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Field study of water infiltration into a vegetated sustainable three-layer landfill cover system

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ABSTRACT: A landfill cover field test was conducted at the Xiaping landfill in Shenzhen, China, to evaluate the field performance of the vegetated three-layer cover system using recycled crushed concrete. The field test was composed of two sloping areas, one sloping area was vegetated with *Cynodon dactylon* (Bermuda grass), while the other was left bare. Without using geomembrane, the cover was compacted with a bottom layer of sieved completely decomposed granite, an intermediate coarsely crushed recycle concrete layer and a top unsieved completely decomposed granite layer. Pore-water pressure, volumetric water content, percolation and atmospheric parameters were monitored continuously for a period of 13 months under natural climatic condition. The cumulative rainfall depth was about 2950 mm over the monitoring period. Pore-water pressure and volumetric water content variation in both cover systems under a rainfall event of 172 mm depth were selected to assess the water infiltration process. At the end of monitoring, percolation was about 27 mm and 20 mm for the bare and grass covered landfill cover system, respectively. This implies that Bermuda grass is effective in minimizing percolation into a three-layer cover system using recycled concrete at humid climates.

1 INTRODUCTION

Landfill cover systems are primarily used to minimize water infiltration and reduce percolated water into the waste. A conventional landfill final cover system uses low water permeability materials such as compacted clay to prevent the water percolation. However, these conventional covers are very expensive to construct (Licht et al. 2001), and their performance decreases over time due to the deterioration of the used materials (Barnswell & Dwyer 2012). Furthermore, compacted clays desiccate after being subjected to multiple seasonal drying. The occurrence of cracks due to desiccation increases the saturated permeability of compacted clay and compromises the integrity of landfill cover systems (Sinnathamby et al. 2014).

Alternative cover systems are thus considered. One example of an alternative cover is a two-layer cover with capillary barrier effects (CCBEs). A CCBE consists of two soil layers, namely a layer of fine-grained soil overlying a layer of coarse-grained soil. By making use of the contrasting permeability of these two soil layers, a landfill cover system with CCBE could work effectively in controlling the downward migration of water under unsaturated conditions. However, the observed performance of

CCBEs in controlling water infiltration and minimizing percolation under humid climates has been proven to be unsatisfactory (Albright et al. 2004).

As a result, a new three-layer landfill cover system is proposed for minimizing rainfall infiltration under humid climatic conditions (Ng et al., 2016a). In this new cover system, a low permeability soil layer, such as compacted clay, was added underneath a CCBE. The working principle of the three-layer cover system in minimizing water infiltration is based on unsaturated soil mechanics theory. The infiltrated water through the three-layer landfill cover system could be reduced by utilizing the capillary barrier effects by the upper two soil layers and the low permeability of the soil in bottom layer. During heavy rainfall events, the capillary barrier effect is not able to be sustained as the increase of volumetric water content in the coarse-grained soil layer (Knidiri et al., 2017). However, the excessive percolation through the landfill cover could be prevented by the addition of the low-permeability layer. In addition, due to the presence of the capillary barrier, the bottom layer can be kept at high degree of saturation and minimize the occurrence of desiccation cracks.

For the pursuit of environmental protection and sustainability, plants are commonly used after landfill cover placement. Recently, some studies revealed

that the soil matric suction induced by plant transpiration could significantly reduce water infiltration and enhance the soil-water retention capacity (Ng et al. 2014, 2016b; Leung et al. 2015). The water infiltration process through soil is influenced by the evapotranspiration of plants. However, most of the previous studies were conducted in single layer soil. The effects of plants on water infiltration into layered soils such as landfill cover system are not yet fully understood and worth to be investigated.

A full-scale landfill cover system was constructed in Shenzhen, China. In order to promote sustainability, recycled waste materials were selected as the intermediate layer of the three-layer landfill cover system. One side of the test plot was transplanted with *Cynodon dactylon* (Bermuda grass) while the other one was left bare for comparison. The main objective of this study is to assess the field performance of a vegetated three-layer landfill cover system using recycled construction waste at a humid site. The variations of pore-water pressure and volumetric water content during a rainfall event of 149 mm in 4 June 2017 were selected. This is to investigate the effects of grass on water infiltration process in the three-layer landfill cover system. In addition, the monitored cumulative percolation data of 13 months (from June 2016 to July 2017) for bare and grass covered three-layer landfill cover system were also compared.

2 MATERIALS AND METHODS

2.1 Test setup and arrangement of instruments

The field test plot evaluated in this study was constructed at the Xiaping landfill, located in Shenzhen, China. The test plot consisted of two 20 m × 6 m sloping areas, each with a slope inclination of 30° (Figure 1). One sloping area (6 m width) was transplanted with *Cynodon dactylon* (Bermuda grass) turfs while the other one was covered with a geotextile to control surface erosion.

Figure 2 shows the cross-section of the field test plot. The landfill cover composed of three-layers, namely a 0.8 m thick sieved completely decomposed granite (CDG), a 0.2 m thick coarsely crushed concrete (CC) and a 0.6 m thick unsieved completely decomposed granite (CDG) from the bottom to the top. To prevent the migration of fine grains into the coarsely crushed concrete layer, a geotextile was placed between the top and intermediate layer. The unsieved, sieved CDG and coarsely crushed concrete was compacted at the target degree of compaction (DOC) of 95%.

In order to estimate the field performance of the landfill cover system, the percolation through the landfill cover, the variations of pore-water pressure and volumetric water content within the cover were monitored under natural climatic conditions. For the

bare and grass covered landfill cover, six lysimeters (1 m diameter) spaced 5 m apart were installed at the 1.8 m depth to monitor the water percolation through the three-layer landfill cover. Each lysimeter was connected with a drainage pipe to obtain gravity flow of the percolated water. The variations of pore-water pressure and volumetric water within the landfill cover were monitored by jet-fill tensiometers (JFTs) and SM 300 moisture probes. The JFTs and SM 300 probes were installed at different depths (i.e., 0.2 m, 0.4 m, 0.8 m, 1.2 m and 1.6 m) within the mid cross-section of the slope (Figure 2). Moreover, an automated weather station was also installed at top of the slope test area to measure the atmospheric parameters (rainfall, relative humidity, solar radiation, air temperature, wind speed and wind direction).

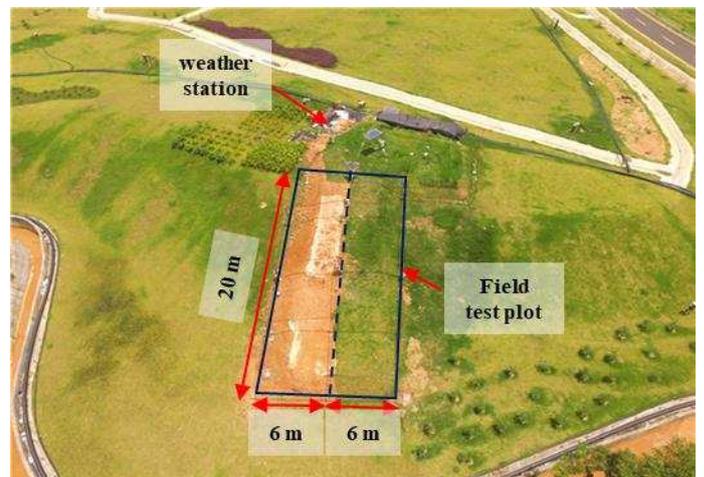


Figure 1. Aerial view of the field test plot

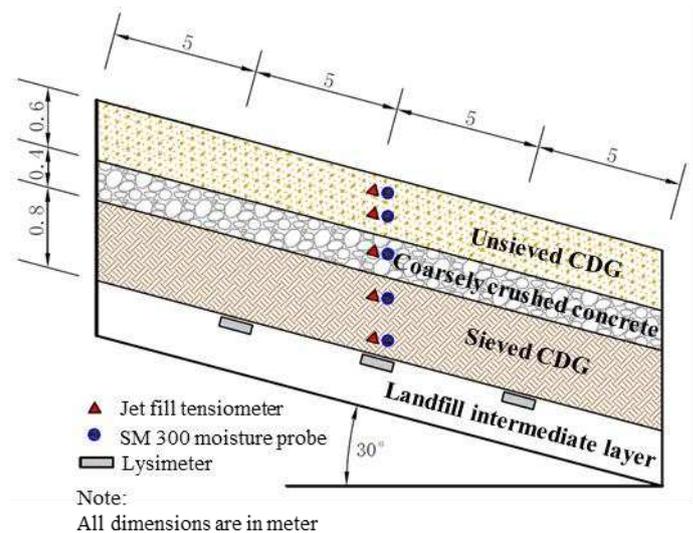


Figure 2. Typical cross section view and instrumentation arrangement in the field test plot

2.2 Soil type and index properties

Three types of soils were used to construct the field test plot, namely unsieved CDG, coarsely crushed concrete (CC) and sieved CDG. The CDG soil selected for testing was excavated from a slope near

the test plot. In addition, the fraction of CDG soil that was sieved to less than 10 mm was used for the low permeability layer. The coarsely crushed concrete was provided by a recycling plant in Shenzhen.

The measured basic properties of the cover materials are summarised in Table 1. Particle size analyses were obtained based on the sieve analysis described in ASTM D422 (ASTM 2007). Specific gravity tests were carried out by using the test method ASTM D854 (ASTM 2010a). Atterberg limit tests were performed by conducting standard test method in ASTM D4318 (ASTM 2010b). According to the Unified Soil Classification System (USCS; ASTM 2010c), the unsieved and sieved CDG soil are classified as clayey sand (SC), the CC is classified as poorly graded grave (GP).

Based on the test method described in ASTM D5084 (ASTM 2010d) using the flexible wall permeameter, the measured saturated permeability for the sieved and un-sieved CDG was 8.1×10^{-8} m/s and 5.7×10^{-5} m/s, respectively. Based on the constant-head method as described in test method ASTM D2434 (ASTM 2006), the measured saturated permeability of CC was 7.5×10^{-2} m/s.

Table 1. Measured index properties of cover materials

Index property	Unsieved CDG	CC	Sieved CDG
<i>Standard compaction tests</i>			
Maximum dry density (kg/m^3)	1860	1890	1820
Optimum moisture content (%)	12.6	-	14.4
<i>Grain size distribution</i>			
Fine content (< 0.075 mm, %)	29.3	0	32.2
Coarse content (>4.75 mm, %)	11.2	99.1	4.1
D ₆₀ (mm)	0.42	16	0.29
D ₃₀ (mm)	0.077	11.3	0.071
D ₁₀ (mm)	0.005	6.7	0.003
Coefficient of uniformity	-	2.39	-
Coefficient of curvature	-	1.19	-
Specific gravity	2.63	2.45	2.61
<i>Atterberg limits</i>			
Plastic limit (%)	20	-	20
Liquid limit (%)	37	-	37
Plasticity index (%)	17	-	17
<i>Unified soil classification system</i>			
	SC	GP	SC

3 OBSERVED FIELD PERFORMANCE

3.1 Monitored rainfall conditions

Figure 3 shows the daily and cumulative rainfall at the field test plot from June 2016 to July 2017. The cumulative rainfall was around 2950 mm. According to the figure, the rainy season of the test plot can be

identified as the months of June to October. It can be observed that daily rainfall varies from as low as 6 to 20 mm during the dry season and up to 150-200 mm during the rainy season. This shows that relatively long drying period can facilitate some suction recovery after the rainy season. It is noted that three heavy rainfall events with different intensities and duration occurred during the pore water pressure and volumetric water content monitoring. The rainfall event on 4 May 2017 had a rainfall duration of 4 hours with a total depth of around 79 mm. On the other hand, the rainfall event on 4 June 2017 had a much longer duration (i.e. 12 hours) with a total depth of around 150 mm. The rainfall event on 2 July 2017 had a similar rainfall duration (i.e. 12 hours) as the previous rainfall but with a total depth of only around 115 mm. The three rainfall events correspond to return periods of 3 years, 2 years and less than 2 years, respectively.

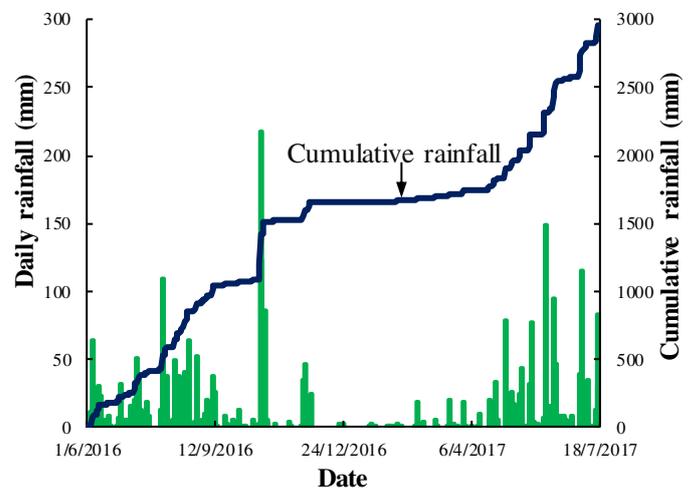


Figure 3. Daily and cumulative rainfall from June 2016 to July 2017 at the field test plot

3.2 Variations of pore-water pressure profile

Figure 4 shows the variations of pore water pressure profiles in both the bare and grass covered three-layer landfill cover system before and after a rainfall event recorded in 4 June 2017. The total depth for this rainfall event was 149 mm. In the bare landfill cover, the pore water pressure before rainfall at 0.2 m depth was -43 kPa, and increases with depth, to -2 kPa at 0.8 m depth and -6 kPa at 1.6 m depth. As for the grass covered three-layer landfill cover, the pore water pressure before rainfall along the depth was -37 kPa at 0.2 m depth, and raise to -3 kPa at 0.8 m depth and -4 kPa at 1.6 m depth. Prior to the rainfall event, the initial pore-water pressure in the bare landfill cover system at 0.2 m depth was lower than the pore-water pressure in the grass covered landfill cover system at the same depth. After rainfall, the pore water pressure at 0.2 m depth increased to -17 kPa in the grass covered landfill cover while the pore water pressure in the bare landfill cover increased to -8 kPa. A lower pore-water pressure was expected in

the grass covered landfill cover in the first layer than the bare landfill cover before rainfall. Based on the field test, Leung (2016) showed that pore-water pressures induced by evapotranspiration (ET) in grass covered soil under drying could be higher than the evaporation induced ones in bare soils. Due to the insufficient aeration in soil, the grass ET induced pore water pressure in relatively wet soil could be 20% higher. However, the presence of grass roots could occupy soil pores resulting in the alteration of soil structures and reduction of soil permeability (Buczko et al. 2007; Scanlan & Hinz 2010). Thus, grass helps soil in retaining lower pore-water pressure as compared to the bare soil after rainfall event.

Despite the total rainfall depth was 149 mm, the measured pore water pressure at the deeper depths (i.e. 1.2 m and 1.6 m) at bare and grass covered landfill cover system remained stable. These observed results may be due to the presence of capillary barrier effects at the interface of the upper two-layer.

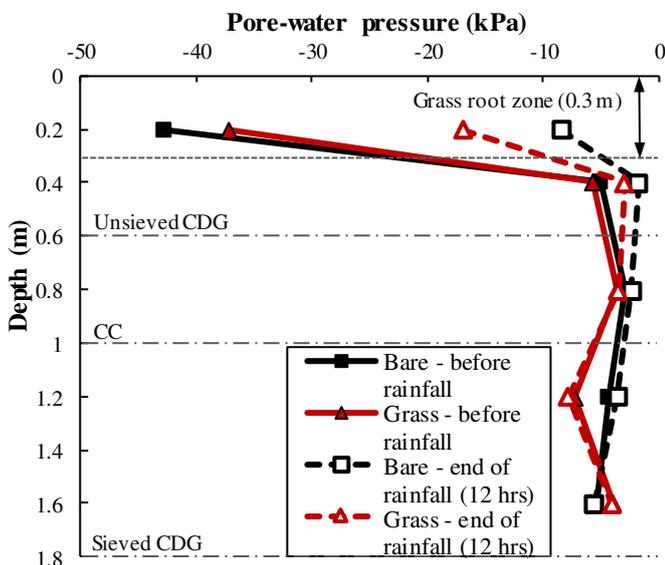


Figure 4. Measured pore-water pressure profiles in bare and grass covered three-layer landfill cover system

3.3 Variations of volumetric water content profile

Figure 5 shows the variations of volumetric water content profiles in the bare and grass covered three-layer landfill cover system before and after a rainfall event that occurred on 4 June 2017. The measured volumetric water contents were consistent with the measured pore-water pressures. Volumetric water contents near the surface were the first to be influenced by the rainfall. Similar low initial volumetric water content is measured at 0.2 m depth for both landfill covers. However, after rainfall, volumetric water content increased to a higher value of about 26% and 22% for the bare and grass covered landfill cover, respectively. Similar trends with the pore-water pressure measurement (Figure 4) could be observed. Only slight change of volumetric water content is observed at 0.8 m, 1.2 m and 1.6 m depth. This implies that the CC layer could work as a capil-

lary barrier and control the downward movement of water due to the relatively low unsaturated permeability at particular water contents. However, during this heavy rainfall event, the capillary barrier effects could not sustain. As showed in Figure 5, an increase of volumetric water content was recorded in the intermediate layer. The increase of volumetric water content indicated that water began to migrate into the CC layer which implies the failure of the upper two-layer CCBEs (Zhan et al. 2017). After water breakthrough at the upper two layers, water could reach the lowest layer (i.e. 1.2 m and 1.6 m depth). However, percolated water through the landfill cover could be prevented due to the sieved CDG layer.

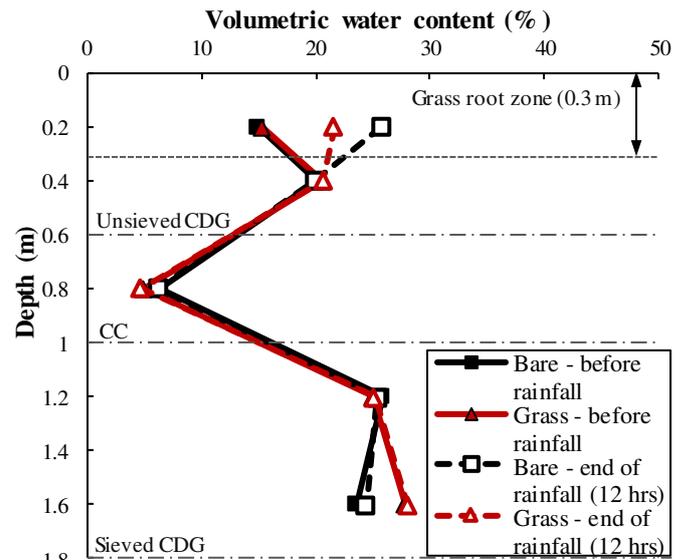


Figure 5. Measured volumetric water content profiles in bare and grass covered three-layer landfill cover system

4 MEASURED CUMULATIVE PERCOLATION

Since the measured cumulative percolation exhibited similar characteristics for the three different locations in the slope (i.e. crest, middle, toe), typical monitored results at crest in both bare and grass covered three-layer landfill cover from June 2016 to July 2017 have been selected and are shown in Figure 6. The measured cumulative percolation at crest was the largest among the three locations not only in the bare three-layer landfill cover system, but also in grass covered one. The figure shows the changes of cumulative percolation at crest in both cover systems. The cumulative rainfall depth is also showed with a total value of about 2950 mm. It was observed that percolation increased at a relatively steady rate and showed little variation in response to daily rainfall events during the first 6 months (i.e. June 2016 to November 2016). This finding implies the three-layer landfill cover system worked effectively in minimizing excessive percolation through the cover system. However, during a long period of drying from December 2016 to May 2017, the measured

percolation for both landfill covers increased by about 10 mm. This result may be due to the mild desiccation cracks observed on the soil surface at the end of this long period drying.

At the end of the 13 months monitoring, the cumulative percolation for the bare and grass covered three-layer landfill cover was about 27 mm and 20 mm, respectively. As mentioned in the previous section, this difference should be due to the low permeability induced by the presence of grass roots. By occupying soil pores, the grass roots could reduce the water infiltration rate (Buczko et al. 2007; Scanlan & Hinz 2010) and thus lead to less percolation.

The recommended design criterion by USEPA (1993) is 30 mm/year for compacted clays. Both bare and grass covered landfill covers could meet this recommended value. Although the rainfall amount received by the three-layer landfill cover system was much higher (i.e. more than 2900mm), the measured percolation could be much less compared to a compacted clay-barrier cover with a 260 mm average annual percolation that was reported by Albright et al. (2006). This study shows that the three-layer landfill cover system is a promising alternative landfill cover system for humid climates.

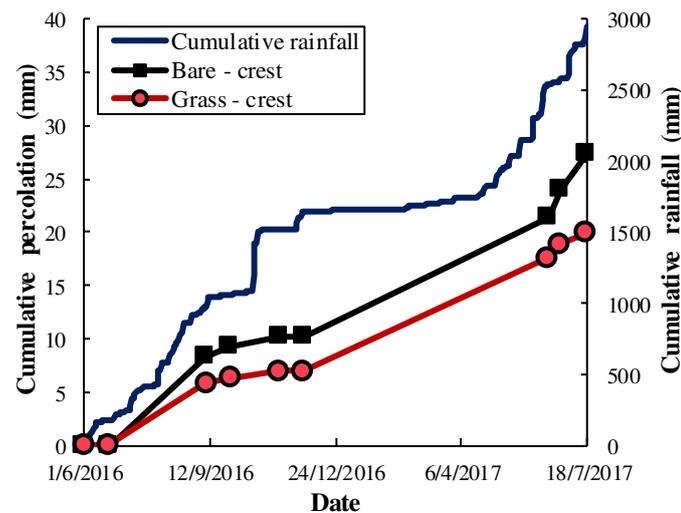


Figure 6. Cumulative percolation in the bare and grass covered three-layer landfill cover system from June 2016 to July 2017

5 CONCLUSIONS

Based on the full-scale test of a three-layer landfill cover system carried out in Shenzhen, China, the following conclusions could be summarized:

- After a relatively heavy rainfall event (i.e. rainfall intensity higher than 70 mm/d), lower pore-water pressure and volumetric content was retained in the top layer of the grass covered landfill cover compared with the top layer of bare landfill cover. This is due to the presence of grass roots which reduces soil permeability.
- At the end of monitoring, percolation was about 27 mm and 20 mm for the bare and grass covered landfill cover, respectively. Compared with other

types of landfill covers (e.g. conventional compacted clay covers), the three-layer landfill cover system is more effective.

- The observed results validate the potential of a grass covered three-layer landfill cover system using recycled concrete as a promising alternative landfill cover system for humid climates where annual rainfall of over 2000 mm is quite common.

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