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A Novel Waste-Cover-Waste Three-layer Landfill Cover System without Geomembrane: from Theory to Practice

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ABSTRACT

This paper describes the theoretical framework for a novel waste-cover-waste three-layer landfill cover system without the use of geomembrane but vegetation. The research methodology adopted includes laboratory column tests quantifying the transpiration-induced suction in vegetated three-layer cover systems using construction waste without geomembrane but with different plant species, and full-scale monitoring of field performance of the novel three-layer landfill cover system using natural soils for 6 years, in the areas where the annual rainfall exceeded 2,000mm. Moreover, the research also includes the combined use of vegetation and biochar together with construction waste in another field trial of the novel three-layer landfill cover system without geomembraner for 16 months. The results of laboratory and field-monitored matric suction, volumetric water content and percolation will be reported and explained. Design recommendations will be given.

Keywords: plant, biochar, construction waste, three-layer landfill cover, water infiltration

1 INTRODUCTION

Cover systems are commonly used in landfills, which are important for controlling water infiltration and reducing the percolation into the waste underneath. Different types of landfill final cover systems, like conventional and alternative covers, were designed to achieve these goals. By utilising low permeability materials (e.g., compacted clay), conventional covers can perform well in minimising rainfall infiltration for a short period (Albright et al., 2006). However, due to the desiccation-induced cracks, their long-term performance was unsatisfactory (Ng et al., 2016a). Another example of an alternative cover is a cover system considering capillary barrier effects (CCBE). A CCBE is a two-layer cover system that is a coarse-grained soil layer overlain by a fine-grained soil layer. With the contrasting permeability of these two soil layers, CCBE can minimise the downward movement of water through the interface between them. However, most of the previous research work was carried out under dry and semi-dry climates (Aubertin et al., 2009). The performance of CCBEs under humid climates has so far been unsatisfactory (Khire et al., 2000; Albright et al., 2004).

To accommodate humid climates, a new three-layer landfill cover system is proposed to improve the performance of CCBE (Ng et al., 2016a). In this cover system, a low permeability soil layer is added underneath a CCBE. Based on unsaturated soil mechanics, this cover system can take advantage of the capillary barrier effects formed by the first two soil layers and the low permeability of the bottom layer as it approaches full saturation. Water infiltration can therefore be minimised through this proposed three-layer cover system. To investigate the performance of the three-layer landfill cover system in reducing water infiltration, Ng et al. (2015a; 2016a) conducted a one-dimensional soil column and two-dimensional flume model test by using silt, gravel sand and clay soils. Both test results showed that this three-layer landfill cover system could work satisfactorily under extreme rainfall conditions. However, the soils used for the previous studies were idealised soils, which would not typically be used for landfill covers. Using pure kaolin clay as the low-permeability soil layer is impractical as it may not be readily available to supply a large amount of soil required to construct a landfill cover, aside from being expensive and difficult to construct. Thus, locally available soil with sufficiently low permeability is recommended for the lowest layer. Furthermore, to promote sustainability, using construction waste in geotechnical construction is highly recommended (Basu et al., 2015). As reported by Rahardjo et al. (2013), construction waste may have a better water retention capacity than natural soils. It is thus proposed that construction waste materials can be used as at least one of the components of the novel three-layer landfill cover system. The use of waste materials can help reduce the amount of waste deposited in landfills, preserve natural resources, and help alleviate the burden of landfill volume storage (Basu et al., 2015). Ng et al. (2015b) compared the gas emission rate through a single clay layer cover, a CCBE and a three-layer landfill cover during continuous drying. The results show that the gas emission rate through the three-layer landfill cover was the lowest among them and the only one met the recommended design value of Australian government (CFI, 2013).

Due to aesthetic and ecological considerations, plants have been considered an essential part of landfill final cover systems. Plant species can uptake water from the landfill cover soil by evapotranspiration and thus influence moisture distribution, soil suction and water infiltration (Ng et al., 2014; Sinnathamby et al., 2014). Studies have been conducted to quantify the suction induced by plants in the field (Pollen-Bankhead and Simon, 2010) and in the laboratory (Ng et al., 2014), and their effects on water infiltration. Some field studies found that when compared with bare ground, infiltration rates in the vegetated ground were lower because of the presence of plant roots (Meek et al., 1992; Leung et al., 2015). Due to its influences on soil suction and water infiltration, plants can enhance the performance of landfill cover systems in modulating the water percolation into the waste and balancing the water storage capacity (Abichou et al., 2015). However, most previous studies were carried out in single-layer uniform soil. Hence, the effects of plants on the suction distribution of layered soils, such as the three-layer landfill cover system during drying and wetting, should be investigated.

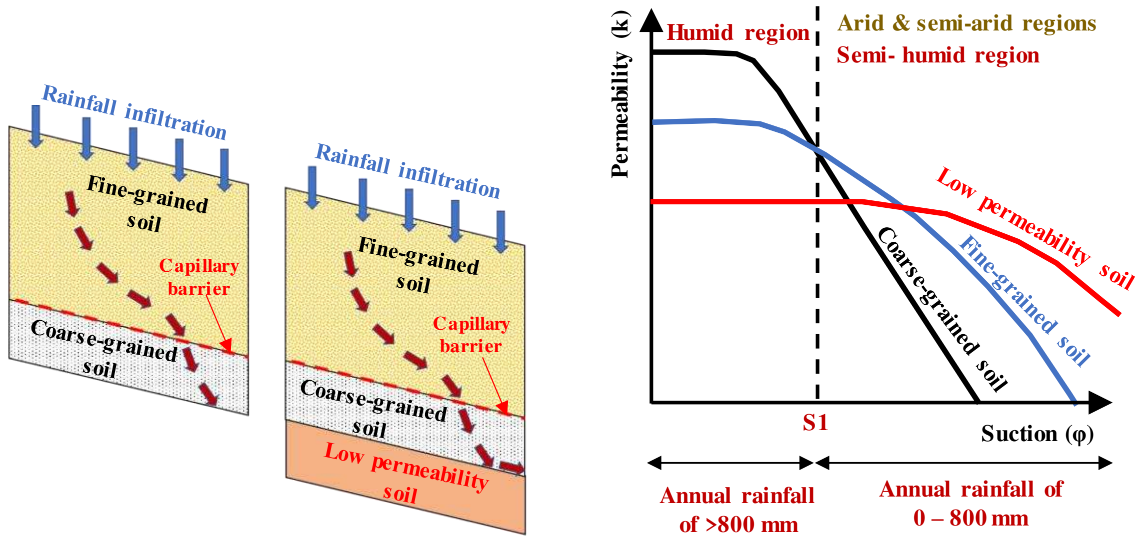
Recently, biochar application to soils has been widely propagated as a potential way to improve soil quality and thereby help plant growth (Laird et al., 2009). The addition of biochar to vegetated soils could benefit the growth of plants by providing plant-available and mineralisable nutrients from biochar pores and a favourable biochemical living environment with proper pH and sufficient aeration (Jones et al., 2012; Schulz et al., 2013). Biochar is an organic product from the pyrolysis or gasification of plant biomass (Lehmann and Joseph, 2009). Due to its highly porous and large specific area, biochar can change soil bulk density, porosity and thereby influence soil water retention capacity (Major et al., 2010; Ouyang et al., 2013; Wong et al., 2017). Earlier studies revealed potential applications of biochar in landfill final covers for removing odorous compounds (e.g., hydrogen sulphide) by adsorption (Xu et al., 2014), and reducing methane emission by promoting microbial methane oxidation (Sadasivam and Reddy, 2015). However, there is a lack of information on the effects of biochar on unsaturated soil properties and plant growth related to the design and performance of landfill final covers, including plant characteristics, soil-water retention curve, and permeability function. The studies about modelling the effects of plant-biochar-soil interactions on soil hydraulic properties, such as soil water retention ability, were also limited. Furthermore, it is still unclear how the interactions between biochar and plant roots affect water infiltration and the associated suction response in multi-layer soils such as three-layer landfill cover systems.

To promote sustainability, the authors propose to use construction waste as at least one of components of a three-layer landfill cover system. This paper report laboratory column tests and long-term field performance of a novel three-layer waste-cover-waste landfill cover system using construction waste but without a geomembrane under humid climates. Field monitoring was carried out at a full-scale in Shenzhen Xiaping landfill, China. Matric suction and percolation were monitored continuously.

2 THEORETICAL CONSIDERATIONS OF THE ALL-WEATHER UNSATURATED LANDFILL COVER SYSTEM

The conceptual diagrams of the CCBE and the three-layer landfill cover are shown in Figure 1(a). The figure shows that the CCBE consists of two soil layers, a fine-grained soil layer overlying a coarse-grained soil layer. The CCBE relies on the capillary barrier effects induced by the contrasting permeability of the two soil layers to prevent water infiltration. The newly proposed landfill soil cover is a three-layer cover system (as shown in Figure 1(a)), comprising a low permeability soil layer, a coarse-grained layer, and a fine-grained layer, compacted successively from the bottom to the top. According to the water permeability functions illustrated in Figure 1(b), infiltrated water through the upper two layers can be intercepted by the bottom low-permeability soil layer, which has a lower water permeability even at a high degree of saturation in a humid climate. In turn, the bottom low-permeability soil layer is protected by the upper CCBE from desiccation during dry seasons because the upper CCBE has a low water permeability at high suction.

In Figure 1(b), when soil suction in the three-layer landfill cover exceeds S1, as is often the case in semi-arid or arid climates, cover soils are relatively dry. Water permeability of the fine-grained soil layer is much higher than that of the coarse-grained soil layer, which acts as a relatively impermeable layer at this stage. Infiltrated water is collected in the fine-grained soil layer and drains away in this layer (i.e., no infiltrated water into the coarse-grained soil layer underneath). That implies the two-layer CCBE system is described as effective (Ng et al., 2016a).



(a) (b)

***Figure 1**. (a) Conceptual diagrams of a capillary barrier landfill cover and the three-layer landfill cover; (b) Schematic diagram showing the water permeability functions of fine-grained soil, coarse-grained soil, and low-permeability soil*

When soil suction in the landfill soil cover falls below S1 (Figure 1(b)) under heavy or prolonged rainfalls, which are common in humid climates, cover soils are (nearly) saturated. At this point, the capillary barrier effects created by the upper fine-grained soil layer and underlying coarse-grained soil layer are lost, allowing water to infiltrate into the coarse-grained soil layer with higher permeability. The low-permeability soil layer intercepts the infiltrated water but can be drained through the coarse-grained soil layer with relatively high saturated permeability. In this way, the head of water on the underlying low-permeability soil layer is reduced, so the amount of water percolation will be minimised (Ng et al., 2015a). The addition of a low-permeability soil layer beneath the CCBE thus makes the proposed landfill cover suitable for any weather conditions.

The functionalities of the upper two layers of this proposed landfill cover are fundamentally different from those of a conventional three-layer compacted clay cover in accordance with regulatory requirements (USEPA, 1993). As mentioned previously, the upper two layers of the newly proposed system function as a CCBE, whereas the upper and lower layers of a conventional compacted clay system simply act as a vegetation support layer and a drainage layer, respectively, which may enhance the desiccation through vegetation roots and water drainage. Therefore, the upper layer of a conventional three-layer compacted clay cover is not necessarily designed to be a CCBE.

3 EFFECTS OF VEGETATION ON WATER INFILTRATION INTO A THREE-LAYER LANDFILL COVER SYSTEM: 1-D COLUMN STUDY

3.1 Effects of shrub on water infiltration into a three-layer landfill cover system

To improve aesthetics, plants are often grown on landfill covers. However, most related studies were performed in single-layer uniform soil. There are limited studies on plant effects on water infiltration into layered soil, such as the three-layer landfill cover system. The schematic diagram of a one-dimensional (1D) soil column is shown in Figure 2(a). In this test, two soil columns of the same size and with the same layer system were set up. One column was transplanted with a shrub species (*Schefflera arboricola*, S) and the other used bare soil (B) as a reference (Lin et al., 2019). The four soil layers, namely the clay, gravelly sand, silt, and completely decomposed granite (CDG) soil layers, were compacted successively from the bottom to the top. The corresponding layer thicknesses were 0.4, 0.2, 0.3, and 0.1 m, respectively. At the top boundary, a constant-head ponding of 0.1 m was applied to the soil surface of each soil column. During ponding, soil matric suction and water infiltration amount were measured by tensiometers through the depth and electronic balance under the Mariotte bottle.

The measured matric suction distributions along the depth of the bare and shrub columns are shown in Figure 2(b). Before ponding, the initial suction in the shrub column after 104 days of drying was much higher than that in the bare soil column, especially in the top soil and silt layers. This might have been due to the root zone which was mainly located in the top soil layer. The higher initial suction corresponds to lower permeability, which can reduce water infiltration. After 8 hours of ponding (equivalent to rainfall with a return period of more than 60 years in Hong Kong; Lam and Leung, 1995), matric suction in the gravelly sand layer of the bare soil column decreased from 18 kPa to 15 kPa. However, 4 kPa and 23 kPa of soil suction were maintained at 150 mm and 350 mm depths in the shrub column. The suction in the gravelly sand layer and the clay layer remained unchanged. This shows that after the rainfall with a return period of 60 years, the capillary barrier (silt / gravelly sand) in the bare soil column failed, while that in the shrub column remained effective, mainly due to the higher initial suction induced by the shrub in the column than that in the bare soil column. The test results convincingly show that shrubs can greatly enhance the performance of the three-layer coverage system in reducing water infiltration.

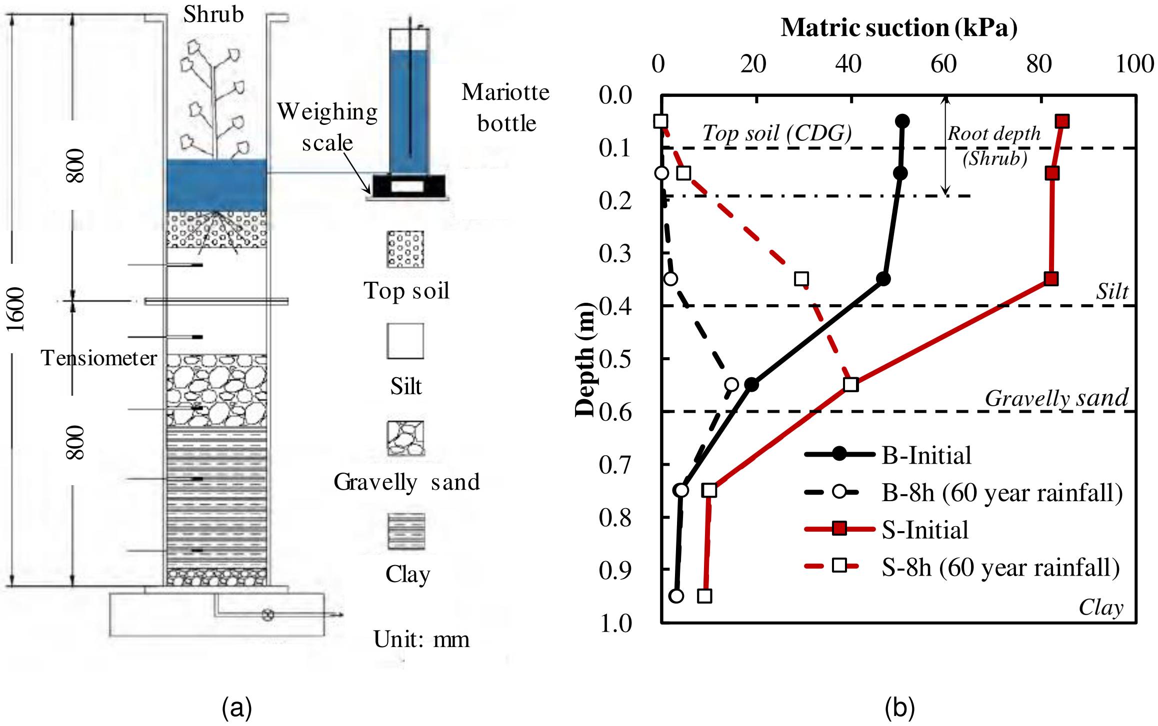


Figure 2. *(a) Schematic diagram of a soil column vegetated with a shrub; (b) Measured matric suction distributions along the depth of the soil column in the water ponding test (Lin et al., 2019)*

3.2 Effects of vegetation type on water infiltration into a three-layer waste-cover-waste landfill cover system

In order to quantify the effects of evapotranspiration (ET, which is the sum of soil evaporation and plant transpiration) on matric suction in the novel three-layer landfill cover using construction waste, 1D soil column tests were first carried out at the HKUST (Ng et al., 2019). The study used three columns, each with an inner diameter of 300 mm and a height of 1,500 mm (as shown in Figure 3(a)). Each column was compacted with CDG, fine recycled concrete aggregate (FRC) and coarse recycled concrete aggregate (CRC) overlying completely decomposed volcanic rocks (CDV). The selected grass species (*Cynodon dactylon*, G) and shrub species (*Schefflera arboricola*, S) are native to southern China, including Hong Kong (Ng et al., 2019). A bare soil (B) was utilized as a reference. All three columns were irrigated daily with 200 ml/day of water for 4 months. After drying, a 48-hour ponding with a constant water head of 100 mm was applied (equivalent to a rainfall with a return period of more than 1,000 years in Hong Kong; Lam and Leung, 1995). Soil matric suction was measured continuously during the drying and wetting periods.

Figure 2(b) shows the laboratory test results comparing the matric suction responses in the bare and vegetated three-layer landfill covers. Vegetated covers exhibited up to 95% higher suction than that under the bare cover because of ET before ponding. Compared with grass, shrubs induced an additional 25%–30% suction in the FRC and CRC layers. After 48 hours of ponding, suction in the top CDG and FRC layers was almost reduced to zero. For the bare cover, suction in the bottom CDV layer decreased from 52 kPa to 3 kPa during ponding. Percolation was observed under the bare cover, amounting to 35 g of water, equivalent to a water depth of 0.5 mm in the column. However, for the vegetated covers, a relatively high suction (52 kPa for the grass and 57 kPa for the shrub cover) was maintained in the bottom layer of CDV. Comparing the two vegetated cover systems, the levels of suction maintained under the cover with shrubs in the FRC, CRC, and bottom CDV layers were 2–6 kPa, 6 kPa, and 5 kPa higher than those maintained under the cover with grass, respectively. No percolation was observed under either of the vegetated covers. It is evident that the vegetated three-layer cover system using construction waste can effectively minimise water infiltration under extreme rainfall (i.e., rainfall with a return period exceeding 1,000 years).

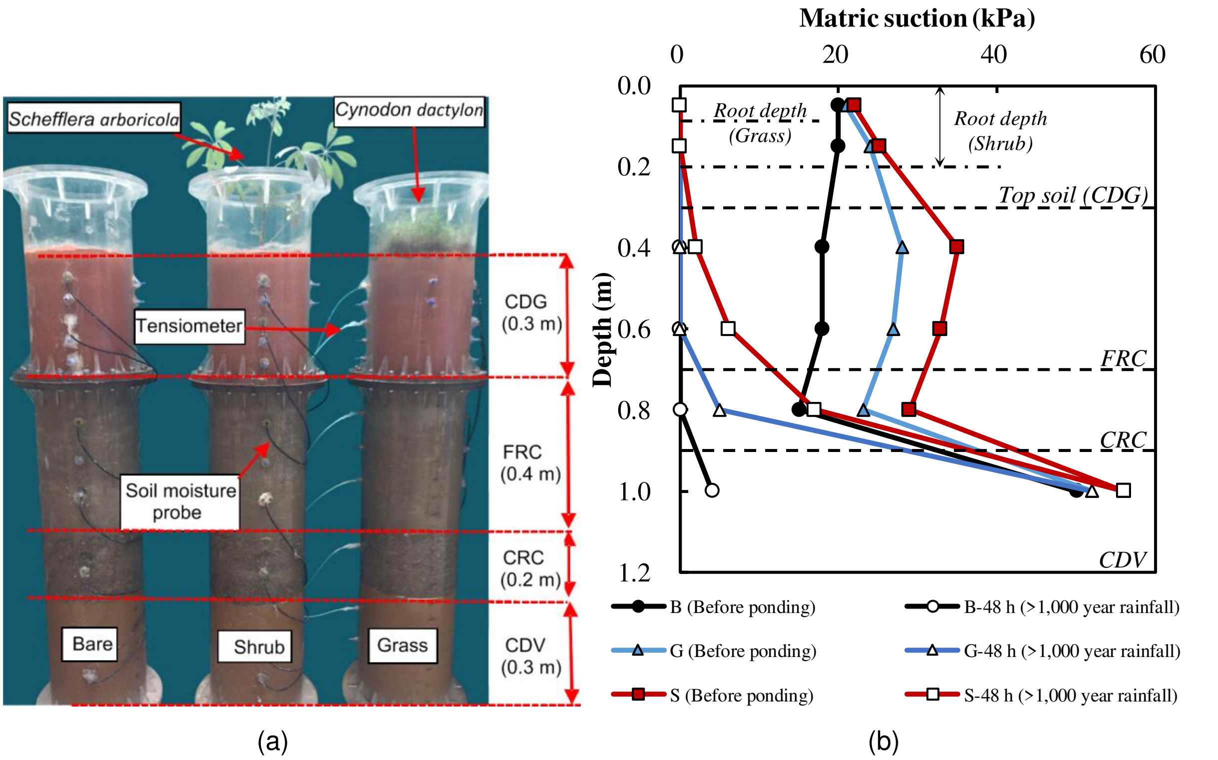


Figure 3. *(a) Overview of the three soil columns; (b) Matric suction distributions along the depth of a three-layer waste-cover-waste landfill cover system in the water ponding test (Ng et al., 2019)*

4 FIELD INVESTIGATION OF A VEGETATED THREE-LAYER LANDFILL COVER SYSTEM USING CONSTRUCTION WASTE AND BIOCHAR

4.1 Description of the field test site

The Xiaping municipal solid waste landfill in Shenzhen is one of the largest landfills in China, and it has been operated since 1997. The landfill is located in Xiaping valley (22°35'37" N-114°5'8" E), which is near the downtown area of Shenzhen. Till now, the Xiaping landfill has a total area of around 150 ha, more than 70% of which has reached its design storage capacity. The height of the waste body ranges from 80 to 110 m under the final cover system. The field test site is under a humid climate since the ratio of its annual rainfall to the potential evapotranspiration (PET) is larger than 0.75. Most of the rainfall occurs between April and October each year.

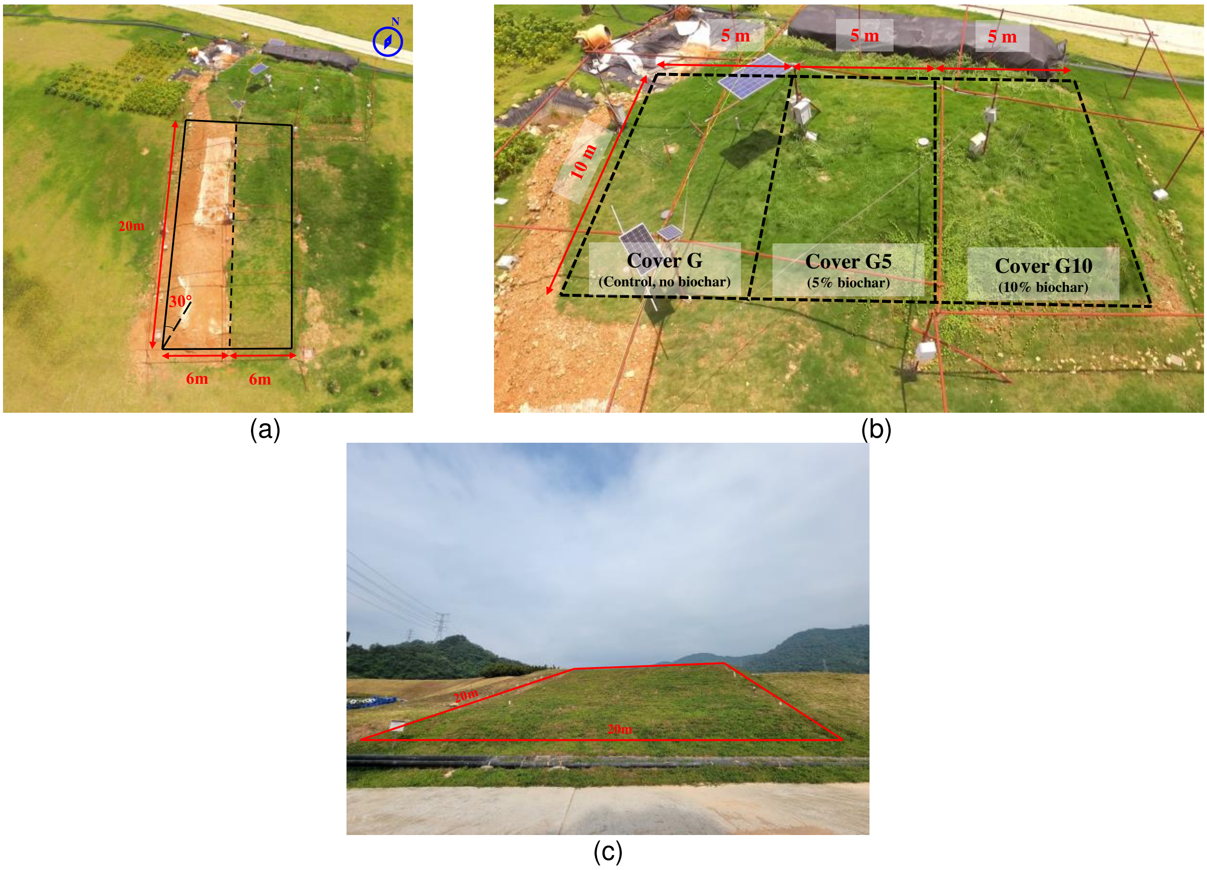


Figure 4. *Aerial view of the field test site within the Xiaping landfill, Shenzhen, China, used to investigate the performance of a three-layer landfill cover system using (a) natural soils (NS cover); (b) biochar amended natural soils and (c) the three-layer waste-cover-waste system (WCW)*

Figure 4 shows the overview of the field test site, constructed in the west part of the second phase at the Xiaping landfill. Three neighbouring areas (i.e., two slope areas and one flat ground area) were selected to construct the novel three-layer landfill cover system. As shown in Figure 4(a), one of the slope areas has a length of 20 m and a width of 12 m with an inclination angle of 30°.

Locally available soil, CDG, was sieved (fine-grained CDG) to construct the bottom soil layers in the three-layer landfill cover system. The unsieved CDG (coarse-grained CDG) soil were used in the top layers for the three plots. To save natural resources, CRC produced from construction waste was used for the middle layer of three-layer landfill cover systems. Half of the slope was covered with *Cynodon dactylon* (Bermuda grass) (G-NS), while the other was left non-grassed (NS) for comparison. As shown in Figure 4(b), the flat ground was divided into three plots, namely, cover G (control, no biochar), G5 (5% biochar; m^3/m^3) and G10 (10% biochar; m^3/m^3) according to the biochar content in the top-soil layer of the cover system. Each plot has a length of 10 m and a width of 5 m. The inclination angle of the cover systems is less than 2° to eliminate surface ponding under heavy rainfalls. Fine-grained CDG and CRC were used for the bottom and middle soil layers in the cover system, respectively. The coarse-grained CDG amended with peanut shell biochar at 0% (cover G), 5% (cover G5), and 10% (cover G10) (m^3/m^3) were used in the top layers for the three plots, respectively. All the tested plots were covered with *Cynodon dactylon* (Bermuda grass). To further promote sustainability, a three-layer waste-cover-waste system (WCW) using construction waste in all the layers was constructed in the other slope area (Figure 4(c)). The tested area is around 20 m in length and 15-18 m in width. The inclination angle of the slope area is 30°. The top layer for the cover is FRC, while the middle and bottom layer is CRC and 10% bentonite amended FRC, respectively. Similarly, the cover system was also covered with Bermuda grass. The grass species *Cynodon dactylon* (Bermuda grass) was selected because it has high drought tolerance and commonness under subtropical and tropical climates such as Hong Kong and southern China (Hu et al., 2010). This grass species can also survive under a wide range of pH (i.e., 4-6) and soil types (Ng et al., 2022). In addition, as a warm-seasoned perennial grass species, Bermuda grass is widely cultivated in Asia for the restoration of slopes and landfills (GEO, 2011). In this study, grass turfs with a leaf area index (LAI) of 1.99±0.08 and a root depth of 20±2 mm were transplanted at the top of the cover system. The fill age for the waste body underneath the test site was about 1 year at the time of construction.

4.2 Field instrumentation and monitoring

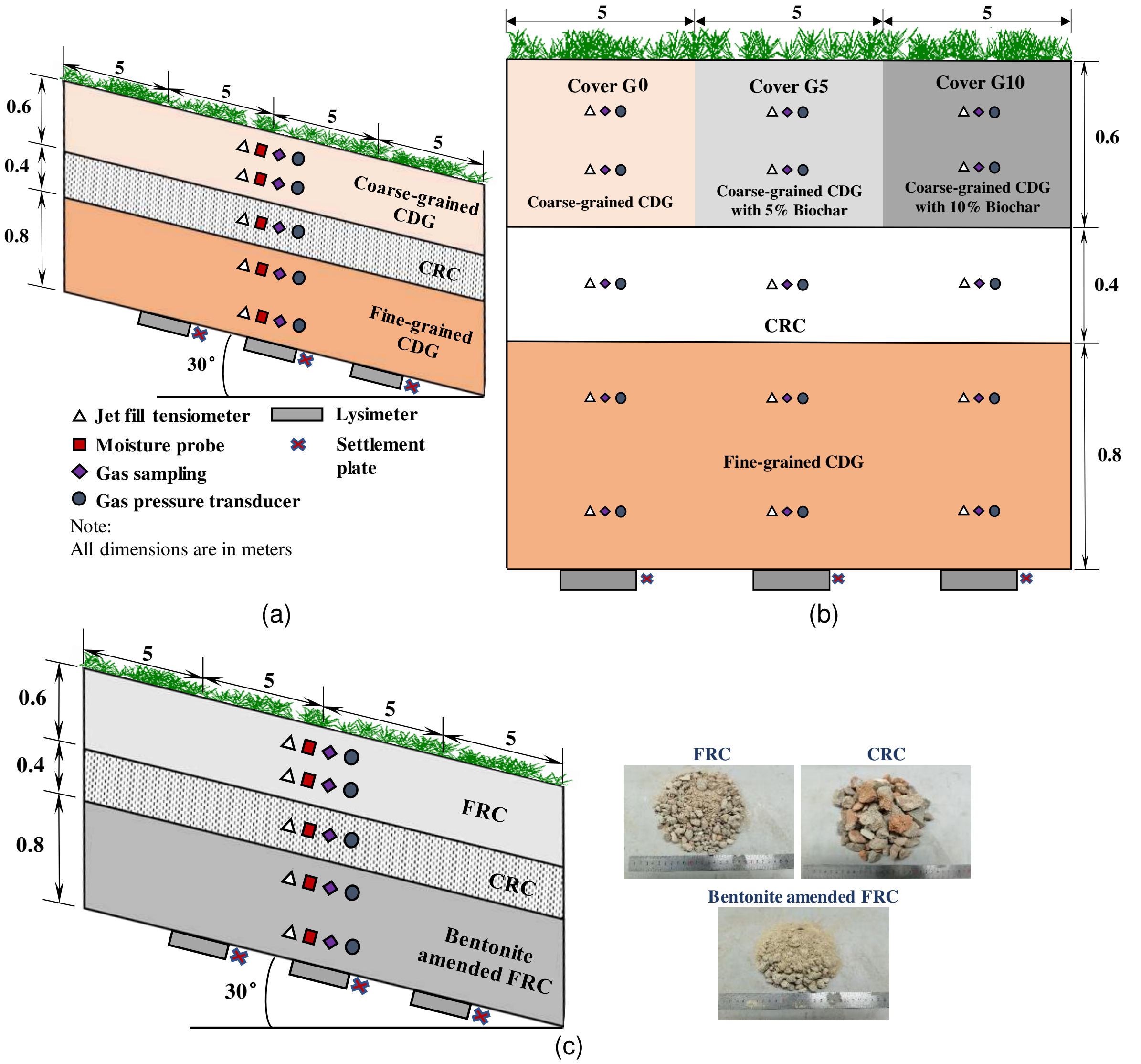


Figure 5. *Cross–section and layout of instrumentation of the three-layer landfill cover system using (a) natural soils (NS cover); (b) biochar amended natural soils and (c) the three-layer waste-cover-waste system (WCW)*

During the monitoring, the field performance of the three-layer landfill cover systems was studied by measuring percolation, matric suction, and VWC under humid climatic conditions. Percolation through the NS cover was monitored by using lysimeters with 1 m diameter since 1 June 2016. Six lysimeters at the spacing of 5 m were installed at the bottom of the NS and G-NS cover system (i.e., 1.8 m depth) (see Figure 5(a)). As shown in Figure 5(b), three lysimeters were installed at 1.8 m of cover G, G5 and G10. Moreover, three lysimeters were also installed at the bottom of the WCW cover system at a spacing of 5 m (see Figure 5(c)). Each lysimeter was connected to an independent reservoir by using drainage pipes. Matric suction and VWC within the landfill cover systems were also measured. Jet fill tensiometers (JFTs, Soilmoisture Equipment Corporation) and SM300 moisture probes (Delta-T Devices Ltd) were installed at 0.2 m, 0.4 m, 0.8 m, 1.2 m, and 1.6 m depths to assess the variations of matric suction and VWC at the middle cross-section of each cover system (see Figure 5). The JFTs were connected with pressure transducers. Hence, they can measure matric suction from 0 kPa to 100 kPa. Before installation, each JFT was fully saturated with de-aired water. Any air bubbles inside the JFTs were removed by using a vacuum hand pump. To install the JFTs at the targeted depth, vertical soil holes with a diameter larger than ceramic cup were drilled. Then, JFTs were installed in the pre-drilled holes. The ceramic cup of the Jet-Fill tensiometer was covered by a slurry of kaolin clay to ensure good contact between gravel and ceramic. (Leung, 2011). SM300 moisture probes can determine the VWC of soils by measuring their dielectric permittivity. Following the method of installing JFTs, vertical holes were drilled to the targeted depth at each soil layer right after the construction of this layer. The SM300 probes were inserted in the holes. To ensure good contact between the cover materials and probes, each hole was backfilled with the materials at the bottom, in the middle and at the top layers, respectively, and recompacted to their desired bulk density. Before field measurement, laboratory and in situ calibration were carried out for all the JFTs and SM300. The accuracy was ±1 kPa and ±3% for measuring matric suction and VWC, respectively. Please note that the details for gas and settlement monitoring of the three-layer landfill cover system are beyond the scope of this paper.

4.3 Effects of grass on the measured matric suction in the three-layer cover system using natural soils

Figure 6 shows the variations of measured matric suction along depth in the non-grassed (NS) and grassed (G-NS) landfill covers using natural soils before and after rainfall from 29 to 30 August 2018. The total rainfall depth during those two days was around 350 mm. During the entire monitoring, the highest daily rainfall intensity of 230 mm with a duration of 17 hours occurred on 30 August 2018, equivalent to a 15-year return period of rainfall in Shenzhen (Shenzhen Meteorological Observatory, 2015). Before this heavy rainfall, the tested site experienced a long antecedent rainy season with a total rainfall of about 1900 mm. According to previous studies, most types of alternative cover systems (e.g., ET cover, Albright et al., 2004; three-layer inclined capillary barrier, Zhan et al., 2014; dual capillary barrier, Rahardjo et al., 2016) cannot perform satisfactorily under such a rainy season. However, in this study, relatively high matric suctions were retained in G-NS and NS three-layer landfill cover systems (i.e., nearly 15 kPa and 10 kPa, respectively) after the prolonged rainy season. The measured matric suctions in G-NS cover were substantially higher than those in NS cover, especially in the shallow depth (i.e., 0.2m and 0.4 m). Beyond the plant root zone (i.e., 0.6 m), the root system can still help to preserve high matric suction through root water uptake (Leung et al., 2015). Consequently, a higher matric suction was measured in the middle CRC layer of G-NS than that in NS cover. The higher matric suction in the middle layer potentially enhances the performance of the upper two-layer CCBE in reducing water infiltration into the bottom layer. This has been identified as one of the main reasons why less percolation was measured through the vegetated cover system (Ng et al., 2019). The difference in the measured matric suction between NS and G-NS covers was up to 5 kPa (i.e., in the top layer), largely due to the plant root blockage of soil pore throat (Ng et al., 2016b) and ET.

At the end of rainfall, the measured matric suctions along the depths increased substantially in both cover systems. Under this heavy rainfall, water breakthroughs of the top CCBE occurred, and matric suction in the CRC and fine-grained CDG layers decreased. Matric suctions at the middle layer in G-NS and NS covers reached about 0 kPa. After the water breakthrough, the middle CRC layer functions as a drainage layer. This also indicates the feasibility of CRC used as the middle layer of the three-layer landfill cover system. Matric suctions decreased in the bottom fine-grained CDG layer for both cover systems, indicating water infiltration into the bottom soil layer. Even though the increase of percolation was observed after the prolonged and heavy rainfalls, the bottom layer remained unsaturated due to its low water permeability. The matric suction at the bottom of the lowest layer increased to 3 kPa, which corresponded to water permeability close to 1×10^{-9} m/s, meeting the required value by Benson et al.

(2001). The measured and computed results demonstrate that even after heavy rainfall, the NS and G-NS three-layer landfill cover systems using construction waste without geomembrane still effectively minimising water infiltration.

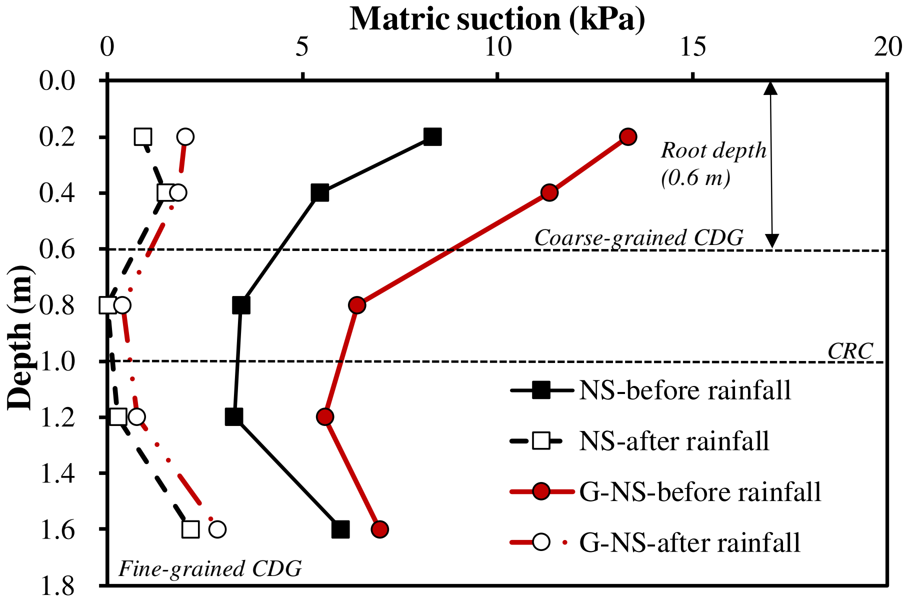


Figure 6. *Variations of measured matric suction profiles in the non-grassed (NS) and grassed (G-NS) three-layer landfill cover systems using natural soils before and after the rainfall from 29 to 30 August 2018*

4.4 Effects of grass on the measured percolation

Figure 7 shows the measured cumulative percolation by lysimeters at three locations (i.e., crest, middle and toe) in both the NS and G-NS three-layer landfill cover systems from June 2016 to June 2022. For ease of comparison, the measured cumulative rainfall over the span of six years is also included in the figure. During the six-year monitoring, the total amount of rainfall was over 12,500 mm, with 80% occurring between April and October each year. As expected, measured percolation increased steadily during wet seasons and corresponded to the cumulative rainfall well during the entire six-year of monitoring. Despite the fact that there was no measured percolation data from December 2016 to May 2017, the measured percolation in May 2017 was the cumulative value during this period.

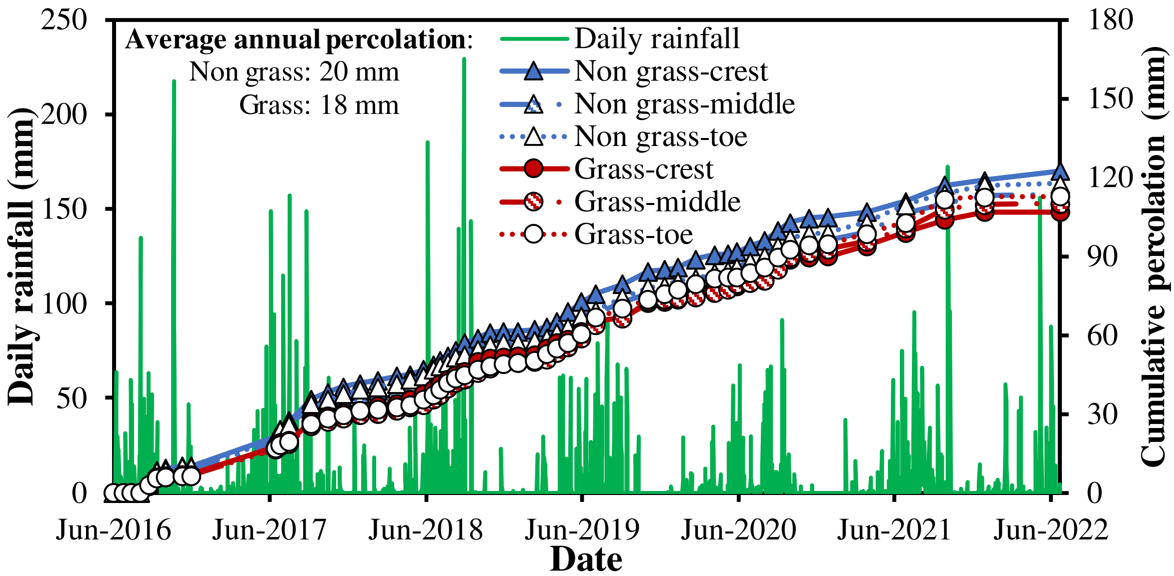


Figure 7*. Measured cumulative percolations in the non-grassed (NS) and grassed (G-NS) three-layer landfill cover systems using natural soils*

The recorded maximum annual percolation among the three locations for the NS landfill cover was 21 mm, 25 mm, 26 mm, 20 mm, 24 mm, and 12 mm, respectively, over a monitoring period of six years. The measured average annual percolation of the NS cover was about 21 mm. However, the maximum annual percolation through the G-NS cover was 18 mm in the first year and 20 mm in the second year because of grass effects. There was up to 22% reduction in annual percolation in the early two years of monitoring in the grassed cover compared with the NS one. This was due to the higher matric suction induced by grassroots. The measured results were also consistent with the one-dimensional column tests conducted by Ng et al. (2019). The higher matric suction reduced water permeability (Buczko et al., 2007) and hence less percolation. However, root channels and macropores may be formed due to root growth (Ghestem et al., 2011). The grassed landfill cover system increased progressively after March 2019, which led to the increase of infiltrated water and hence percolation through the grassed cover system. As a result, the maximum annual percolation through the grassed cover system was 25 mm, 22 mm, 21, and 10 mm in the following four years of monitoring. They were close to or larger than the measured percolation through a NS landfill cover system. At the end of field monitoring, the measured average annual percolation of the G-NS cover was about 19 mm. Nonetheless, the measured maximum annual percolation of both cover systems meets the recommended design criterion (30 mm/year) by the USEPA (1993). This proves the effectiveness of the three-layer landfill cover system using construction waste without a geomembrane to prevent excessive percolation.

4.5 Effects of grass-biochar Interactions on the measured percolation

Figure 8 shows the measured cumulative percolation through the grassed three-layer landfill cover systems, namely G, G5 and G10, during the monitoring from June 2017 to June 2020. The recorded cumulative rainfall depth was about 6,200 mm. The cumulative percolation collected by lysimeters under the cover G, G5 and G10 was 60 mm, 53 mm, and 50 mm, respectively. The measured percolation from the three cover systems was closely related to the rainfall events, especially those with daily rainfall depths larger than 100 mm. The amount of percolated water through cover G was the largest among the three cover systems.

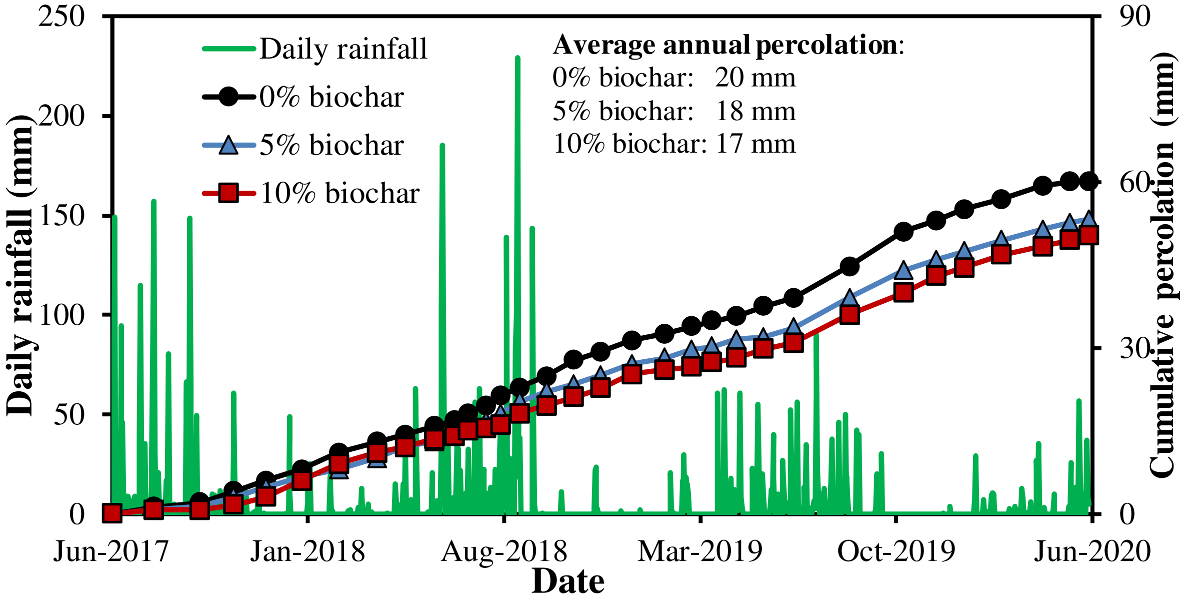


Figure 8. *Measured cumulative percolation through the grassed three-layer landfill cover using natural soils with 0% biochar (control, cover G), 5% biochar (cover G5) and 10% biochar (cover G10) from June 2017 to June 2020*

At the end of each year, the measured annual percolation for cover G was 16 mm, 22 mm, and 23 mm, respectively. More rainfall water infiltrated the cover system in the last two years than in the first year due to the increased saturated water permeability (k_s) of top layer soil induced by grass root growth, especially in the third year. The annual percolation through the cover G5 was 13 mm, 19 mm, and 21mm, respectively. With a further increase of biochar content to 10%, the annual percolation through cover G10 was reduced to 13 mm, 16 mm, and 21 mm, respectively. Applying biochar to the grassed three-layer landfill cover system can reduce cumulative percolation by up to 16.7%. The reduced percolation in biochar amended cover may be attributed to the improved water retention capacity, larger LAI (nearly 25%) and higher ET induced by biochar-grass interactions. Furthermore, it is also attributed to the alleviation of negative effects of grass growth on soil water permeability due to biochar addition. During the three-year monitoring, the k_s of top layer soil in biochar amended cover increased by 15%, much less than cover G (i.e., 53%). The measured cumulative percolation in cover G5 and G10 during the entire monitoring were very close (i.e., 53 mm and 50 mm), less than cover G (i.e., 61 mm). The insignificant difference in percolation between covers G5 and G10 was because the hydraulic properties (i.e., soil water retention curve, SWRC and k_s) and plant characteristics (i.e., LAI) of those covers were very close. The measured and computed annual percolation was less than 30 mm for G, G5 and G10 and met the design criterion recommended by the USEPA (1993). This implies the effectiveness of the bioengineered three-layer landfill cover system using plant and biochar in minimising water percolation. It is also clear that the grass-biochar interactions significantly influence plant growth and water infiltration through the three-layer landfill cover system.

4.6 Field-measured percolation through a grassed three-layer waste-cover-waste system

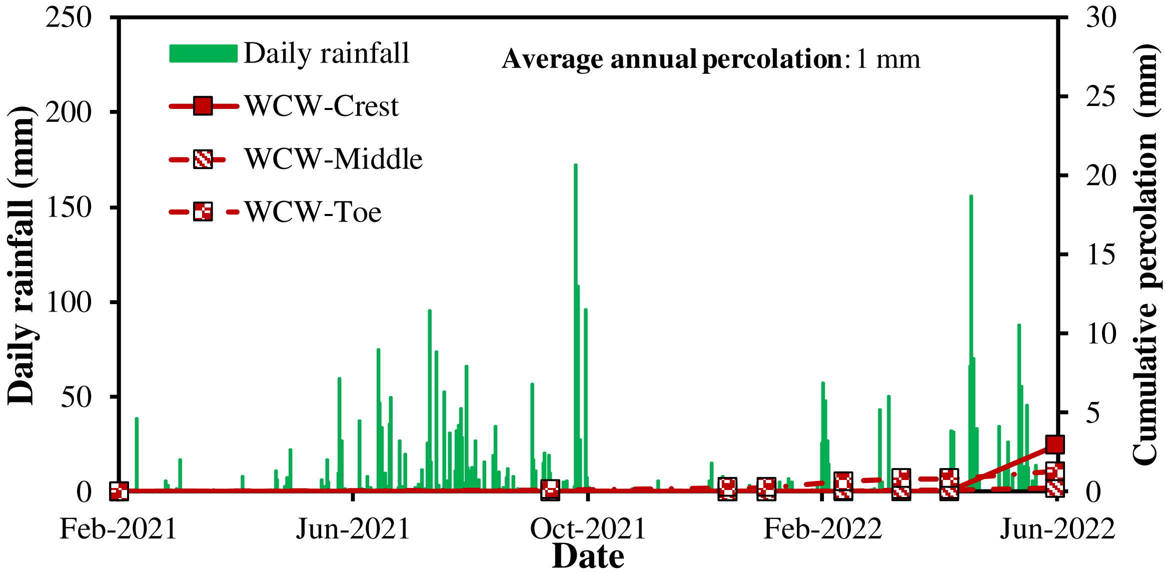


***Figure 9**. Measured cumulative percolation through a grassed three-layer waste-cover-waste system (WCW) from February 2021 to June 2022*

Figure 9 shows the field-measured cumulative percolations at the three-layer waste-cover-waste system (WCW) using construction waste from February 2021 to June 2022 (16 months). The percolations were collected at quartile points (i.e., crest, middle and toe) along the slope direction of this three-layer waste-cover-waste system. Daily rainfall during this monitoring period is also included as a reference. No obvious change was observed during the first 12-month field monitoring. The cumulative percolation for the three lysimeters remained close to 0 mm. This can be attributed to the relatively dry state of the cover system after construction. The rainfall depth from Feb 2021 to Feb 2022 (i.e., 8 months) was 959 mm, which occupies 41% of the annual rainfall. Most of the rainfall water can be stored in the cover system due to the high water retention capacity of construction waste during the rainy season while released to the atmosphere because of ET in the dry season. It indicates the effectiveness of the three-layer landfill cover system using construction waste. Starting from April 2022, the cumulative percolations increased dramatically. This is caused by the rainy season with large and frequent rainfalls. During the 16-month monitoring, the measured cumulative percolation at the crest, middle and toe was 3 mm, 0 mm, and 1 mm, respectively. The cumulative rainfall was more than 3,000 mm, with maximum daily rainfall over 150 mm. The largest ratio of cumulative percolation to cumulative rainfall was less than 0.1%. It implies that most of the rainfall water has been prevented by the cover system into solid waste. As mentioned in the previous section, the infiltrated water would be removed by the sufficient surface runoff, lateral diversion, and water storage capacity provided by using construction waste as well as plant ET. The measured annual percolation was much lower than the recommended value of 30 mm/year by the USEPA (1993). The measured results from the 16-month monitoring period clearly reveal the effectiveness of the novel three-layer landfill cover system using construction waste even without the use of a geomembrane in humid climates, especially with the enhancement of grass in minimising water percolation.

5 CONCLUSIONS

A novel waste-cover-waste three-layer unsaturated landfill cover system using plants, biochar and construction waste was studied through a multidimensional research programme. In the one-dimensional column tests, vegetated three-layer waste-cover-waste cover recorded up to 95% higher suction than that in the bare three-layer cover before ponding. After 48 hours of ponding (equivalent to rainfall with a return period greater than 1,000 years in Hong Kong), matric suctions in the bare cover was reduced to within 3 kPa, which was 18 times lower than those in vegetated cover. No percolation was observed through the vegetated cover during the ponding. It demonstrates the effectiveness of the three-layer vegetated waste-cover-waste cover system in reducing water infiltration under extreme rainfall (i.e., rainfall with a return period exceeding 1,000 years).

During the 6-year field monitoring in humid climates with an average of 2,000 mm rainfall per year, the maximum annual percolation was 27 mm in the bare three-layer landfill cover system using natural soils, whereas the annual percolation in vegetated three-layer landfill cover was 21, which is reduced by 22% attributed to the presence of grass. By using biochar, the measured cumulative percolation in the biochar-amended vegetated cover using natural soils was further reduced by up to 17%. Over a period of 16 months of field monitoring with an average of 2,000 mm rainfall per year, the measured average annual percolation through the grassed three-layer waste-cover-waste system was less than 1 mm from three lysimeters consistently. All those measured annual percolations meet the recommended criterion of 30 mm/year by USEPA (1993). The measured results evidently demonstrate that, even without using a geomembrane, the three-layer vegetated waste-cover-waste landfill cover system can perform effectively in minimising rainfall infiltration under humid climates.

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