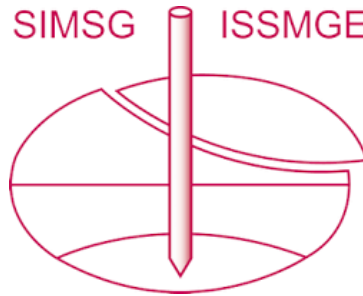


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Exploring hydrological effects of plant height on geotechnical infrastructures

Analyse des effets hydrologiques de la hauteur des plantes sur les infrastructures géotechniques

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ABSTRACT: Construction and maintenance of geotechnical infrastructures are always accompanied by local plants unintentionally or intentionally. Plants can induce and retain additional soil suction by root water uptake, which is significantly affected by plant natural variability in morphology. However, plant morphological effects on different geotechnical infrastructures (e.g. slopes, embankments and landfill cover) are rarely discussed. This study aims to explore the effects of one of the most representative plant characteristics, plant height, on induced and retained suction distribution and infiltration in drying and wetting process. Laboratory tests were conducted using *Schefflera Heptaphylla* in cylindrical model drums. Soil suction distributions of twenty individuals with various morphology were monitored during a typical drying-wetting cycle in subtropical climate. Taller plants, generally with larger leaf area (LA) appear to have more efficient water uptake when drying. However, they not always induce higher local suction especially near centre of root zone, as their total water uptake are dispersed in generally larger root zones. Shorter individuals tend to induce shallow local excessive suction, while taller ones induce more evenly distributed suction and higher suction at deep depth. Infiltration rate for taller plants during prolonged rainfall also appears higher. Consequently, taller plants with larger LA and root depth likely promote slope stability better by retaining higher soil shear strength near deep located failure plane. The higher infiltration rate of taller plants can reduce surface runoff and soil erosion. Taller plants also reduce percolation, which is desirable for designing landfill cover system.

RÉSUMÉ : La construction et l'entretien des infrastructures géotechniques sont toujours accompagnés par des plantes locales, de façon involontaire ou intentionnelle. Les plantes peuvent induire et retenir une succion supplémentaire du sol par l'absorption d'eau par les racines, qui est considérablement affectée par la variabilité naturelle de la morphologie des plantes. Cependant, les effets morphologiques des plantes sur différentes infrastructures géotechniques (par exemple, les pentes, les remblais et la couverture des décharges) sont rarement analysés. La présente étude vise à explorer les effets de l'une des caractéristiques les plus représentatives des plantes, la hauteur des plantes, sur la distribution de la succion induite et retenue et sur l'infiltration dans les processus de séchage et de mouillage. Des tests de laboratoire ont été effectués en utilisant *Schefflera Heptaphylla* dans des tambours modèles cylindriques. Les distributions de succion du sol de vingt individus de morphologie différente ont été suivies pendant un cycle typique de séchage-humidification en climat subtropical. Les plantes plus hautes, généralement avec une plus grande surface foliaire (LA) semblent avoir une absorption d'eau plus efficace lors du séchage. Cependant, elles n'induisent pas toujours une aspiration locale plus élevée, en particulier près du centre de la zone racinaire, car leur absorption totale d'eau est dispersée dans des zones racinaires généralement plus grandes. Les individus plus courts ont tendance à induire une succion locale excessive à faible profondeur, tandis que les plus grands induisent une succion plus uniformément répartie et une succion plus élevée à grande profondeur. Le taux d'infiltration pour les plantes plus grandes lors de pluies prolongées semble également plus élevé. Par conséquent, les plantes plus hautes avec des LA et des racines plus profondes favorisent probablement une meilleure stabilité des pentes en retenant une plus grande résistance au cisaillement du sol près du plan de rupture situé en profondeur. Le taux d'infiltration plus élevé des plantes plus hautes peut réduire le ruissellement de surface et l'érosion du sol. Les plantes plus hautes réduisent également la percolation, ce qui est souhaitable pour la conception du système de couverture des décharges.

KEYWORDS: vegetation; suction; infiltration.

1 INTRODUCTION

The application of vegetation to solve geotechnical problems has been widely explored, such as the stability of man-made/natural slopes (Greenwood et al., 2004; Hubble et al., 2010; Rahardjo et al., 2014), water storage capacity in evapotranspirative landfill covers (Cureton et al., 1991; Rianna et al., 2014; Ng et al., 2016) and differential settlement problems of railway caused by perched water table or seasonal shrinkage and swelling (Fatahi et al., 2010; Powrie and Smethurst, 2018). The major threats for the safety of these geotechnical infrastructures are large infiltration during heavy rainfall and wetting induced soil deformation (Tsaparas et al., 2003; Luino, 2005). As a countermeasure, vegetation could introduce plant root water uptake to induce soil desaturation and additional matric suction (Garg et al., 2015; Leung et al., 2015a; Ng et al., 2016). The induced soil suction

would result in a decrease in soil permeability (Ng and Menzies, 2007; Ng and Leung, 2012) and an increase in soil shear strength (Ng and Menzies, 2007). Some studies have revealed that water uptake of plants and stability of slopes could be significantly influenced by plant characteristics (Genet et al., 2008; Ng et al., 2019; Ng et al., 2021). However, it is still a common challenge to select plants with proper characteristics in practice to ensure the engineering performance of plants, caused by the rare quantitative study on effects of plant morphology on soil suction distribution and infiltration during typical wetting and drying cycles.

Among all the plant morphological characteristics, such as leaf area (LA) and root length (RL), plant height is a representative and easily measurable parameter. Although previous studies have shown that plant age and gene are the dominant factor for all plant characteristics, most plant

individuals have inner correlations between different characteristics, tending to have larger leaf area and root length with relatively greater plant height (O'Brien et al., 1995; Forrester et al., 2010). Therefore, a potential empirical approach to control plant engineering performance by selecting plant with height could be designed. It requires comprehensive studies on effects of plant height on plant-soil interactions during different climate conditions.

The objective of this study is to investigate the effects of plant height on soil matrix suction and infiltration rate during a typical drying and wetting cycle. A series of tests were conducted in solar radiation, temperature and humidity controlled room. The tests were conducted with *Schefflera heptaphylla*, a typical tree species in tropical and semi-tropical regions, which are commonly used for engineering or ecological restoration purposes. Twenty tested individuals were carefully selected in three different height groups. Samples experienced a six-day drying (the average drying duration in Hong Kong) followed by a ten-year return period rainfall. Water infiltration and two-dimensional distribution of soil suction were continuously monitored. The results were analysed combined with plant height, leaf and root characteristics to evaluate any effects of plant height on soil suction and infiltration rates.

2 MATERIALS AND METHODS

2.1 Test Setup and Instrumentation

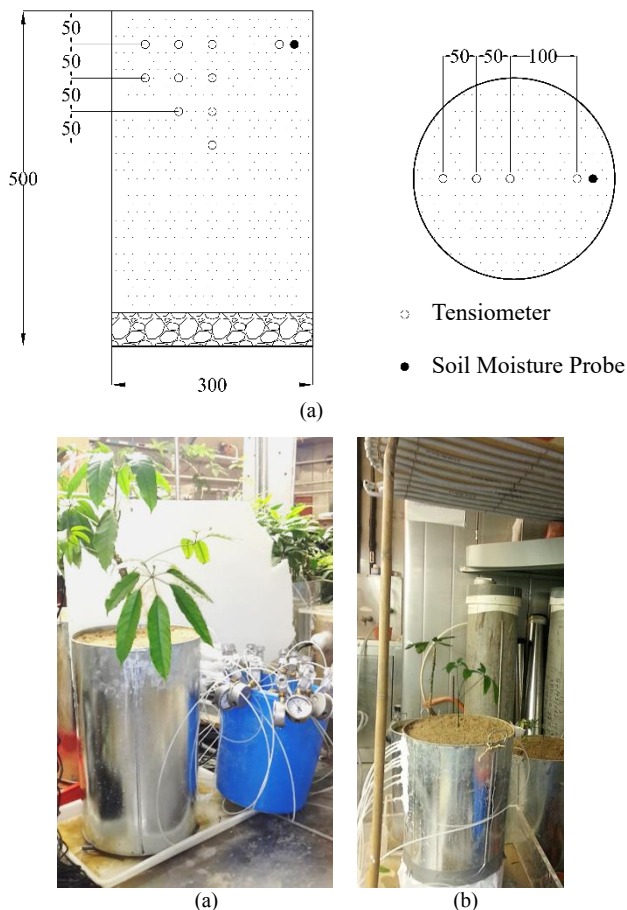


Figure 1. The overview of (a) drying tests and (b) wetting tests.

A total of 21 tests were conducted, with 1 test for bare soil (control), 8 tests for individuals around 500 mm tall (series S500), 6 tests each for height group of 300 mm (series S300) and 800 mm (series S800). As shown in Fig. 1, all tests were conducted in aluminum alloy drums with a height of 500 mm and

a diameter of 300 mm. A 50-mm-thick layer of gravel was placed at the bottom of each drum to facilitate free bottom drainage condition. All bare and vegetated tests were conducted in an atmosphere-controlled plant room where air temperature, wind speed, humidity and solar radiation were controlled. The air temperature and humidity were kept at $25 \pm 1^\circ\text{C}$ and $60 \pm 5\%$, respectively. Wind speed was zero. Light was provided by cool white fluorescent lamps with an intensity of around $120 \mu\text{mol}/\text{m}^2/\text{s}$ near leaf surface in the 400–700 nm waveband, which is beneficial for the growth and photosynthesis of the plant individuals (Ng et al., 2016).

In each drum, ten tensiometers were installed vertically and horizontally with a spacing of 50 mm to measure suction. Silicon grease was added around the gap of each installation hole to prevent the horizontal drainage and evaporation. Four of the tensiometers were installed at the centreline of the root zone, while the others were distributed uniformly on the same vertical plane. Two tensiometers were installed both at the depth of 50 mm and the distance of 100 mm away from the centreline of root zone with the aim of measuring soil water retention curve (shown in Appendix).

2.2 Properties of Soil and Plants

In this study, completely decomposed granite (CDG) was used for testing. The results from standard Proctor tests show that the maximum dry density is $1870 \text{ kg}/\text{m}^3$, corresponding to the optimum volumetric water content of 12%. The gravel, sand, silt and clay contents of the CDG were 19, 42, 27 and 12%, respectively. The plastic limit and liquid limit of CDG are 26 and 44%, respectively. According to the Unified Soil Classification System (ASTM, 2011), CDG is classified as silty sand. In this study, CDG was compacted to a degree of compaction (DOC) of 95%, which is common for practical engineering projects, such as slope design requirements in Hong Kong (GEO 2011) and suitable for plant survival and germination of roots and leaves (Ng et al., 2016).

Schefflera heptaphylla was selected as tested species in this study. It is widely grown in tropical or semi-tropical countries, such as southern China, Japan, Vietnam and India (Hau and Corlett, 2003). The purpose of selecting *Schefflera heptaphylla* is for its significant ornamental and ecological value for slope rehabilitation and reforestation (GEO 2011) and its high drought resistance (Hau and Corlett, 2003). Before transplantation, the tested individuals were raised together in a nursery under identical soil and atmospheric conditions. Each individual was transplanted to drum over 3 months before each test. The 3-month duration is for trees to recover root water uptake ability, adapt to the environment in laboratory and repair the potential damage to root caused by transplantation (Kitao et al., 2006).

2.3 Test Procedures

The soil in each drum was initially wetted with de-aired water from the top by applying a constant water head. After the process of initial wetting, planted cylindrical drums were kept in the atmosphere-controlled plant room, with soil surface exposed to atmosphere, setup as shown in Fig. 1(a). No further water was supplied during the drying stage. Soil surface was kept uncovered for any soil surface evaporation throughout the tests. The involvement of evaporation enables the tests to simulate natural evapotranspiration process and better evaluate the actual suction inducing ability of tested plants. The drying process lasted for 6 days, which is the average length of drying days in Hong Kong (Peacock, 1972).

Immediately after the drying, rainfall with an intensity of $73 \text{ mm}/\text{hr}$ was supplied by the rainfall simulator placed above the top of plant, as shown in Fig. 1(b). The rainfall was continuously supplied by 2 hours, which is equivalent to the return period of 10 years in Hong Kong (Lam and Leung, 1995). The entire

experiments simulated typical drying and wetting cycles for the climate in Hong Kong. The readings of tensiometers were taken every 5 minutes. The runoff at soil surface and percolation at drum bottom were collected by two separate containers. As water without running off is infiltrated, the infiltration rate shall be deduced accordingly.

After the completion of wetting and drying stages, plant morphological characteristics, including LA, RL and root length density (RLD), were measured. The image of each leaf placed on a grid paper was taken by a high-resolution camera. LA was then determined by image analysis (Photoshop CS6) of each leaf and summarizing surface areas of all leaves together. Roots were excavated after each test for measurements of RL and RLD. RLD is defined as RL per unit volume of soil. RL was measured by partitioning the excavated root system into single root hairs without branches. The length of each root was measured by ruler and then RL is obtained by summing up all root lengths. By knowing the total root length within a given soil volume ($50 \times 50 \times 50 \text{ mm}^3$), RLD can be calculated.

3 RESULTS AND INTERPRETATIONS

3.1 Correlations of leaf area and root length with height

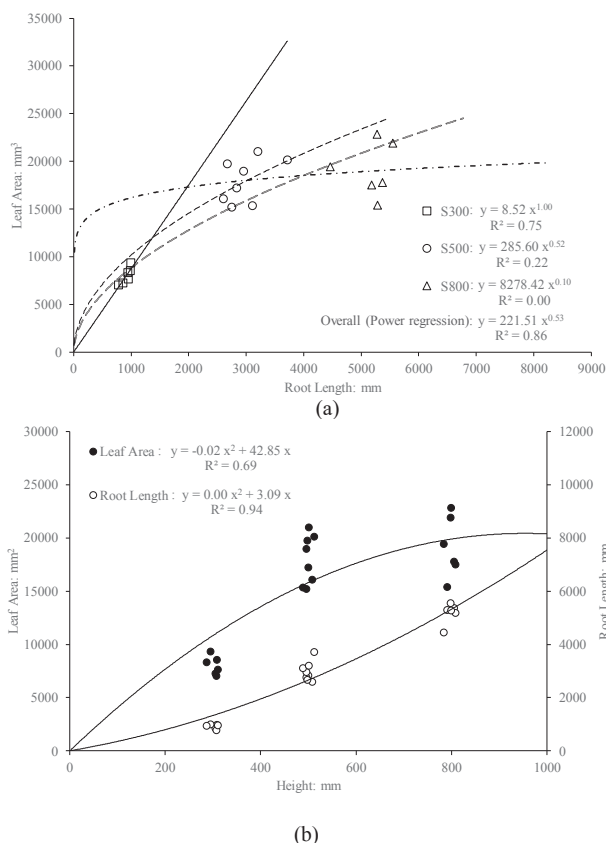


Figure 2. (a) Correlations of leaf area and root length; (b) Correlations of leaf area and root length with plant height.

Figure 2 shows the relationships among plant height, LA and RL. Power regression is taken due to previous observations that LA and RL follow power relationship (Liu et al., 2010). As shown in Fig. 2(a), LA and RL show clear correlations for S300 with 0.75 R-squared, but the relevance is not significant for S500 and S800 with R-squared equal or lower than 0.22. The low relevance of LA and RL for plants with similar heights may be due to rapid leaf litter decay (Lowman, 1988), which is not remarkable for very short trees with leaves mostly just germinated. It is proved by Fig. 2(b), showing high variations of LA for S500 and S800

with about 50% difference between the maximum and the minimum.

On the other hand, as shown in Fig. 2(a), LA and RL show a remarkable power relationship with R-squared as high as 0.86, when tests with all plant heights being considered. The high relevance is mainly caused by effects of plant height on LA and RL shown in Fig. 2(b). Both LA and RL are in power relationship with plant height with R-squared over 0.69. The strong correlations may be the result of plant growing effects. Plant height, leaf and root characteristics have been observed related to plant age (Yu et al., 2007). Moreover, as shown in Fig. 2(b), the increasing rate of LA reduces with plant height, while that of RL is increasing. It is probably because of the one-dimensional growth in height, three-dimensional growth in RL and decelerating growth in LA with natural decay (Svejar 1990). It explains why LA increases with RL at a reducing rate in Fig. 2(a).

3.2 Root Architecture of trees with different heights

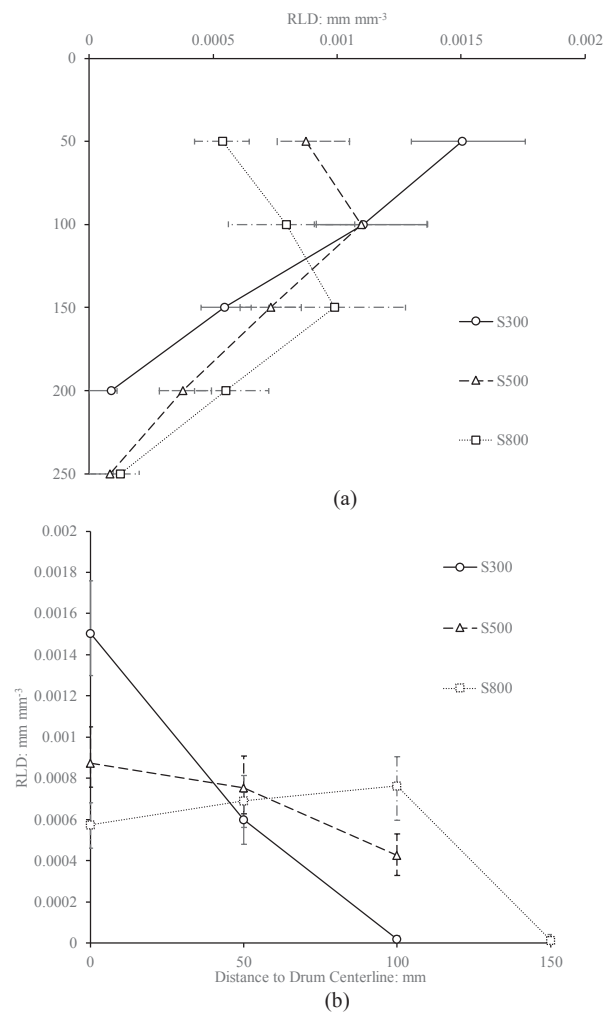


Figure 3. Distributions of root length density (RLD) in (a) vertical direction along drum centreline and (b) radial direction at 50 mm depth.

Figure 3(a) shows the vertical distributions of RLD along drum centreline. Taller individuals tend to have larger root depth, from 200 mm for S300 to 350 mm for L1200. The depth of peak RLD is also observed deeper for taller plants, from 50 mm depth for S300 to 200 mm depth for L1200. The increase of root depth and the shift of peak location of RLD imply that taller Schefflera heptaphylla tend to grow roots at deeper depth, in order to enhance the water uptake ability in deep soil. Similar growing pattern is also found by Garg et al. (2015b) testing the same

species. Meanwhile, it is interesting to find that the RLD at 50 mm depth decreases with plant height for S300, S500 and S800. It is because very short plants develop mostly long and dense fine roots in this region, while mainly coarse roots are observed near the centre of root zones for relatively tall individuals. It has been proved that fine roots contribute more to root length density and water uptake ability than coarse roots (Gwenzi, 2011).

Fig. 3(b) shows RLD distribution along radial direction at 50 mm depth. RLD is maximum at drum centreline for S300, but the peak of RLD shift farther to drum centreline for taller plants. For S800, the maximum RLDs locate at 100 mm away from drum centreline. In addition, root zone is observed to spread farther to drum centreline for taller plants, from 50 mm for S300 to over 100 mm for S800. The growing pattern of *Schefflera Heptaphylla* shown above may be resulted by different water and nutrient availability in soil (Coutts, 1989; Rhizopoulou and Davies, 1991) and gene of trees. The enlargement of root zone and the shift of peak RLD enable taller trees to absorb the water from a larger scope and prevent generating excessive local soil suction along plant centreline, which may inhibit root water uptake ability and growth.

3.3 Drying induced soil suction distribution

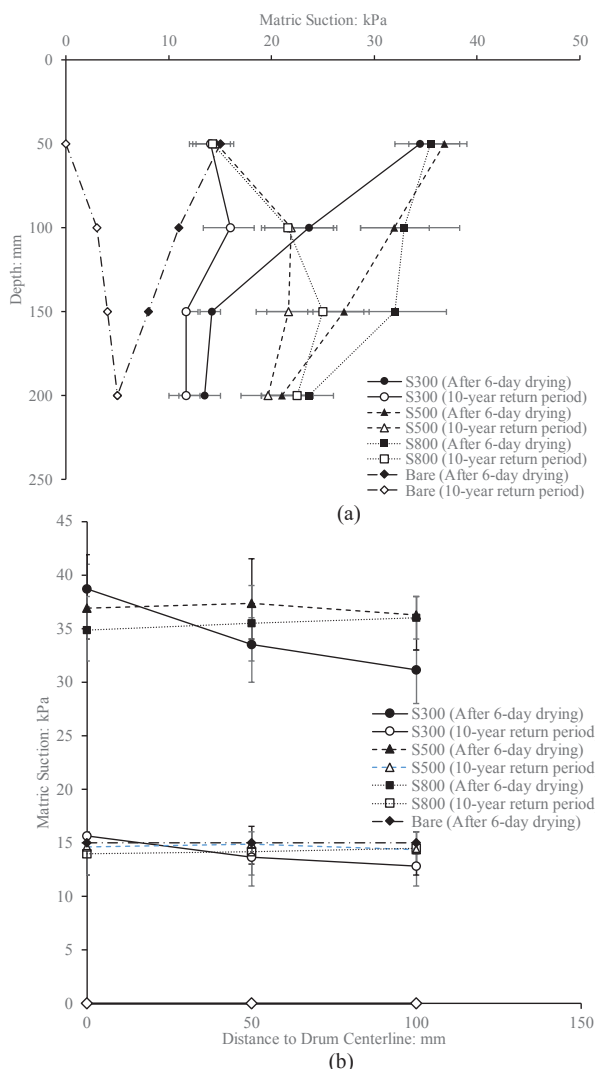


Figure 4. Measured matric suction and calculated WUI distribution in (a) vertical direction and (b) radial direction (after 6-day drying and 10-year return period rainfall).

Figure 4 shows the measured suction distribution of small drum tests after drying for 6 days and rainfall likely happening every

10 years. As shown in Fig. 3(a), soil suction is observed to decrease along depth for all plotted series instead of peaking where highest RLD appears in Fig. 3. It is attributed to combined effects of root water uptake and evaporation, more significant in shallow soil. The induced suction increases with plant height, except the observation that the greatest average suction at 50 mm depth is generated by S500, not the greatest or the smallest plant height. It may be explained by the distribution of RLD, which is reflecting local root water uptake ability. RLD at 50 mm depth reaches its maximum for S300 and decreases with plant height. However, as shown in Fig. 3(b), RLD drops dramatically for S300 in radial direction away from centreline, but RLD for S800 increases. It suggests that suction at 50 mm depth along centreline for S300 is mainly induced by local intensive root water uptake, but that for S800 is mainly a consequence of the root water uptake at a distance to centreline. Plants in S500 displayed both mechanisms shown by S300 and S800, hence inducing similar suction. It implies that applying taller individuals is not always the best solution for some specific engineering problems. Plants with a certain height may be more capable to induce suction at a certain depth, and further growth may harm plant engineering performance.

Figure 4 also attempts to relate plant height with size of root influence zone. As shown in Fig. 4(a), the induced suction from 50 mm to 200 mm depth decreases by 73.6%, 60.0% and 40.8% for S300, S500 and S800 respectively. In Fig. 4(b), the induced suction from 0 to 100 mm away from centreline decreases by 24.5%, 14.5% and 6.1% for S300, S500 and S800 respectively. The different decreasing rate tend to suggest that taller plants can induce additional soil suction at deeper depth and farther away from centreline. This is resulted by the larger root zone of taller plants shown in Fig. 3 with higher RLD near the boundary of root zone. The finding reveals the existence of optimal plant height when soil suction at a specific depth is required to be induced. The larger influence zone of taller plants also implies a more severe plant competition for water when closely planted.

3.4 Suction response of vegetated soil during rainfall

As shown in Fig. 4 as well, vegetated soil was found with higher suction than bare soil both before and after wetting in all measurements as expected. It illustrates the effectiveness of vegetation on inducing and retaining soil suction in different climate conditions. Meanwell, no significant correlations were observed between plant height and suction induced by drying or retained after rainfall at 50 mm depth along drum centre (one-way ANOVA, $n = 20$, $P > 0.05$). Little difference was detected at 100 mm depth for S500 and S800, either (one-way ANOVA, $n = 14$, $P = 0.6$ and 0.3 before and after rainfall). Otherwise, plant height appears to have positive effects on induced and retained soil suction with statistical significance (one-way ANOVA, $n = 20$, $P < 0.03$). It could be explained by the different root architecture for plant with different heights. According to the RLD distribution shown in Fig. 3, roots of S300 are mainly distributed in length at 50 mm depth near to the drum centre. The root water uptake of S300 was therefore concentrated there, compensating the negative effects of less transpiration and resulting in similar suction with other series locally. The effects are more evident in radial direction at 50 mm depth as shown in Fig. 4(a). Higher soil suction for S300 tended to be induced and retained near drum centre, while that for S800 happened 100 mm away from drum centre. In contrast, trees in S500 and S800 mainly distribute their roots at about 100 mm and 150 mm depth in Fig. 3(a), respectively. More roots were also observed away from drum centre for taller plants shown in Fig. 3. Plant height thus appears to have major effects on increasing suction induction and retention at deeper soil depth and away from centre, resulting in greater influence zone.

3.5 Effects of tree height on infiltration and percolation

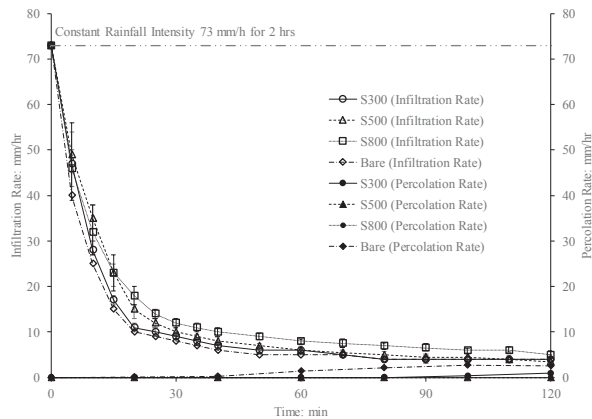


Figure 5. Measured variations of infiltration and percolation rates with time for bare soil and soil vegetated with a tree of about 300 mm (S300), 500 mm (S500) and 800 mm (S800) heights.

Figure 5 shows the measured variations of infiltration and percolation rate with time during the two-hour rainfall. No percolation was observed for S500 and S800, and slight percolation was observed for S300. However, significant percolation was observed in the bare soil after raining for 60 minutes and it eventually reached 87% of infiltration rate after the 10-year return period rainfall. The results reveal positive effects of vegetation, especially taller plants, on reduction of soil layer percolation.

In all series, infiltration rate decreased exponentially with time at a decreasing rate, agreeing with most previous studies (Leung et al., 2015b). Meek et al. (1990) and Murphy et al. (1993) observed reduced infiltration rates in soil wetting when plants are actively growing in plant height. It is interesting that the results in this study show no support on their conclusions, with no statistically significant influence of plant height to infiltration rate after 5 minutes of rainfall (one-way ANOVA, $n = 20$, $P = 0.451$). However, infiltration rate is found to be significantly affected by plant height in all measurements after 10 minutes of rainfall (one-way ANOVA, $n = 20$, $P = 0.003$), with S500 and S300 as maximum and minimum in series with vegetation. The change of significance level implies that some parameters other than plant height have significant effects only at early stage of rainfall. Afterwards, the significance level maintains high with rainfall duration longer than 15 minutes (one-way ANOVA, $n = 20$, $P < 0.01$), but infiltration rate shows maximum for S800 and decreases with plant height, opposite to findings by most previous researchers. Leung et al. (2017) had similar observations that infiltration rate had significant increase with plant age. One possible explanation is that plants in this study experienced a full drying-wetting cycle similar to natural conditions, while most infiltration tests reported in previous studies (Meek et al., 1990 and Murphy et al., 1993) were conducted on well wetted grounds. The larger induced soil suction by S800 during drying shown in Fig. 4 could cause higher hydraulic gradient at shallow soil surface, causing higher infiltration rate by Darcy's law. Plant height seems to take major effects on long term infiltration.

4 DISCUSSION

When related to practice in constructing different types of geotechnical infrastructures, the requirements for the vegetation being used are also different. This study could suggest different plant height selecting strategies for different demands in engineering practice.

For vegetating plants on slopes to enhance slope stability, taller plants with deeper root depth could be more appropriate. Slope shallow failures most likely happen at the depth of about 0.5 m. The depth is beyond the general root depth of most plants vegetated for engineering. It has been observed in Fig. 4 that taller plants can induce and retain higher suction at deeper depth. It could motivate higher soil shear strength at potential failure plane located below the bottom of root zone. The suction retained by 800 mm tall trees after 10-year return period rainfall at very low depth can be still as high as about 20 kPa.

When vegetation is introduced to reduce soil erosion or percolation, effects of plant height on water infiltration rate is the most significant factor to consider. As shown and discussed in Fig. 5, taller plants could induce higher prolonged infiltration rate. The higher infiltration rate of taller plants benefits the protection of soil erosion by reducing surface runoff and thus decrease soil mass being washed away. The results also show that taller plants could reduce percolation rate in landfill cover system. It could prevent leakage of water into landfill, which results in both safety and environmental problems.

Soil volume change and settlement are the key properties affecting the design of railway embankments. Based on this study, taller plants could induce higher change in soil water content, which could be a reason to increase soil volume change. According to Fig. 4, the suction change of taller trees before and after rainfall at all depths are higher. The suction change of taller trees, such as 800 mm tall trees, is from about 33 kPa to about 20 kPa, which is the desaturation zone in soil water retention curve shown in Appendix. However, different root growth could also affect the volume change of vegetated soil. Further studies should be conducted to verify the effects of plant height on soil volume change.

5 CONCLUSIONS

This study explore the effects of plant height of a tree species, *Schefflera Heptaphylla* on induced and retained suction distribution and infiltration in drying and wetting. Based on the test results obtained from 20 individuals in 3 different plant height groups in the laboratory, the following conclusions may be drawn:

Plant height can be considered as an engineering controlling parameter for plant selection due to significant positive effects of plant height on leaf area (LA) and root length (RL). Taller plants tend to shift their centre of root distribution deeper and away from plant centre. During drying, the resulted root distribution patterns could cause greater soil suction influence zone for taller plants and excessive soil suction at shallow depth for shorter plants. The findings reveal that taller plants are more capable to induce suction in wider range and deeper soil, but they are potentially weak in inducing shallow layer suction.

During and after rainfall, taller plants are more capable to retain suction in deep depths and thus more helpful to slope stability during rainfall. Soil suction before rainfall appears to have larger variations laterally for shorter plants. Soil vegetated by taller individuals has greater infiltration rate and lower percolation during prolonged rainfall. This could also benefit soil erosion protection and landfill cover system. However, taller plants could induce greater change in soil water content during drying and wetting, which could possibly be a reason for larger soil volume change.

6 ACKNOWLEDGEMENTS

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8 APPENDIX

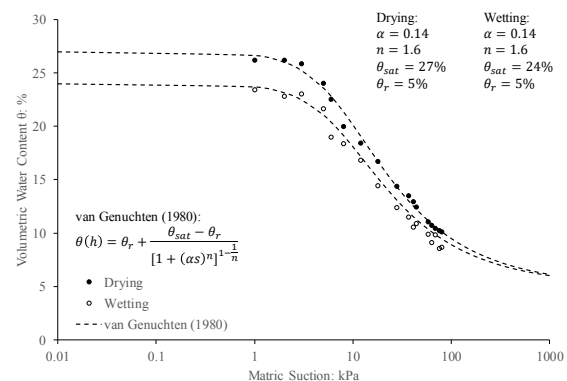


Figure A1. Measured and fitted soil water retention curve (SWRC) of CDG.