Effects of plant characteristics and soil type on transpiration reduction

J. J. Ni, C. W. W. Ng & H. W. Guo
Department of Civil and Environmental Engineering, the Hong Kong University of Science and Technology, Hong Kong

ABSTRACT: Plant transpiration affects soil matric suction in geotechnical infrastructures, such as vegetated slopes. Understanding the response of plant transpiration to soil suction (i.e., transpiration reduction) is important to quantify soil suction scientifically. This study investigated the effects of plant characteristics (LAI, leaf area index) and soil type on transpiration reduction. One tree species (*Schefflera heptaphylla*) with various LAIs was transplanted in small pots. Completely decomposed granite (silty sand) and kaolin clay were used as soil media, respectively. In total, 6 tree seedlings (4 planted in silty sand and 2 planted in clay) were subjected to drying tests. The results show that at larger LAI, plant transpiration decreased more rapidly with soil suction. Plant transpiration was more sensible to soil suction when transplanted in clay. Threshold value of transpiration reduction in clay (36 kPa) was 55% smaller than that in sand (80 kPa). Plants with LAI of 2.8 can induce 4 times higher suction than plants with LAI of 1.0 after 4 days of drying, while the difference was only 50% after 8 days of drying, due to much faster reduction of transpiration at larger LAI.

1 INTRODUCTION

Soil bio-engineering using vegetation has become popular in stabilizing slopes (Smethurst et al. 2015; Garg et al. 2017). Besides its mechanical root reinforcement, evapotranspiration-induced soil suction increases factor of safety significantly, as induced suction decreases soil permeability and increases soil shear strength (Ng and Menzies, 2007). It is thus important to quantify soil suction accurately in vegetated soils.

Transpiration reduction function refers to the ratio of actual to potential transpiration rate of plant with soil suction (Feddes et al., 1978). It indicates the root water uptake ability under different soil suction levels. There are some empirical transpiration reduction functions widely used in geotechnical fields, such as the models proposed by Feddes et al. (1978) and van Genuchten (1987). In Feddes et al. (1978) model, when soil suction is lower than an anaerobiosis point (deficiency of oxygen in soil) or higher than the wilting point, root water uptake was negligible. Between these two points, root water uptake first increases linearly, then keeps constant and finally decreases linearly to zero. In van Genuchten (1987) model, there are two empirical parameters, namely the suction value corresponding to 50% reduction in transpiration and a constant related to the salt content in the soil. There is a curved relationship between transpiration and soil suction. Both models were derived based on the measurements from crop species. Engineers in geotechnical fields assume the same transpiration reduction functions (Fatahi et al. 2010; Nyambayo & Potts 2010), even though plant species in those studies was not the same as those crop species. As leaf area index (LAI; ratio of the total green leaf area to the projected canopy area on plan) affects intercepted solar radiation, photosynthesis and potential transpiration rate (Asrar et al. 1984), it may potentially affect transpiration reduction function.

The transpiration reduction function was determined from crop species, such as wheat and potato. The agricultural soil is often loosely compacted and has rich organic and nutrient concentrations (Guber et al., 2008). On the contrary, non-crop species for stabilizing slopes are normally vegetated in densely compacted soil (95% degree of compaction). It has been demonstrated that plants, such as trees and shrub, can survive and thrive under such high level of compaction (Ng et al., 2016; Ni et al., 2017). On the other hand, plants used in slope stabilization are normally maintenance free and have the nature of drought tolerant. They even do not require frequent irrigation, which, however, is specifically required for crop species (Zhang et al., 2004). The comparison above indicates that there should be differences in transpiration reduction function between crop and non-crop species. Empirical equations for crop species may not be directly applicable to non-crop species in vegetated slopes.

Till now, there were limited studies quantifying the transpiration reduction function for non-crop species (Garg et al. 2015, 2017). Garg et al. (2015) quantified transpiration reduction function for a non-crop species, *Schefflera heptaphylla*. They found that *S. heptaphylla* with higher LAI had lower tolerance of water stress as their transpiration rate reduced at much lower suction, when compared with those with lower LAI. On the other hand, it is well known that fine grained soils have higher water retention ability when compared with coarse grained soils. Induced suction in vegetated clay soil may increase more rapidly under given evapotranspiration. This would potentially affect the response of transpiration rate to soil suction.

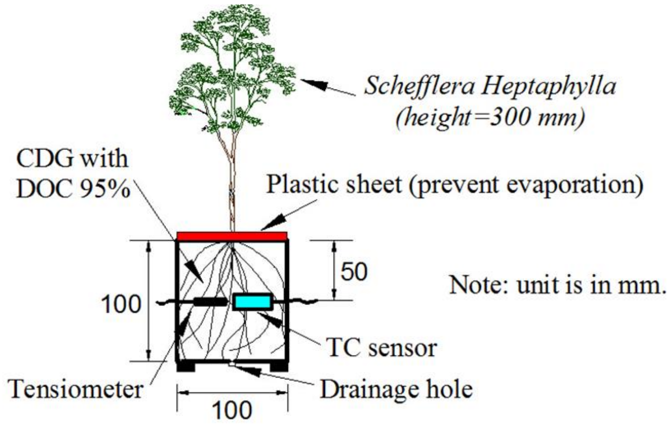
The objectives of this study are to investigate the effects of plant characteristics (LAI) and soil type on transpiration reduction and induced soil suction. One tree species (*S. heptaphylla*, which is commonly found in Asia) with various LAIs (1.0-2.8) was transplanted in small pots (100 mm in diameter and 120 mm in height). Silty sand (CDG, completely decomposed granite) and clayey soil (kaolin clay) were used as the soil medium. In total, six individuals of *S. heptaphylla* were tested in a plant room, where the atmospheric conditions were well controlled.

2 MATERIALS AND METHODS

2.1 *Test setup and instrumentation*

Six test pots were purpose-designed. Figure 1 shows the overview of the typical test pots vegetated with a tree individual. Each pot has a dimeter of 100 mm and a height of 100 mm. At the bottom of each pot, there were multiple drainage holes with diameter of 5 mm. The purpose was to create free flow boundary conditions during testing. Four of them was compacted with CDG, while the other two were compacted with kaolin clay. All the pots were transplanted with *S. heptaphylla*. All the pots were put in the temperature- and humidity-controlled plant room. The daily temperature and relative humidity (RH) in the room were controlled to be 25 ± 1 °C and 60 ± 5%, respectively. The light intensity provided by cool white fluorescent lamps near leaf surface was controlled around 120 μmol/m^2/s in the 400-700 nm waveband, which is beneficial for effective photosynthesis and plant growth (Ng et al. 2016a).

Miniature-tip tensiometer was used in the tests, as shown in Figure 1. Miniature-tip tensiometers were installed at the mid-depth of each pot. It should be noted that prior to installation, the ceramic tip and the plastic tube of each tensiometer was fully saturated with de-aired water. Due to the cavitation of water, the minimum pore water pressure that can be recorded by each tensiometer is -90 kPa. During the testing period, should air bubbles accumulate in a tensiometer, the tensiometer was re-saturated immediately. For suction higher than 90 kPa, it was measured by thermal conductivity sensor (TC, Figure 1). To determine the transpiration rate, a balance with accuracy of ± 1% was used. The weight of each pot was measured regularly during testing. By knowing the changes of pot weight within a given time interval, plant transpiration rate can be determined by dividing changes of pot weight by the time interval.



(a)

(b)

Figure 1. (a) Schematic diagram for test setup and instrumentations and (b) Overview of test setup in plant room

2.2 *Soil type and property*

There are two types of soils tested, namely CDG and kaolin clay. CDG is commonly found in tropical and sub-tropical areas, such as Hong Kong. In terms of the particle-size distribution, the contents of gravel, sand, silt and clay are 19, 42, 27 and 12%, respectively. The plastic limit is 26% and liquid limit is 44%. According to the Unified Soil Classification System (USCS; ASTM 2010), CDG can be classified as silty sand (SM). The maximum dry density and corresponding optimum gravimetric water content are 1870 kg/m^3 and 12% respectively. Air entry value is estimated to be about 3.5 kPa (Figure 2). Saturated permeability was measured to be 1.2×10^{-6} m/s by the falling head method (Ng et al., 2016a).

Kaolin clay is commercially available. The contents of gravel, sand, silt and clay are 0, 5, 53 and 42 respectively. The plastic limit and liquid limit are 32% and 59%, respectively. The standard compaction tests show that maximum dry density was 1264 kg/m^3 and the corresponding optimum water content was 36%. Air entry value is estimated to be approximately 70 kPa (Figure 2). Saturated permeability was determined to be 5.7× 10^{-9} m/s by the constant-head method (Ng et al., 2016b). Other properties of tested soils were summarised in Table 1.

Each pot was compacted with CDG or kaolin clay by moisture tamping at degree of compaction (DOC) of 95%, which corresponded to dry density of 1777 kg/m^3. DOC of 95% was selected due to slope design criteria against rainfall infiltration in some countries such as Hong Kong (GCO, 2000) and USA (TDOT, 1981). It has been demonstrated that the species selected in this study, *S. heptaphylla*, is able to thrive under this level of compaction (Ng et al., 2016a; Ni et al., 2017). During the compaction, total height of each compacted soil was divided into 4 layers, with 30 mm each. Between each layer, the soil surface was scarified for better contact.

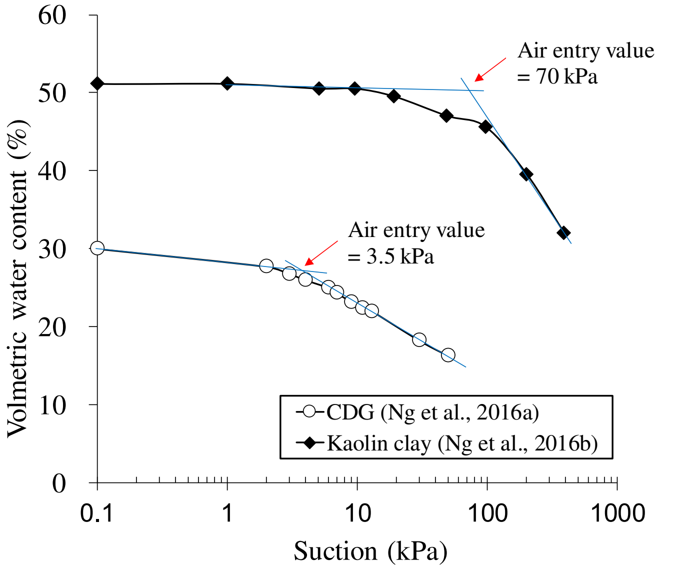


Figure 2 Soil water retention curves (SWRCs) of tested soils

Table 1. Summary of measured index properties of tested soils

Index property	CDG	Kaolin
Standard compaction tests		
Maximum dry density (kg/m^3)	1870	1264
Optimum moisture content (%)	13	36
Grain size distribution		
Gravel content (> 2 mm, %)	19	0
Sand content (≤ 2 mm, %)	42	5
Silt content (≤ 63 μm, %)	27	53
Clay content (≤ 2 μm, %)	12	42
Specific gravity	2.60	2.52
Atterberg limits		
Plastic limit (%)	26	32
Liquid limit (%)	44	59
Plasticity index (%)	18	27
Unified soil classification system (USCS)	Silty sand	Clay
Saturated soil permeability (m/s)	1.2×10^{-6}	5.7× 10^{-9}

2.3 *Plant species*

The plant seedling investigated was *S. heptaphylla*, which has sharp leaves and is broadly distributed in South China, Japan, Vietnam and India. The species is evergreen all the year around and commonly used for slope rehabilitation. Six tree seedlings with various LAIs from 0.8 to 2.8 were selected for testing. The heights of tree seedlings were 300 ± 25 mm. When transplanting the tree seedlings, soil covering tree roots was washed away and the roots were put into the pre-dug holes in each pot. After putting all the seedlings in the designated locations, CDG or kaolin clay was backfilled into the holes and recompacted to ensure good contact between tree roots and soils. Then the transplanted seedlings were allowed to grow for two months, during which seedlings were irrigated regularly every three days, following the technique adopted by Wang et al. (2007). It should be noted that no fertilizer was added during the growing period, to prevent any induced osmotic suction caused by solutes in the soil pore water.

2.4 *Test procedures*

After two months, all the six pots in the plant room were then subjected to a drying test. Before drying, the soil surface in each pot was ponded until (i) all the installed tensiometer reading decreased to 0 and (ii) percolation from the bottom drainage holes were observed. Then all excess water on the soil surface was removed away and all six pots were exposed to the same and constant atmospheric conditions. Bottom holes under the pots were open for free drainage during the testing period. Variation of suctions were monitored continuously after the test began. The drying test lasted for 15 days, during which the light was turned on for 24 hours each day.

3 TEST RESULTS

3.1 *Effects of LAI on transpiration reduction*

Figure 3 shows the effects of LAI on the relationship between normalised transpiration rate and soil matric suction in CDG soil. Normalised transpiration means the ratio of actual to potential transpiration. When soil suctions were lower than a threshold value (~60 kPa for LAI of 2.6 and 2.8; ~80 kPa for LAI of 0.9 and 1.1), the normalised transpiration reduced slowly with suction. There are almost no differences between four cases for LAI ranging from 1.0 to 2.8. However, when LAI was larger than the corresponding threshold value, the normalised transpiration rate of *S. heptaphylla* with a higher LAI (i.e., 2.6 and 2.8) showed more significant reduction, when compared with those with lower LAIs (i.e., 0.9 and 1.1). When soil suction was higher than 200 kPa, the decreasing rate of normalised transpiration with suction kept almost constant, which was independent of LAI. Normalised transpiration rate of trees with higher (2.6 and 2.8) can be twice those with lower LAI (0.9 and 1.1) at higher suction (larger than 200 kPa).

Results from Garg et al. (2015) was also superimposed in the same figure for comparison. Garg et al.

(2015) tested the same plant species and soil type. The differences were (i) shoot length in Garg et al. (2015) was 30-35% higher than that in this study and (ii) relative humidity and solar radiation in Garg et al. (2015) was 12% smaller and 28% higher, respectively. That means the potential transpiration rate in Garg et al. (2015) was higher according to Penman-Monteith equation (Allen et al., 1998). In Figure 3, the threshold values in the present study was 50% higher than that in Garg et al. (2015). This is because plants with higher potential transpiration rate would suffer higher water stress. This additional water stress was due to a higher atmospheric demand.

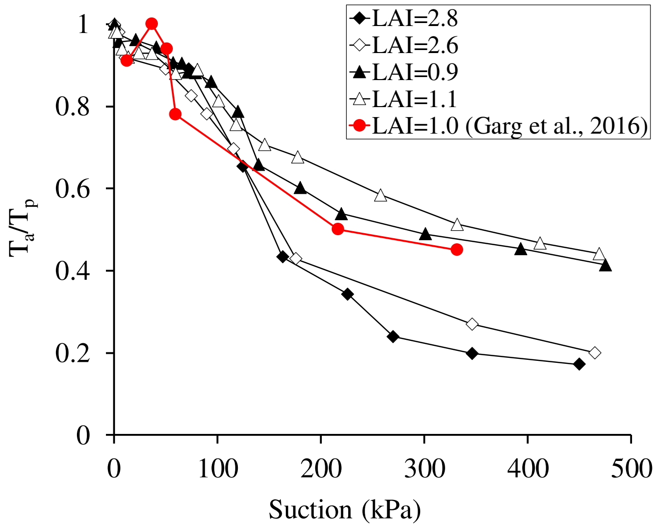


Figure 3 Effects of LAI on transpiration reduction function

3.2 *Effects of soil type on transpiration reduction*

Figure 4 shows the variations of normalised transpiration rate with soil suction in two different soils (i.e., clay and silty sand). Selection of similar LAIs (0.8-1.1) was for better comparison of two soils. Normalised transpiration rate decreased with an increase in suction. It is interesting to find that the threshold value of plants in clay soil (36 kPa) was 55% smaller than that in sand (80 kPa). This is consistent with the findings by Gadi et al. (2016) that the threshold value varies with soil types. Beyond the threshold value, the normalised transpiration rate decreased more rapidly in clay soil. At higher suction (i.e., 345 kPa), the differences between two soils can be up to 200%. The differences in transpiration reduction between two tested soils can be explained as follows. As shown in Figure 1, the clay has higher water retention ability, which is indicated by larger air entry value (i.e., 70 kPa) and higher volumetric water content at a given suction. High water retention ability means high resistance of losing water during root water uptake. On the other hand, based on the atmospheric condition in the plant room, potential transpiration rates of plants in tested clay and sand were similar (i.e., 2.51 mm/d, equivalent to 3×10^{-8} m/s). They were almost 5 times the saturated permeability of kaolin clay (5.7×10^{-9} m/s), while only 2.5 % of that of CDG (1.2×10^{-6} m/s). Based on the soil water retention curves shown in Figure 1, the saturated permeability and the potential transpiration rates, it can be deduced that the suction increase in clay can be significantly faster than the silty sand. In response to stressed condition, plants may decrease threshold values and transpiration rates by closing the stomata on leaves (O'Toole and Cruz, 1980).

The observed phenomena have high implications to engineered slopes. When modelling soil hydrology in vegetated slopes, transpiration reduction was normally assumed based on the crop species reported in literature, such as Feddes et al. (1978) and van Genuchten (1987). Those assumptions may overestimate soil suction, resulting in unconservative factor of safety. The results in this study can provide engineers with more accurate transpiration reduction functions for non-crop species, such as *S. heptaphylla* and hence more reliable evaluation of vegetated slope stability. It should be noted that transpiration reduction function may be species-dependent. For other non-crop species used in slope stabilization, their transpiration reduction functions should be tested individually.

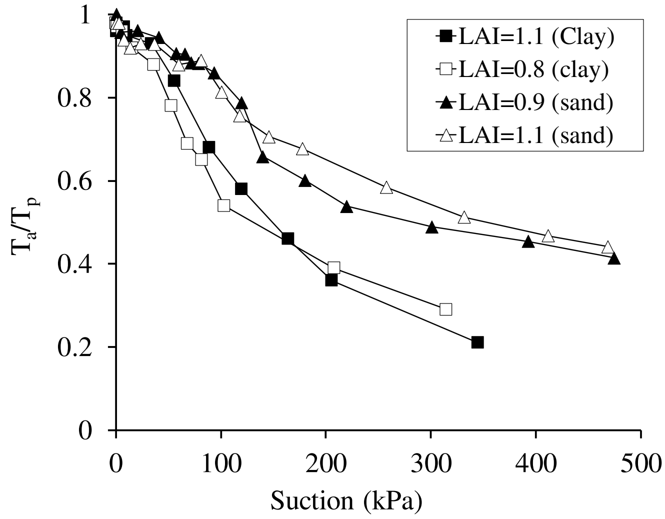


Figure 4. Effects of soil type on transpiration reduction function

3.3 *Effects of transpiration reduction on induced soil suction*

In order to study the effects of LAI on induced soil suction considering corresponding transpiration reduction, numerical analysis was carried out. Two scenarios were considered, namely LAI of 1.0 and 2.8. Two scenarios considered the same atmospheric conditions, as presented in this study. Transpiration reduction function for each LAI refers to Figure 3. An infinite slope with an angle of 40° and thickness of 10 m was considered. The slope geometry chosen for analysis falls within the typical ranges for man-made slopes in Hong Kong (GEO 2011). The soil considered in the simulation is CDG, with the SWRC shown in Figure 1. The saturated permeability of 1.22×10^{-6} m/s was input. When plant was included, the root depth was considered to be 1 m (typical root depth found in CDG, Leung et al., 2015). Root distribution was in parabolic shape, which was commonly observed for tree species in Hong Kong, such as *S. heptaphylla* (Ng et al., 2016a). The initial suction was zero. Other detailed numerical implementation can refer to Ni et al. (2018).

Figure 5 shows the numerical results about effects of LAI on induced soil suction considering transpiration reduction. After drying, induced soil suction all decreased exponentially along depth, with the maximum suction near ground surface. After four-days of drying, suction induced by plants with LAI of 2.8 can be up to 4 times that with LAI of 1.0. However, after another 4 days of drying, this difference was only about up to 50% at depths between 0.85-1.20 m. Differences near ground surface almost diminished. This is because at higher suction, transpiration rate for LAI of 2.8 decreased more substantially, compared with LAI of 1.0 (Figure 3). The reduction was most significant near the ground surface. The numerical study highlighted the important role of plant characteristics (LAI) on transpiration reduction and hence induced soil suction in an infinite slope. Engineers should take cautions in selecting suitable transpiration reduction functions when conducting transient seepage analysis in vegetated slopes.

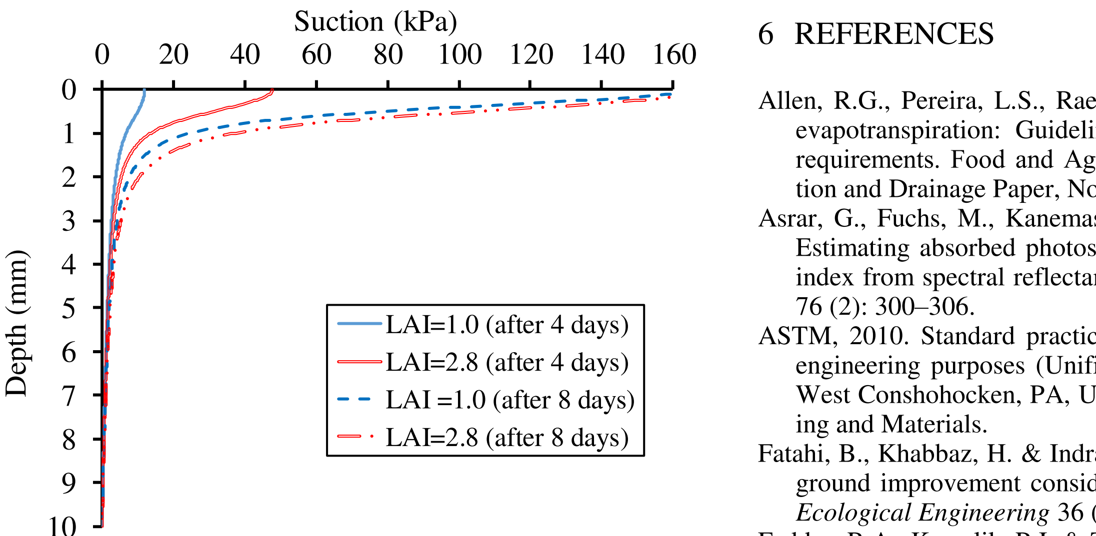


Figure 5. Effects of LAI on induced soil suction

4 CONCLUSIONS

This study investigated the effects of LAI and soil type on transpiration reduction for one tree species, *S. heptaphylla*. The importance of the transpiration reduction on induced soil suction in an infinite vegetated slope was also numerically illustrated.

The results show that at larger LAI, plant transpiration decreased more rapidly with soil suction. Plant transpiration was more sensible to soil suction when transplanted in clayey soil. Threshold value of reduction in clay (36 kPa) was 55% smaller than that in sand (80 kPa). The numerical simulation shows that plants with LAI of 2.8 can induce 4 times higher suction than plants with LAI of 1.0 after 4 days' drying, while the difference was only up to 50% after 8 days of drying when considering transpiration reduction. Engineers should be cautious when selecting suitable transpiration reduction functions during transient seepage analysis in vegetated slopes. It should be noted that only one tree species was investigated in this study. Further studies should be carried out on other vegetation types, such as shrub and grass species. Moreover, more replicates should be taken into account for each tested species.

5 ACKNOWLEDGEMENTS

The authors acknowledge research grant 2012CB719805 from the National Basic Research Program (973 Program) administered by the Ministry of Science and Technology of the People's Republic of China, research grants HKUST6/CRF/12R awarded by the Research Grants Council of the Government of the Hong Kong SAR and research grants no. 51778166 awarded by the National Natural Science Foundation of China.

6 REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. & Smith. M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Food and Agricultural Organization's Irrigation and Drainage Paper, No. 56.

Asrar, G., Fuchs, M., Kanemasu, E.T. & Hatfield, J.L. 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agronomy Jounal* 76 (2): 300–306.

ASTM, 2010. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). West Conshohocken, PA, USA: American Society for Testing and Materials.

Fatahi, B., Khabbaz, H. & Indraratna, B. 2010. Bioengineering ground improvement considering root water uptake model. *Ecological Engineering* 36 (2): 222–229.

Feddes, R.A., Kowalik, P.J. & Zaradny, H. 1978. Simulation of field water use and crop yield, Centre for Agricultural Publishing and Documentation.

Gadi, V. K., Bordoloi, S., Garg, A., Kobayashi, Y. 2016. Improving and correcting unsaturated soil hydraulic properties with plant parameters for agriculture and bioengineered slopes. *Rhizosphere* 1, 58-78.

Garg, A., Hazra, B. & Ng, C.W.W. 2018. Stochastic hydro-mechanical stability of vegetated slopes: An integrated copula based framework. *Catena* 160: 124-133.

Garg, A., Leung, A.K. & Ng, C.W.W. 2015. Transpiration reduction and root distribution functions for a non-crop species *Shefflera heptaphylla*. *Catena*, 135: 78-82.

Garg, A., Li, J.H., Hou, J.J., Berretta, C., Garg, A. 2017. A new computational approach for estimation of wilting point for green infrastructure. *Measurement* 111: 51-358.

Geotechnical Control Office (GCO). 2000. Geotechnical manual for slopes. Hong Kong: Geotechnical Control Office.

GEO (Geotechnical Engineering Office). 2011. Technical guidelines on landscape treatment for slopes. Hong Kong, China: Geotechnical Engineering Office.

Guber, A.K., Gish, T.J., Pachepsky, Y.A., van Genuchten, M. T., Daughtry, C. S. T., Nicholson, T.J. & Cady, R.E. 2008. Temporal stability in soil water content patterns across agricultural fields. *Catena* 73 (1): 125–133.

Leung, F.T.Y., Yan, W.M., Hau, B.C.H. & Tham, L.G. 2015. Root systems of native shrubs and trees in Hong Kong and their effects on enhancing slope stability. *Catena* 125: 102–110.

Nyambayo, V P. & Potts, D M. 2010. Numerical simulation of evapotranspiration using a root water uptake model. *Computers and Geotechnics* 37 (1): 175–186.

Ng, C.W.W. & Menzies, B. 2007. Advanced unsaturated soil mechanics and engineering. London: Taylor & Francis.

Ng, C.W.W., Ni, J.J., Leung, A.K., Zhou, C. & Wang, Z.J. 2016a. Effects of planting density on tree growth and induced soil suction. Géotechnique 66(9): 711–724.

Ng, C.W.W., Coo, J.L., Chen, Z.K., & Chen, R. 2016b. Water infiltration into a new three layer landfill cover system. *Journal of Environmental Engineering* 142, 4016007.

Ni, J.J., Leung, A.K., Ng, C.W.W. & So, P.S. 2017. Investigation of plant growth and transpiration-induced suction under mixed grass-tree conditions. *Canadian Geotechnical Journal* 54(4): 561 – 573.

Ni, J.J., Leung, A.K., Ng, C.W.W. & Shao, W. 2018. Modelling hydro-mechanical reinforcement of vegetation to slope stability. *Computers and Geotechnics* 95: 99-109.

O'Toole, J.C. & Cruz, R.T. 1980. Response of water potential, stomatal resistance, and leaf rolling to water stress. *Plant Physiology* 65:428-432.

Smethurst, J.A., Briggs, K.M., Powrie, W., Ridley, A. & Butcher, D.J.E. 2015. Mechanical and hydrological impacts of tree removal on a clay fill railway embankment. *Géotechnique* 65(11): 869–882.

TDOT. 1981. Subgrade construction and preparation: Specifications for road and bridge construction. Kingsport, Tennessee, USA: Tennessee Department of Transportation (TDOT) Bureau of Highways.

van Genuchten, M.T. 1987. A numerical model for water and solute movement in and below the root zone. United States Department of Agriculture Agricultural Research Service US Salinity Laboratory zone.

Wang, D., Kang, Y. & Wan, S. 2007. Effect of soil matric potential on tomato yield and water use under drip irrigation condition. *Agricultural Water Management* 87(2): 180 – 186.

Zhang, Y., Kendy, E., Qiang, Y., Liu, C., Shen, Y. & Sun, H., 2004. Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. Agric. *Water management* 64 (2): 107–122.