Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.jzus.zju.edu.cn; www.springerlink.com
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Effects of shrub on one-dimensional suction distribution and water infiltration in a three-layer landfill cover system*#

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https://doi.org/10.1631/jzus.A1800145

1 Introduction

One essential function of a landfill cover is to prevent water infiltration into the waste so as to reduce the generation of leachate. Plants are commonly found on landfill covers to protect soil from erosion and provide an attractive natural environment. Moreover, plants extract moisture from landfill cover soils by transpiration and hence influence soil suction and water infiltration (Khire et al., 1997; Albright et al., 2010; Sinnathamby et al., 2014; Ng et al., 2016b). Some studies have been carried out to quantify the suction induced by plants during drying in the field (Pollen-Bankhead and Simon, 2010; Ishak et al., 2013; Garg et al., 2015b; Ni et al., 2017) and in the laboratory (Woon et al., 2011; Ng et al., 2013a, 2013b, 2016a). Some researchers have investigated the effects of plants on water infiltration in soil and soil permeability (Leung et al., 2015; Jotisankasa and Sirirattanachat, 2017). However, all the above studies were conducted in uniform soil. The effects of plants on suction distribution and water infiltration in layered soils, such as those in a landfill soil cover system, during drying and wetting have not been investigated thoroughly.

In this study, two soil columns of a three-layer landfill cover system with a topsoil layer were tested. The landfill cover system consisted of a topsoil layer for plants, a two-layer cover with a capillary barrier effect (CCBE) (i.e. a silt layer overlying a gravelly sand (GS) layer), and an underlying clay layer. One soil column was planted with a shrub, *Schefflera arboricola*, while the other was left bare. The effects of the shrub on the 1D suction distribution in soil layers of the landfill cover system during drying and wetting were investigated. During drying, the effects of the shrub on measured suction were interpreted in terms of suction recovery, peak suction, and the suction influence zone. The suction induced by plant transpiration was examined. During wetting, the effectiveness of the three-layer landfill cover system in preventing water infiltration was investigated, based on the suction retention capacity of planted soil in relation to the CCBE of the three-layer landfill cover system.

2 Testing program and procedures

The experimental set up and instrumentation in this study are provided in Data S1, and the information of the tested soils and plants is also provided in Data S1.

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* Project supported by the National Natural Science Foundation of China (Nos. 51778166, 51578196, and 51608152) and the Environment and Conservation Fund Project (No. 85/2018), Hong Kong, China

Electronic supplementary materials: The online version of this article (https://doi.org/10.1631/jzus.A1800145) contains supplementary materials, which are available to authorized users

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After soil compaction, instrumentation, transplantation, and the adaptation period of three months, both soil columns were subjected to one drying-wetting cycle. To achieve the same initial testing condition, the two columns were saturated before the drying-wetting cycle. This was performed by applying constant-head ponding of 0.09 m to each soil column, and stopped when all tensiometers recorded zero suction and there was percolation from the bottom of the columns. It took over 13 d to saturate the soil columns. The constant-head ponding was then reduced to 0.015 m in both columns because the hole on the wall of each column was at an elevation of 0.015 m above the soil surface. Even though the tensiometers showed zero, the soil layers may not have been fully saturated because water infiltration by ponding may trap air bubbles in the soil layers. The free drainage bottom that was open to the atmosphere minimized the possibility of local compression of entrapped air within the soil columns. The drying test was then carried out. During drying, the top boundary was exposed to laboratory atmospheric conditions (a temperature of (20±5) °C and relative humidity of (60±10)%), while draining was allowed at the bottom boundary of the columns. The side boundaries were impermeable for both the drying and wetting tests. The drying test was terminated when the measured suction was close to 90 kPa (maximum suction measured by the tensiometer). The drying test lasted for 104 d and the measured suction profiles of the different soil layers are shown in Fig. 1.

The wetting test was then conducted. Similar to the saturation stage, a constant-head ponding of 0.09 m was applied to the soil surface of each soil column. The bottom boundary was opened for percolation measurement. The wetting test lasted for 7 d after reaching the steady state condition. After testing, the vertical depth and lateral width of the root zone were examined by flushing water on the soil surface. The depth of the root zone could be seen from outside through the transparent column wall. The vertical root zone depth of the shrub (d_r) was 0.2 m and the average lateral width (l_r) was the whole column diameter of 0.28 m. The value of d_r was used as reference when interpreting the measured suction during drying and wetting.

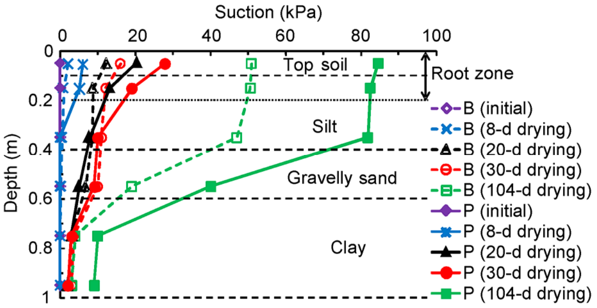

Fig. 1 Measured suction distribution profiles of the bare soil column (B) and planted soil column (P) during drying

3 Test results and discussion

3.1 Effects of shrub on soil suction distribution during drying

Fig. 1 shows the measured suction distribution profiles of the bare and planted soil columns during drying from a nearly saturated condition. The measured d_r of 0.2 m is shown in the figure for a reference. The initial suction at all depths of each soil column was 0 kPa consistently. After 8 d of drying, the suction within the root zone (i.e. at depths of 0.05 and 0.15 m) of the planted soil column increased to about 6 and 5 kPa, respectively. At the same time, no significant suction had developed at the corresponding depths of the bare soil column. As expected, the suction recovery of the planted soil column was faster than that of the bare soil column due to plant transpiration in addition to soil evaporation. Note that there was an initial surface ponding of 0.015 m on the soil surface of both soil columns at the beginning of the drying test (discussed in previous section). Hence, the evaporation and transpiration processes were inhibited by the saturated condition of the soil layers, in which soil aeration is poor (Feddes et al., 1976), during the initial stage of the drying test. Suction recovery can be a primary function of the initial soil conditions before drying, atmospheric conditions (Woon et al., 2011), and plant parameters such as the leaf area and root area indexes. All suction measurements below the root zone (0.2 m deep) remained close to 0 kPa in both soil columns. Therefore, after 8 d of drying, the depth of influence of suction due to soil evaporation and plant transpiration was restricted to within the root zone (0.2 m deep).

After 30 d of drying, the suction of both soil columns increased to some extent down the whole column depth of 1 m. The suction of the planted soil column was about 58% to 75% higher than that of the bare soil column within the root zone. But the suction of both columns below the root zone was approximately equal. This means that while soil evaporation had an effect down the whole depth of 1 m, plant transpiration occurred mainly within the root zone, where it induced significant suction. Generally, the vertical suction influence zone of both soil columns due to soil evaporation was 1 m (five times the root depth) after 30 d of drying. After 104 d of drying, the measured suction in both soil columns had increased substantially. Generally, the increasing suction trend was the same in both soil columns. The maximum suction in the planted soil column (85 kPa) was 0.6 times higher than that in the bare soil column (52 kPa). The measured suction in the planted soil column was about 60% to 200% higher than that in the bare soil column at different depths down to the bottom of the soil column (1 m). Since both soil columns were tested under identical atmospheric and test conditions, the increased suction in the planted soil column shows the additive effect of plant transpiration. Past laboratory (Ng et al., 2013a, 2013b, 2016a; Garg et al., 2015a) and field (Garg et al., 2015b; Ni et al., 2017) studies also reported higher induced suction in planted soil. However, those studies were conducted in uniform soil less than 0.5 m thick. The suction influence depth may be difficult to estimate accurately in a shallow uniform soil layer. The suction influence depth of uniform soil (0.28 m thick) in the study of Ng et al. (2013a) after 20 d drying was not conclusive, while an influence depth of about 1 m after 20 d drying was estimated in this study. We also observed that a constant suction profile was obtained in the topsoil and silt layers of both soil columns after 104 d drying. This means that the hydraulic gradient was about 1, and the water flow in these layers was driven mainly by gravity (Ng et al., 2013a, 2013b). If the underlying GS layer was replaced by the silt, the depth of the constant suction profile would extend further downward. Thus, a suction of 80 kPa should be expected at a depth of 0.6 m for a uniform silt layer. However, the GS had a lower water retention capability than the silt leading to a smaller induced suction due to plant transpiration (Fig. 1). In both soil columns, a strong suction gradient between the silt and clay layers could be seen. However, due to the low unsaturated hydraulic conductivity of the GS layer, the clay layer still maintained a high degree of saturation (or low suction) after being subjected to a drying period of 104 d.

Past studies using replicated tests showed that the suction induced by plant transpiration was not influenced significantly by either different shoot lengths or variability in the leaf area index (LAI) (Ng et al., 2013a; Leung et al., 2015). Hence, the measured suction based on a single planted soil column can still provide a qualitative description of the effects of plant transpiration on the induced suction in a three-layer soil cover. To quantify the effects of plant variability on the induced suction, more replicated tests are required.

3.2 Effects of shrub on cumulative infiltrated water volume during wetting

During wetting, the cumulative volume of infiltrated water in the soils was calculated by recording any changes of water level in the constant-head water supply system. Fig. 2 shows the measured cumulative volume of infiltrated water in the bare and planted soil columns during 7 d of wetting. The volume increased at decreasing rates in both soil columns. After applying the constant-head ponding of 0.09 m, the cumulative amount of infiltrated water in the bare soil column increased rapidly for 8 h, steadily from 8 to 72 h, and then gradually from 72 to 168 h. In the planted soil column, the cumulative amount of infiltrated water increased rapidly for 12 h, then gradually from 12 to 168 h. The cumulative volume of infiltrated water in the planted soil column was higher than that of the bare soil column. From 2 to 8 h, the cumulative volume of the planted soil column was around 20% higher than that of the bare soil column. The greatest difference, of about 37%, occurred after 12 h, and the smallest difference, of about 6%, between 72 and 96 h. After 168 h (i.e. the end of constant-head ponding), the cumulative infiltrated water volume of the planted soil column was higher by about 18%.

In general, planted soils may have either lower or higher water infiltration than bare soils. Some studies (Huat et al., 2006; Leung et al., 2015) showed that planted soil exhibited lower water infiltration than bare soil, but others (Zhan et al., 2007; Ng et al., 2014; Li et al., 2016) reported that planted soil can exhibit higher infiltration. Compared to bare soils, the water infiltration in planted soils is lower when the roots are actively growing and higher when they have decayed (Barley, 1954; Mitchell et al., 1995; Ng et al., 2014). The age of the shrub in this study was over one year. There may have been a preferential flow path caused by some mature roots. There might also have been preferential flow between the soil and the wall of the soil column when the roots grew along the wall.

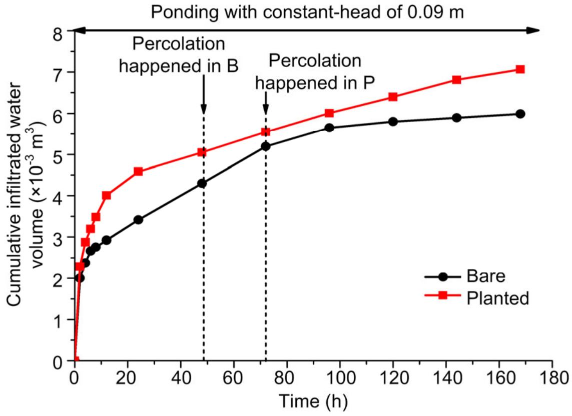

Fig. 2 Measured cumulative infiltrated water volume in the bare soil column (B) and the planted soil column (P) during wetting

3.3 Effects of shrub on suction distribution during wetting and the effectiveness of landfill cover in preventing water percolation

Fig. 3 shows the measured suction distribution profiles of the bare and planted soil columns during wetting. The measured d_r of 0.2 m is also shown in the figure as a reference. After applying the constant-head ponding of 0.09 m, the suction at a depth of 0.05 m (within the root zone) in the topsoil layer of both soil columns became 0 kPa after 4 h. In fact, the measured suction in both soil columns had declined to 0 kPa in less than 1 h. A similar rapid reduction in measured suction at 0.03 m for both planted and bare soils was observed by Woon et al. (2011), despite a higher suction measured in the planted soil. However, a suction of 4 kPa in the bare soil column and 8 kPa in the planted soil column was retained at a depth of 0.15 m (within the root zone). At a depth of 0.35 m (below the root zone), a suction of 20 kPa in the bare soil column and 63 kPa in the planted soil column was observed. Therefore, after 4 h of wetting, the suction retained in the planted soil column was 100% higher than that in the bare soil column at a depth of 0.15 m (the lower part of the root zone), and over 200% higher at a depth of 0.35 m (below the root zone). After 8 h, the suction at depths of 0.15 and 0.35 m in the bare soil column was almost zero. On the other hand, the suction at those depths in the planted soil column remained at 5 and 30 kPa, respectively. Thus, the ability to retain suction in the planted soil was obviously higher than that in the bare soil because of its initial higher suction (by from 60% to 200%) before wetting. Ng et al. (2013a) also verified that an initial higher suction (about 70%) of planted soil at 0.08 m retained 40% higher suction after wetting when compared to bare soil. However, they applied the same amount of irrigation to both soils for wetting. Leung et al. (2015) observed that suctions retained in vegetated soil were always higher than those in bare soil, but their water infiltration in planted soil was less than that in bare soil by up to 50%. In this study, the infiltrated water volume in the planted soil column was over 20% higher than that in the bare soil column, but 100% of the suction was retained at a depth of 0.15 m and 200% at a depth of 0.35 m, after 4 h of wetting. Therefore, it can be concluded that planted soil can retain a higher suction than bare soil, regardless of whether the infiltration of water is lower or higher.

After 12 h of wetting, the suction in the GS layer of the bare soil column decreased from 19 to 16 kPa, whereas in the planted soil column, the suction remained unchanged. The suction in the GS layer of the planted soil column began to reduce after 24 h of wetting. This means that by that time the infiltrated water had entered the GS layer and the effectiveness of the upper two-layer CCBE in preventing water infiltration had failed. The suction in the GS layer decreased to near 0 kPa in the bare soil column after 36 h of wetting, and in the planted soil column after 48 h of wetting, because of continuous water infiltration.

The GS layers of both soil columns were almost saturated and the upper two-layer CCBE was not effective. Therefore, the upper two-layer CCBE was effective during 8 h of wetting in the bare soil column and during 12 h of wetting in the planted soil column. The validation of the upper two-layer CCBE was consistent with the water infiltration discussed in the previous section. The effectiveness of the upper two-layer CCBE was maintained for 4 h longer in the planted soil column, in spite of having a higher cumulative volume of water infiltration (26% at 8 h and 37% at 12 h) compared to the bare soil column.

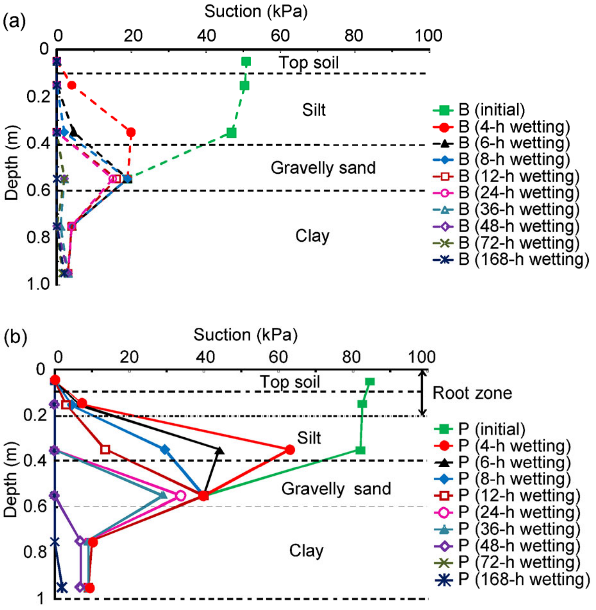

Fig. 3 Measured suction distribution profiles of the bare (a) and planted (b) soil columns during wetting

In the bare soil column, after 36 h, the suction in the upper part of the clay layer (0.75 m deep) had decreased from its initial value of 4 kPa to 1 kPa, and reached 0 kPa after 36 h. The suction in the lower part of the clay layer (0.95 m deep) had decreased from its initial value of 3 kPa to 2 kPa after 72 h. In the planted soil column, after 48 h of wetting, the suction in the clay layer (at depths of 0.75 m and 0.95 m) had decreased from its initial value of around 10 kPa to 7 kPa. After 72 h, the suction at 0.75 m deep had fallen to 0 kPa, and at 0.95 m deep had decreased to 2 kPa. A suction of 2 kPa was retained in the lower part of clay layers (0.95 m deep) of both soil columns from 72 to 168 h. However, this suction pressure was within the measurement accuracy of the tensiometers.

Note that the water infiltration was 1D and there was no lateral drainage in this study, thus representing a worst case scenario for a landfill cover under rainfall infiltration (Ng et al., 2016c). No percolation was observed at the bottom of either soil column during 48 h of wetting. Percolation was observed after 49 h in the bare soil column and after 72 h in the planted soil column. Despite the planted column having a higher infiltration rate, it exhibited a higher initial suction (or lower initial water content) before wetting. Thus, the upper silt layer in the planted column could retain more infiltrated water due to the lower initial water content. As a result, a lower percolation rate was expected for the planted column and it took 23 h longer for the water to percolate to the bottom than in the bare column. Note that if the water flux at the top boundary of the column was applied long enough to cancel the additional water storage capacity in the silt layer of the planted column, more water should percolate through the planted column in the long run because of its higher infiltration rate than in the bare column.

4 Conclusions

Based on the results from drying-wetting tests on two soil columns (one with shrub and the other bare), the following conclusions can be drawn:

1. After 104 d of drying from a nearly saturated condition, measured suction in the planted soil column due to plant transpiration was from 60% to 200% higher than in the bare soil column to a depth of 1 m. The peak suction in the planted soil column (85 kPa) was 0.6 times higher than that in the bare soil column (52 kPa). The vertical suction influence zone of the planted soil column was nearly five times the root depth (0.2 m) after 20 d of drying. The role of the GS layer in "protecting" the clay layer can be clearly seen by the strong suction gradients during drying. As a result, the measured suction in the bottom clay layer was only about 10% of that measured within the top 0.4 m of each column.

2. The cumulative volume of infiltrated water in the planted soil column was higher than that of the bare soil column during the wetting test. The greatest difference, about 37%, was observed after 12 h of wetting, and after 168 h (the end of constant-head

ponding) the difference was 18%. The reason for these differences may have been a preferential channel flow caused by the root system.

3. The suction retention capacity during wetting in the planted soil column was significantly higher than that in the bare soil column, especially in the lower part of the root zone and deep below the root zone. At these depths, after 4 h of wetting, the suction in the planted soil column was 100% to more than 200% higher than that in the bare soil column.

4. The upper two-layer CCBE was effective during 8 h of wetting in the bare soil column and 12 h in the planted soil column, despite higher water infiltration in the planted soil column (26% higher after 8 h and 37% higher after 12 h). This may have been due to the higher initial suction induced by plant transpiration, resulting in a higher water retention capacity in the upper silt layer of the planted column.

5. Suction remained unchanged during 48 h of wetting in the clay layers in both soil columns. Percolation from the bottom was observed after 49 h in the bare soil column, and after 72 h in the planted soil column. Despite the planted column having a higher infiltration rate, it exhibited a lower percolation rate because of the higher initial water storage capacity of the upper silt layer. However, the planted column should percolate more water if the infiltration is applied long enough to cancel the effects of initial high suction on the water storage capacity.

Contributors

Sandar LIN, Jie XU, Charles W.W. NG, and Rui CHEN analyzed the data and wrote the first draft of the manuscript. Charles W.W. NG acquired research funding, supervised the research project, and validated the research output. Sandar LIN, Rui CHEN, Jian LIU, Zhong-kui CHEN performed the experiments and data collection. Chung Fai CHIU revised and edited the final manuscript.

Conflict of interest

Sandar LIN, Charles W.W. NG, Jie XU, Rui CHEN, Jian LIU, Zhong-kui CHEN, and Chung Fai CHIU declare that they have no conflict of interest.

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List of electronic supplementary materials

Data S1 Experimental

中文概要

题　目：灌木对三层填埋场覆盖系统一维吸力分布和水分入渗的影响

目　的： 研究灌木对干燥和湿润过程中三层土质覆盖系统的吸力分布的影响。

创新点： 发现对于三层土质覆盖系统，干燥过程中植物蒸腾作用不仅提高了土的吸力，同时也增加了土层之间的吸力梯度（图 3）。

方　法： 通过土柱试验模拟干燥和湿润过程，并测量吸力的变化。

结　论： 1. 植物蒸腾作用导致植有灌木的土在干燥过程中所产生的吸力较没有植物的土高 60%~200%。
2. 植物蒸腾作用提高了植有灌木的土的持水能力；在湿润过程中水分穿透植有灌木的土所需时间比没有植物的土长 50%（图 3~4）。

关键词： 灌木；填埋场覆盖系统；吸力；土柱试验