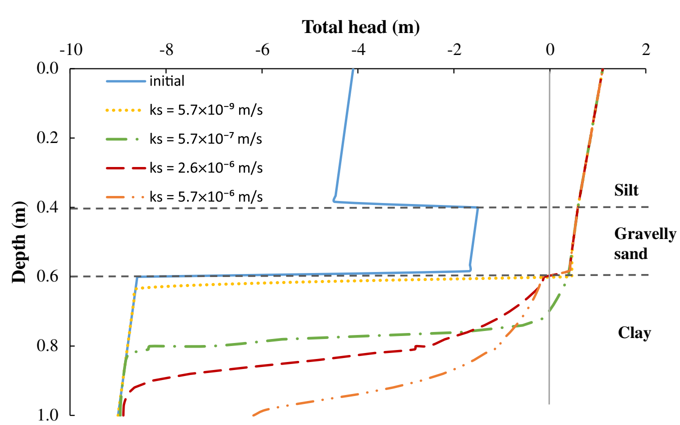

Fig. 13. Computed total head profiles in the infiltration test at elapsed time of 12 h (> 1,000-year return rainfall) with respect to different saturated permeability (k_s) of clay

Influence of Clay-Saturated Permeability

Fig. 13 shows a series of computed total head profiles of constant head ponding at 12 h (>1,000-year rainfall return) with respect to different clay k_s (5.7×10^{-9}, 5.7×10^{-7}, 2.9×10^{-6}, and 5.7×10^{-6} m/s). As mentioned previously, the initial condition was obtained by applying a similar total head profile as that of the experiment. The time that the upper two-layer CCBE was no longer effective and the wetting front reached the clay layer with respect to the reference clay k_s (5.7×10^{-9} m/s) used in the experiment was 12 h. For all k_s values, a positive total head appeared at the upper two-layer CCBE. The k_s had a significant influence on the total head distribution in the clay layer. The greater the k_s, the deeper was the wetting front. This is consistent with Green and Ampt (1911), that the depth of the wetting front during water infiltration is proportional to the k_s. In contrast, if the k_s value is relatively small, the total head near the top surface of the clay layer increased greatly. This is because the infiltrated water accumulated in the shallow portion of clay layer as a result of the low k_s value, and then gradually wetted the deeper portion. In contrast, for a relatively large value of k_s, the downward flow of water was easier. Hence, a moderately uniform distribution of total head was observed over the depth, so a relatively smaller increase of total head would be observed in the shallow portion of clay layer. This result is similar to the finding of Zhan and Ng (2004), that the higher the permeability of soil, the depth of saturation becomes deeper. The percolation obtained from the numerical simulation for the highest k_s (5.7×10^{-6} m/s) was approximately 0.1 mm after 12 h of ponding (> 1,000-year rainfall return). The equivalency percolation criterion for compacted clay cover in landfills should be smaller than 30 mm/year in humid climates (Benson et al. 2001). Following this criterion, the three-layer landfill cover system, despite the severe increase of clay k_s, performs satisfactorily if there is no other occurrence of rainfalls with a return period of greater than 1,000 years within the same year.

Summary and Conclusions

A new three-layer landfill cover was proposed and explored to reduce water infiltration into waste under all weather conditions (i.e., humid and arid climates). The fundamental principle of this new system is that a clay layer is added underneath a conventional two-layer capillary barrier system. The purpose of this clay layer was intended to act as an impending layer to minimize percolation into underlying waste when water breakthrough occurs at the upper two-layer capillary barrier during heavy and prolonged rainfalls. A water-infiltration test was carried out using a one-dimensional soil column to assess the feasibility and effectiveness of the newly proposed three-layer landfill cover system. For verification and improvement of understanding, the experiment was back-analyzed by conducting a transient seepage analysis. A simple parametric numerical analysis was also performed by simulating different values of saturated clay permeability to consider the effects of clay cracking on the three-layer system. Based on the measured and computed results, the following conclusions may be drawn:

1. The laboratory soil column test demonstrates the effectiveness of the three-layer landfill cover system when subjected to a 0.1-m constant head ponding. The effect of the capillary barrier at the upper two layers is effective only up to 6 h (35-year rainfall return). After water breakthrough of the capillary barrier, downward movement of infiltrated water is intercepted and prevented by the underlying clay layer because of its low permeability at low suction. No percolation was observed after further application of constant ponding up to 48 h (>1,000-year rainfall return). This meets the recommended criterion of 3 mm/year for covers with a composite barrier (Albright et al. 2013) if there is no other occurrence of rainfalls with a return period of greater than 1,000 years within the same year.
2. Consistent results were obtained between the 1D test and numerical back analysis of the experiment. The numerical back analysis reveals that for 480 h of 0.1-m constant head ponding (>1,000-year return period), the wetting front is still within the clay layer. In comparison, water breakthrough can occur for a 1-m CCBE with a rainfall of 10 mm/h for 72 h (80-year rainfall return). The three-layer landfill cover system has the advantage over a two-layer CCBE for the application in humid regions with severe rainfall conditions.
3. The saturated permeability of bottom clay has a significant influence on the total head distribution in the clay layer. Increasing the saturated clay permeability used in the experiment by 1,000 times (5.7×10^{-6} m/s), the amount of percolation observed was approximately 0.1 mm after 12 h of 0.1-m constant head ponding (>1,000-year rainfall return). This meets a design criterion of 30 mm/year (Benson et al. 2001) for compacted clays if there is no other occurrence of rainfalls with a return period of greater than 1,000 years within the same year.
4. Based on the results of the soil column test and numerical simulations, this newly proposed three-layer landfill cover system is observed to perform satisfactorily in humid regions under extreme rainfall conditions. This new system is therefore a promising alternative landfill cover. However, further field investigations are required to verify the current laboratory and numerical findings.

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