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A Novel Environmentally Friendly Vegetated Three-Layer Landfill Cover System using Construction Wastes But Without a Geomembrane

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Abstract. The recycling and reuse of construction waste in landfill covers help reduce environmental pollution and promote sustainability. Further enhancement of the performance of the environmentally friendly landfill covers can be made by using vegetation as it is a low-cost, ecologically pleasant solution. Most related studies of vegetation were carried out in single-layer uniform soil while plant effects on water infiltration in layered soil such as a three-layer landfill cover system remain unclear. This keynote presents an integrated research approach combining laboratory one-dimensional tests as well as a 4-year full-scale field trial located in humid climates to explore the hydrological effects of plants on the performance of a novel three-layer landfill cover system using recycled concrete but without the installation of a geomembrane. Matric suction induced by plants was preserved to a greater extent under a novel vegetated three-layer landfill cover than under a bare cover even after an extreme rainfall event with a return period of greater than 1,000 years in humid regions like Hong Kong. During the 4-year field trial, the measured maximum annual percolation was 26 mm in the three-layer bare cover system, which was less than the US EPA-recommended 30 mm. Due to the presence of grass roots, the measured amount of annual percolation in the vegetated landfill cover was further reduced by up to 22%. Both the laboratory tests and field trial demonstrated that the vegetated three-layer landfill cover system using recycled concrete even without a geomembrane can effectively reduce percolation in humid climates.

Keywords: Three-layer landfill cover, Recycled concrete, Vegetation, Without geomembrane, Field monitoring, Water infiltration.

1 Introduction

Considering an increasing population and urbanization of modern societies, the continuous production and disposal of municipal solid waste (MSW) including construction wastes have become a worldwide problem. Due to its simplicity, practicality and cost-effectiveness, landfilling remains one of the major methods of MSW disposal ([1-2]). To reduce water percolation, most modern landfills are covered with geotextile composites and geomembranes. However, geomembranes are highly susceptible to interface instability and defects/holes, which can influence their reliability ([3-4]).

Since the 1990s, a cover with capillary barrier effects (CCBE) has been proposed as an alternative to conventional covers ([5-7]). The CCBE is a two-layer cover system consisting of a fine-grained soil layer (e.g. sand) overlying a coarse-grained soil layer (e.g. gravel). It works by exploiting the contrasting permeability of the two soil layers (Fig. 1). The main advantages of the CCBE include its stability, relatively simple design, low construction costs and long-term durability compared with compacted clays ([8]). Although the use of CCBE has been proven to be effective in minimizing water infiltration into underlying MSW in arid and semi-arid regions, its performance is unsatisfactory in humid climates ([9-12]). In order to improve the performance of CCBE for humid climates, a novel all-weather three-layer landfill cover system has been proposed ([13]). This three-layer landfill cover essentially adds a low permeability soil layer such as clay to the bottom of the original two-layer CCBE (Fig. 1). The innovation of this three-layer cover system lies in its ability to effectively minimize water infiltration in humid climates and gas emission ([14-18]) from the underlying landfill without relying on a geomembrane. The infiltrated water is minimized by exploiting the capillary barrier effects of the two upper soil layers (i.e., fine-grained soil and coarse-grained soil) and the low permeability of the bottom layer even at or close to full saturation ([14-15]). Moreover, the bottom soil layer is expected to reduce landfill gas (the main component is methane) emission because of its inherently low water permeability and thus low gas permeability ([16-17]). Even if a very tiny amount of landfill gas migrates into the landfill cover, it can be oxidated effectively in the soil ([18-20]).

Construction wastes have been popularly recycled and reused in infrastructure applications in recent years ([21-23]). Since recycled concrete aggregates (RCAs) possess similar hydraulic properties to those of natural soils under saturated and unsaturated conditions ([24]), they could potentially serve as materials for landfill cover systems. For aesthetic and ecological reasons, plants are commonly grown on landfill covers ([25]). Plants can remove moisture from soils via evapotranspiration (ET), resulting in a decrease in soil water content and water permeability ([26-28]). To promote sustainability, the combined use of recycled construction wastes and vegetation is highly recommended.

In this keynote, a comprehensive research approach is reported to investigate the hydrological effects of plants on the performance of a three-layer landfill cover using recycled concrete. First, a series of laboratory column tests is reported to investigate plant transpiration-induced soil matric suction in a vegetated three-layer landfill cover system. Two plant species commonly found in Hong Kong were selected for study. Second, a full-scale field trial is described to investigate the influence of vegetation on the performance of the three-layer landfill cover over the span of four years.

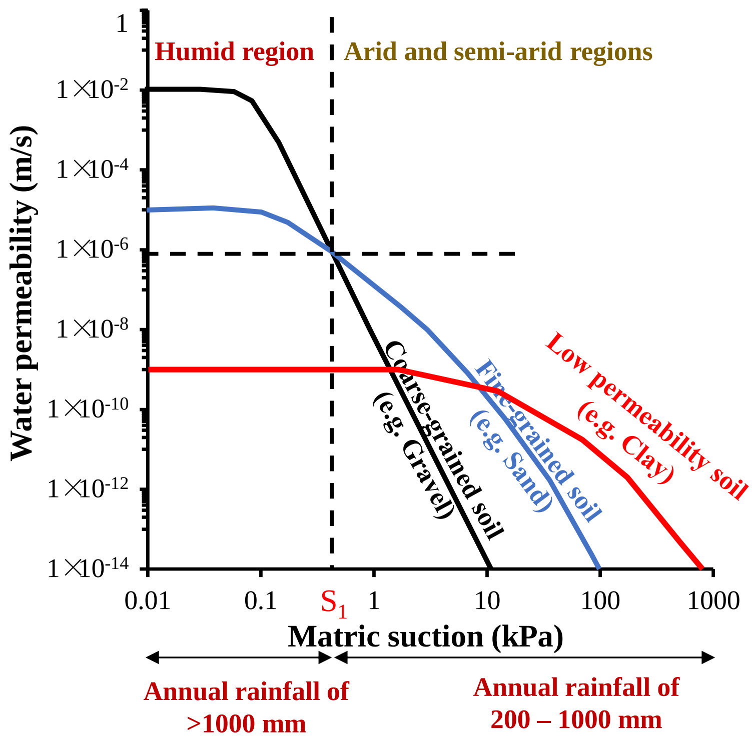

Fig. 1. Schematic diagram showing the water permeability functions of fine-grained soil, coarse-grained soil and low-permeability soil.

2 Effects of Vegetation Type on Water Infiltration Into A Three-Layer Cover System using Recycled Concrete

To promote environmental sustainability, recycled concrete is suggested for civil infrastructure works. In order to quantify the effects of ET, which is the sum of soil evaporation and plant transpiration, on matric suction in the novel three-layer landfill cover using recycled concrete, one-dimensional soil column tests were carried out in a plant room at HKUST ([29]). Three columns were used, each with an inner diameter of 300 mm and a height of 1,500 mm, as shown in Fig. 2. Each column was compacted with completely decomposed granite (CDG), fine recycled concrete (FRC) and coarse recycled concrete (CRC) overlying completely decomposed volcanic rocks (CDV). The selected grass species (C*ynodon dactylon*, G) and shrub species (*Schefflera arboricola*, S) are native to southern China including Hong Kong ([30]). The test in bare soil (B) was used as reference. All the three columns were subjected to daily irrigation at 200 ml/d of water for 4 months. Then they were subjected to one day of drying before 48-hour ponding with a constant water head of 100 mm was applied (equivalent to rainfall with a return period of more than 1,000 years in Hong

Kong [31]). Soil matric suction was measured continuously during the drying and wetting periods.

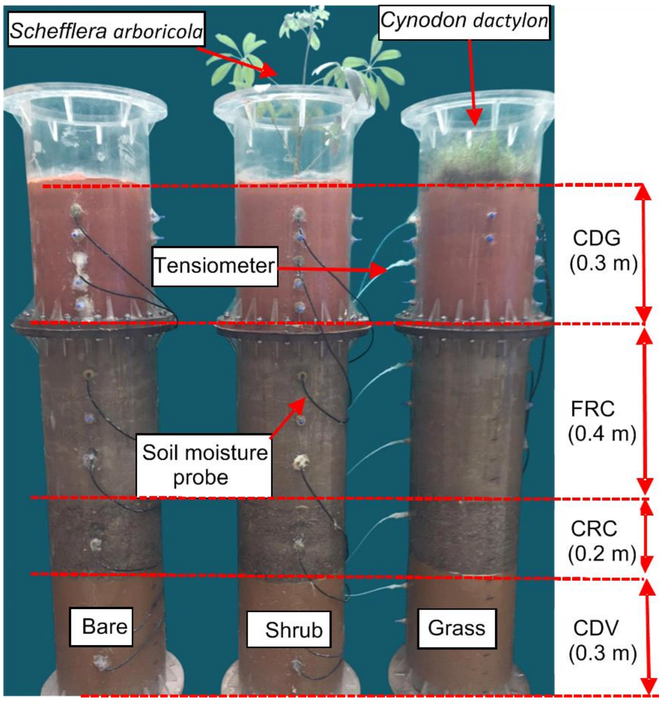

Fig. 2. Overview of the three soil columns ([29]).

Fig. 3 shows the laboratory test results comparing the matric suction response in the bare and vegetated three-layer landfill covers. Due to ET before ponding, suction under vegetated covers was up to 95% higher than that under the bare cover. 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 cover 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 RCAs can effectively minimize water infiltration under extreme rainfall (i.e. rainfall with a return period exceeding 1,000 years).

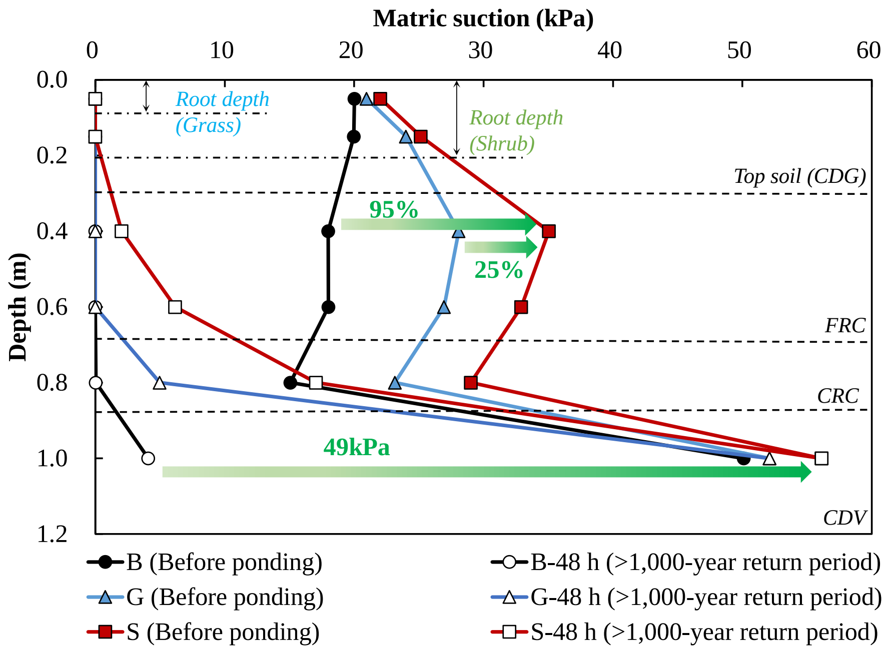

Fig. 3. Matric suction distributions along the depth of the soil column in the water ponding test ([29]).

3 Field Investigation of A Vegetated Three-Layer Landfill Cover System using Recycled Concrete

3.1 Description of the field test site

The use of plants and recycled wastes as landfill cover materials was investigated at a landfill site located in Xiaping, Shenzhen, China (Fig. 4 [32]) in which field monitoring results from June 2016 to July 2020 were reported. The landfill began operation in October 1997. Xiaping landfill currently spans a total area of 149 ha and is Shenzhen's biggest landfill, handling about 30% of the city's total waste (approximately 5000 t/day). The maximum thickness of the waste body is about 40 m.

The three-layer landfill cover test plot was constructed on a 20-m long x 12-m wide embankment in the western part of the Xiaping landfill (Fig. 4). The slope inclination was 1.7H/1V (H and V refer to horizontal and vertical, respectively). The fill age of the waste layer under the test plot was between 3 and 4 years at the time of construction ([32]). The field test plot was located in a humid subtropical climate region, with approximately 80% of annual rainfall occurring between May and September. The annual potential evaporation (PET) was estimated using the Penman-Monteith equation ([33]). The site is considered humid since the ratio of annual cumulative rainfall to PET is higher than 0.75. The lowest monthly mean relative humidity during the driest months (i.e. October to February) is 64%. This implies that care must be taken when selecting the top layer soil. Soils that are resistant to desiccation cracking should be selected. Silty sands, sandy silts and clayey sand are likely suitable for the top layer ([34]).

The main objective of the field test was to validate the proposed novel vegetated three-layer landfill cover system using recycled concrete without installing a geomembrane. The landfill cover consisted of three layers, namely a 0.8-m thick sieved CDG (with a dry density of 1.73 Mg/m^3), a 0.2-m thick coarsely crushed recycled concrete (CRC) (with a dry density of 1.89 Mg/m^3) and a 0.6-m thick unsieved CDG (with a dry density of 1.77 Mg/m^3), from the bottom to the top. A geotextile was placed between the fine- and the coarse-grained layer to minimize fines migration into the CRC layer. The measured saturated permeability values of the sieved and unsieved CDG were 2.1×10^{-8} m/s and 1.9×10^{-5} m/s, respectively, whereas that of CRC was measured to be 7.5×10^{-2} m/s ([32]). Half of the test site (a width of 6 m) was transplanted with Bermuda grass (also known as *Cynodon dactylon*) while the other half was left bare (Fig. 4). Bermuda grass is a warm-seasoned grass species widely cultivated in many parts of Asia. This grass species has high drought tolerance and is commonly used for slope greening and ecological restoration ([35-36]).

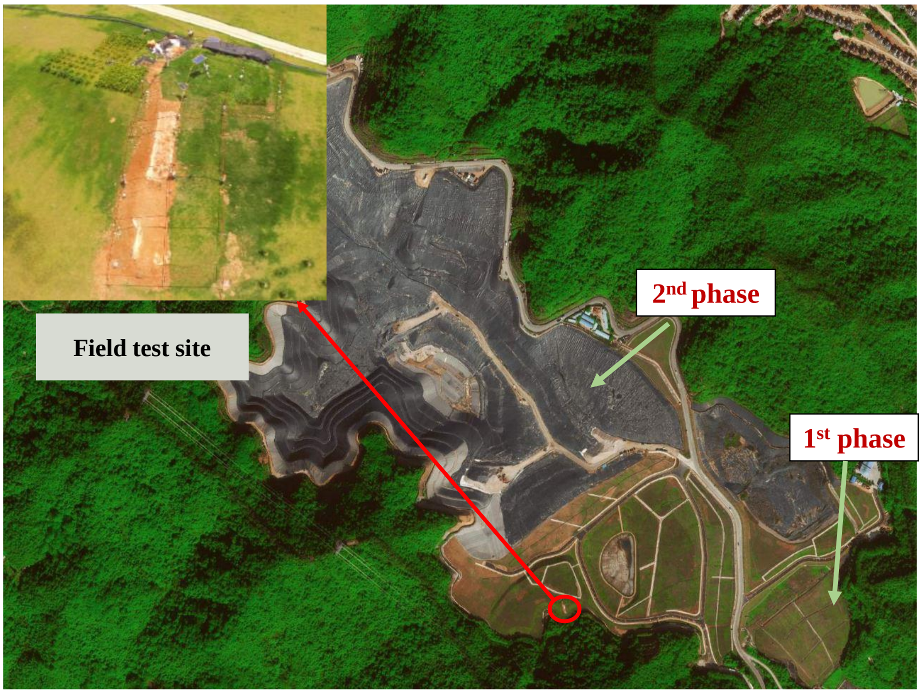

Fig. 4. Aerial view of the field test site within the Xiaping landfill, Shenzhen, China.

3.2 Field instrumentation and monitoring

To assess the landfill cover performance, the test site was heavily instrumented and closely monitored for a period of 4 years (from June 2016 to June 2020) under natural climatic conditions (see Fig. 5). During monitoring, matric suction, volumetric water content, percolation and atmospheric parameters (e.g. relative humidity and rainfall depth/intensity) were measured. Matric suction and volumetric water content distributions under natural climatic conditions (e.g. drying and wetting) in the vegetated and bare three-layer landfill cover systems were compared and interpreted based on the amount of percolation.

Six lysimeters (1 m in diameter) were installed at a depth of 1.8 m, spaced 5 m apart at the bottom of the bare and vegetated landfill covers to monitor water percolation. Each lysimeter was connected to an independent drainage pipe to allow the percolated water to flow towards an independent reservoir under gravity. The lysimeters were operated manually to measure the amount of infiltrated water throughout the monitoring period. To assess the variations in matric suction and volumetric water content in both the bare and vegetated three-layer landfill covers, jet fill tensiometers (JFTs) and moisture 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 (Fig. 5). The JFTs fitted with pressure transducers were used to measure soil matric suction.

Changes in volumetric water content were measured using SM300 moisture probes . The moisture probes estimate the volumetric water content of soil by measuring its dielectric permittivity. Prior to installation, the JFTs and moisture probes were calibrated in the laboratory and *in situ* for all three layers. In addition, an automated weather station was installed at the top of the slope to measure the atmospheric parameters, including rainfall, relative humidity, air temperature, wind speed and wind direction. The gas monitoring and settlement of the landfill cover are beyond the scope of this paper and hence not described.

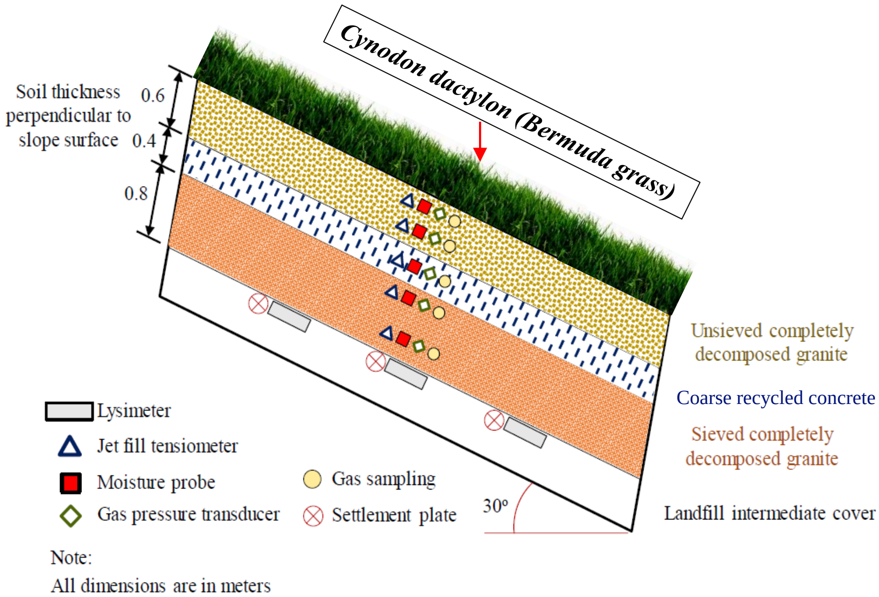

Fig. 5. Cross-section and layout of instrumentation in the field trial site (not drawn to scale).

3.3 Measured cumulative percolation

Fig. 6 shows the field measured cumulative percolation in both the bare and grassed three-layer landfill covers at three different locations (i.e., crest, middle, and toe) from June 2016 to June 2020. The daily rainfall during the 4-year monitoring is also included in the figure for comparison. During the first year of monitoring (i.e., from June 2016 to June 2017), measured percolation increased steadily, corresponding to the cumulative rainfall as expected. Similar results were also observed during the second, third and fourth year of monitoring. At the end of the first, second, third and fourth year of monitoring, the measured annual percolations of the bare landfill cover were 21 mm, 25 mm, 26 mm and 22 mm, respectively. Due to the presence of vegetation, the measured annual percolations of the grassed cover were consistently lower at same corresponding locations, i.e., the crest, middle and toe of the slope, each year. This was because higher soil suction induced by grass roots resulted in a reduction of water permeability and hence less percolation [28-29, 32]. The measured annual percolation was less than 30 mm for both the grassed and bare covers and both met the design criterion recommended by the United States Environmental Protection Agency (USEPA) [37].

At the end of the 4-year monitoring, the measured cumulative percolation for the grassed cover was 88 mm, which was 14 % less than that of the bare cover (i.e., 94 mm). The measured results from the 4-year monitoring period clearly demonstrate the effectiveness of the novel three-layer landfill cover system using recycled concrete even without the use of a geomembrane in humid climates, especially with the enhancement of grass in minimizing water percolation.

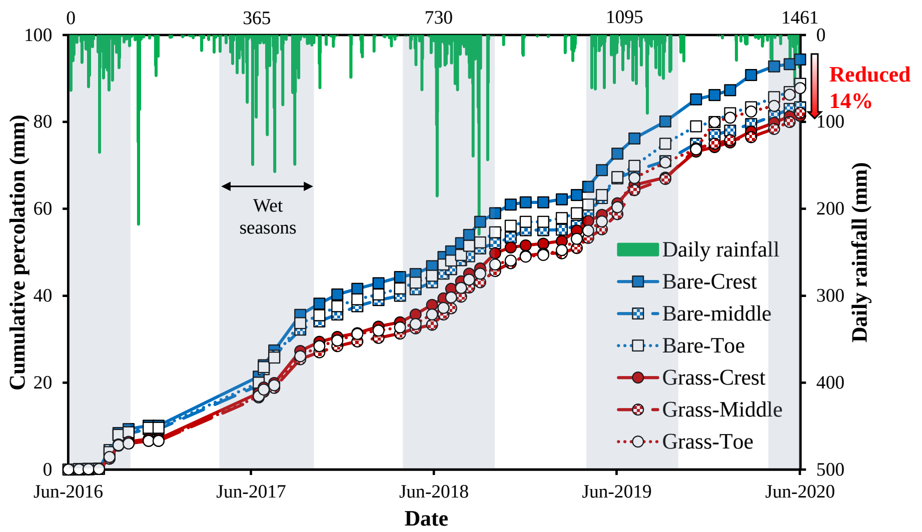

Fig. 6. Cumulative percolation in the bare and grassed three-layer landfill cover systems during the 4-year monitoring.

4 Conclusions

A novel environmentally friendly three-layer unsaturated landfill cover system using plants and recycled concrete was studied through a multidimensional research program. Two different plant species—a shrub (*Schefflera arboricola*) and a grass species (*Cynodon dactylon*)—native to southern China were tested. After 48 hours of ponding (equivalent to rainfall with a return period greater than 1,000 years in Hong Kong) in soil column tests, suction was maintained to a greater extent under the novel vegetated three-layer landfill cover than under the bare cover. Shrubs were found to be more effective than grass at preserving soil matric suction after ponding. During the 4-year field trial in humid climates, the maximum measured annual percolation was 26 mm in the bare cover system, which was less than the USEPA-recommended 30 mm. Due to the presence of grass roots, annual percolation in vegetated landfill covers could be further decreased by up to 22%. It is evident that the vegetated three-layer landfill cover system using recycled concrete even without the installation of a geomembrane can effectively reduce percolation in humid climates.

Acknowledgment

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