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Soil suction induced by grass and tree in an atmospheric-controlled plant room

Succion du sol induite par l'herbe et l'arbre dans une chambre atmosphérique contrôlée

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ABSTRACT: Vegetation is commonly found on soil slopes and landfill covers worldwide. Although mechanical contribution of roots has been considered in some stability calculations, any effects of suction induced by root-water uptake on the reduction of water permeability and the increase of shear strength are generally ignored. Due to a lack of experimental study, relationships among induced soil suction, atmospheric conditions (such as radiant energy) and plant characteristics (such as leaf area index (LAI) and root area index (RAI)) are not well understood. In order to improve our fundamental understanding of soil-water-plant-atmospheric interaction, this study measures and compare induced suction and its distribution by grass (*Cynadon dactylon*) and tree (*Schefflera heptaphylla*) planted in completely decomposed granite (silty sand) in an atmospheric-controlled plant room. By monitoring the responses of induced suction in each vegetated soil for two weeks, the effects of the two different plants on suction distributions are highlighted and discussed. Observed suction induced is interpreted in conjunction with measured interception of radiant energy by plant leaves through LAI and also measured plant root characteristics through RAI.

RÉSUMÉ : La végétation est généralement présente sur les pentes du sol et les couvertures d'enfouissement partout dans le monde. Bien que la contribution mécanique des racines ait été prise en compte dans certains calculs de stabilité, les effets de la succion induite par la racine sur la réduction de la perméabilité à l'eau et sur l'augmentation de la résistance au cisaillement sont généralement ignorés. En raison d'un manque d'études expérimentales, les relations entre la succion du sol induite, les conditions atmosphériques (tels que l'énergie rayonnante) et les caractéristiques de la plante (comme l'indice de surface foliaire (ISF) et l'indice de surface de racine (ISR)) ne sont pas bien compris. Afin d'améliorer notre compréhension fondamentale de l'interaction sol-eau-plante-atmosphère, cette étude mesure et compare la succion du sol et sa distribution par l'herbe (*Cynadon dactylon*) et l'arbre (*Schefflera heptaphylla*) plantés dans un sol en granite complètement décomposé (sable limoneux)) dans une chambre atmosphérique contrôlée. En surveillant les réponses de la succion induite dans chaque sol pendant deux semaines, les effets des deux plantes différentes sur les distributions de succion du sol sont mis en évidence et discutés. La succion du sol observée est interprétée avec l'interception de l'énergie rayonnante mesurée par ISF et aussi les caractéristiques des racines mesurées par ISR.

KEYWORDS: vegetation, suction, unsaturated soil, leaf area index, root area index.

1 INTRODUCTION

Many soil slopes and landfill covers worldwide are covered with vegetation. While there are engineering needs to search for sustainable and environmentally friendly slope stabilisation methods, shallow slopes in particular, vegetation has been considered to be an alternative, through mechanical and hydrological processes (Greenwood et al. 2004). Mechanical root reinforcement has been researched to be beneficial to slope stability (Greenwood et al. 2004). On the contrary, research on the effects of suction due to root-water uptake on the reduction of water permeability and the increase in shear strength is relatively scarce. Due to the lack of rigorous and systematic research, effects due to plant-induced soil suction are generally ignored when analyzing transient seepage and stability of a vegetated soil slope.

As far as plant-induced suction is concerned, some studies reported in literature mainly focused on responses of soil moisture/suction due to the presence of grass species (Ng et al. 2012). Investigation on the effects of other plant species such as tree on root-water uptake and induced changes of soil moisture/suction are rather limited.

It has been well-recognized that the amount of transpiration and root-water uptake of any plant species strongly depend on characteristics of plant leaf and root and atmospheric parameters such as radiant energy. Correlations between intercepted radiant energy and leaf area index (LAI) have been commonly used to interpret plant-induced changes of soil moisture (Monsi and Saeki 1953). LAI is a dimensionless index defining the ratio of total one-sided green leaf area to projected area of a plant on soil surface. For a plant having a higher LAI, a larger leaf area is available to intercept radiant energy for transpiration. While root-water uptake always takes place below ground, this common approach may be less direct because LAI is an index reflecting characteristics of plant leaf above ground. Further investigation on relationship between induced suction and other more relevant plant characteristics such as root area is needed.

To improve our understanding on the interaction among soil, water, plant and atmosphere, a test program was conducted to measure the magnitude and distribution of induced suction in vegetated soil. Two plant species, namely *Schefflera heptaphylla* (tree) and *Cynadon dactylon* (grass), which are commonly found in Hong Kong and other parts of Asia including Vietnam, India and Malaysia, were selected for investigation and comparison. Three test boxes with and without vegetation were purpose-built and they were monitored for two weeks under identical, controlled and constant atmospheric conditions.

2 EXPERIMENTAL SET UP AND TEST PROCEDURES

2.1 Test boxes and instrumentation

In this study, three test boxes were designed and manufactured. Two of them were planted with grass (denoted as test box G) and with tree (denoted as test box T), whereas one was left bare as a control (denoted as test box B). Figure 1 shows the overview of the setup of the three boxes in a room, where air temperature, radiant energy, relative humidity and potential evaporation rate were controlled at 22.3±1°C, 2.1±1 MJ/m^2, 43±7 % and 5 ± 0.2 mm/day, respectively. Each test box has a cross-section dimension of 300 mm x 300 mm and a depth of 350 mm. At depths of 30, 80, 140 and 210 mm below soil surface in each box, miniature-tip tensiometers were installed to measure negative pore-water pressure or suction ranging from 0 to 90 kPa. In order to quantify soil suction induced by tree transpiration in box T, bare soil surface around the tree stem was covered with a plastic sheet to minimize soil evaporation. Similarly, soil surface in bare box B was also covered for fair comparison. In box G, since soil surface was fully vegetated with grass, it was thus not covered with the plastic sheet and exposed to atmosphere during testing. At the bottom of each test box, there were nine drainage holes with diameter of 5 mm each for free drainage during testing (not shown in the figure).

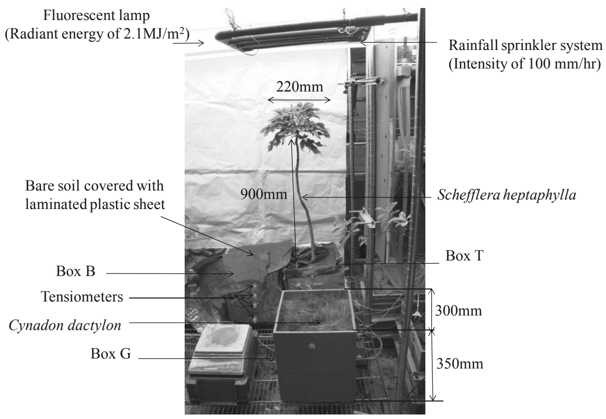

Figure 1. Overview of the three purpose-built boxes B, G and T in an atmosphere-controlled room

To allow for photosynthesis, a fluorescent lamp was used and it was mounted on top of each vegetated test box. The lamp emitted a constant daily radiant energy (R_i) of 2.1 MJ/m^2. In total, 16 measurements of R_i were made along soil surface of boxes B and T using quantum sensors. In box T, any radiant energy difference between the applied and measured radiant energy is equal to the energy intercepted by tree leaves. It should be noted that this calculation neglects (1) reflected radiant energy at each individual leaf surface due to low albedo (0.10 – 0.15; Taha et al. 1988) and (2) radiant energy used to heat up air due to low air density (Blight 2004). Energy distribution could not be measured in box G because soil surface was fully covered with grass where quantum sensor (which has limited size) was difficult to be placed on soil surface for measurements.

2.2 Soil type and selected plant species

Completely decomposed granite (CDG), which is commonly found in Hong Kong, was used. Results from sieve and hydrometer analysis reveal that the gravel, sand, silt and clay contents of CDG are 19, 42, 27 and 12 %, respectively. Based on the measured particle-size distribution and Atterberg limit, CDG may be classified as silty sand (SM) according to the Unified Soil Classification System. Each test box was compacted with silty sand of which the targeted dry density and water content by mass were 1496 kg/m^3 (i.e. degree of compaction of 80 %) and 12%, respectively.

In this study, a grass species (*Cynodon dactylon*) and tree species (*Schefflera heptaphylla*) were selected for investigation. The grass species is commonly known as Bermuda grass, which is a warm-season grass widely cultivated in warm climates of the world. In box B, seeds of Bermudagrass were distributed uniformly on soil surface and they were allowed to germinate and grow for 10 months in the atmosphere-controlled room. After growing for 10 months, the average lengths of grass shoot and depth were found to be 90 and 110 mm, respectively. The LAI of grass is estimated to be 2.2.

For box T, a mature tree, *Schefflera heptaphylla*, which has a shoot height of 900 mm and root depth of 240 mm (50 % longer than grass root), was transplanted to the centre of the box. The tree had a canopy diameter of about 220 mm (73% of the width of the box T) and the shape of the canopy is spindle – shaped. The LAI of the tree is determined to be 4.6. In both boxes G and T, fertiliser was not added to prevent osmotic suction induced by changes of salt concentration in soil (Krahn and Fredlund 1972).

2.3 Test plan and procedures

After preparing all the three test boxes (B, G and T), they were tested in the atmospheric-controlled room. In each box, rainfall with intensity of 100 mm/hour and duration of one hour was applied on box surface using a calibrated rainfall sprinkler system as shown in Figure 1. This applied rainfall event is equivalent to the return period of 10 years of rainfall in Hong Kong (Lam and Leung 1995). Throughout the entire rainfall event, all drainage holes at the bottom of each test box were opened to allow for free downward drainage. After rainfall, soil surfaces in test boxes B and T were covered with laminated plastic sheet, whereas that for grass box G was left exposed. Each test box was then monitored for two weeks and any suction changes at the depths of 30, 80, 140 and 210 mm were recorded continuously. All drainage holes at the bottom of each box remained open during the monitoring period.

3 OBSERVED TREE ROOT CHARACTERISTICS

In order to investigate tree root characteristics such as root area index (RAI) and its distribution within the root zone, the tree was removed from box T after testing. An image analysis was then conducted on tree root system using an open source program, Image J (Rasband 2011). RAI is an index normalising total root surface area for a given depth range □ *h* (assumed to be 10 mm in this study) by circular cross-section area of soil (on plan), whose diameter is defined as the furthest distance between two ends of root. It should be noted that RAI of grass was not measured because the diameter of fine roots was much smaller than the accuracy of the image analysis.

Figure 2 shows the measured distribution of RAI along root depth of the tree. Maximum RAI of 0.74 is found near soil surface. The RAI decreases almost linearly to less than 0.03 at the root depth of 240 mm. Obviously, RAI can vary differently from species to species. While the observed linear RAI profile of the tree in this study is found to be similar to that measured in sweet gum (Simon and Collison 2002), it is different from other tree species, black willow, where non-linear RAI profile was observed (Simon and Collison 2002). In addition to plant species, RAI can also be affected by soil density. Laboratory study carried out by Grzesiak (2009) showed that when soil is denser, plant roots are found to be less uniform along depth. Obviously, this is because an increase in soil density would increase mechanical resistance for plant roots to penetrate through soil. As a result, more roots would concentrate (i.e., higher RAI) in shallower depths and the number of roots would decrease with an increase in depth. The observed RAI profile in this study is useful for interpreting suction induced in vegetated soil with the tree. This is because RAI indicates surface area of roots available for root-water uptake, which would affect the magnitude of suction induced in the soil. Any relationship between RAI and suctions induced in box T is discussed later.

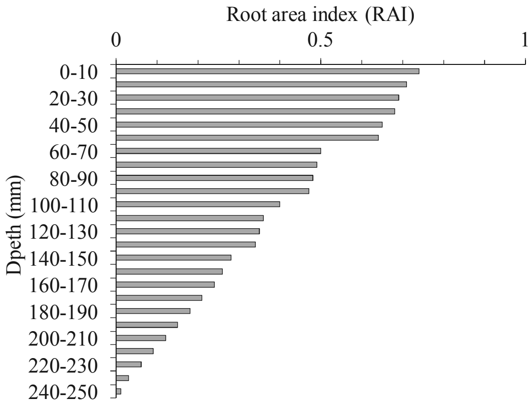

Figure 2**.** Measured distribution of RAI along root depth of the tree in box T

4 EFFECT OF TREE LEAF ON ENERGY DISTRIBUTION

Figure 3 compares the measured horizontal distributions of radiant energy received on soil surface (R_s) for boxes B and T. As expected, the soil surface for bare box B receive almost all the energy (i.e. $R_i \approx R_s$) uniformly along the width of the box. On the contrary, the measured distribution of R_s is different in box T. It can be seen that at the centre of the box, the measured R_s is minimum. This is because of the substantial interception of incoming radiant energy by tree leaves. The maximum percentage of energy interception (i.e. $(R_i - R_s) / R_i$) is estimated to be about 50 %. Moreover, measured values of R_s are found to increase when the distance is further away from the tree stem on both sides of the box. This is because there are smaller number of tree leaves, and hence amount of interception, away from the tree stem (see Figure 1). At the two edges of the box, the measured values of R_s are found to be close to the applied radiant energy of 2.1 MJ/m^2 (see Figure 3). This is expected because energy measurements were made outside the canopy of tree and thus no radiant energy can be intercepted. Similar distribution of intercepted radiant energy was also found by Buler and Mika (2009) for an apple tree of which the canopy was also spindle – shaped. It is obvious that energy distribution is strongly dependent upon the canopy shape of a tree species. For a given apple tree, Buler and Mika (2009) showed that distributions of intercepted energy depended on the shape of canopy (i.e., V – shape and Hybrid – shape). Measured interception of radiant energy in this study is used to interpret plant-induced soil suction later since the magnitude of energy intercepted by tree leaves would affect amount of tree transpiration and hence root-water uptake.

Although the amount of radiant energy interception was not determined for box G due to the full coverage of grass surface, it could be estimated based on LAI of grass (i.e., 2.2) using Beer-Lambart Law, which has been widely used for estimating intercepted radiant energy for various plant species including grass (Kiniry et al. 2007). The law states that amount of light intercepted through grass leaf increases with an increase in leaf area exponentially (Monsi and Saeki 1953). For a given LAI and assuming that the extinction coefficient (i.e., a measure of the absorption of light) to be 1.1 based on the thickness of grass shoot (Kiniry et al. 2007), the percentage of radiant energy interception by grass is estimated to be more than 90%. In other words, a large portion of radiant energy would be intercepted by grass shoot for transpiration, whereas only a limited amount of it would fall on bare soil surface (i.e., less than 10 %) for evaporation. This implies that for a given incoming radiant energy in the atmospheric-controlled room, suction induced in box G would be attributed to grass transpiration mainly.

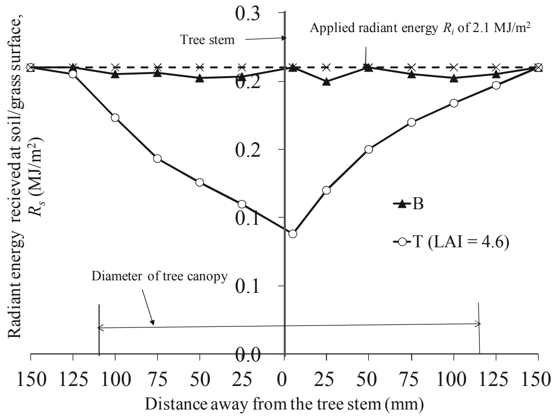

Figure 3. Measured horizontal distributions of radiant energy received at soil surface in boxes B and T

5 COMPARISON OF SUCTION PROFILES WITH AND WITHOUT VEGETATION

Figure 4 compares measured distributions of induced suction along depth in all three test boxes, B, G and T during two weeks of testing. The measured root depths of grass and tree are depicted for reference. The measured initial distribution of suction in bare box B is found to be nearly uniform, suggesting that the hydraulic gradient is about one. In other words, water flow in these two boxes was mainly driven by the gravity, seeping towards bottom drainage holes. When grass was present, suctions recorded at depths within the root zone in box G are slightly higher than those in deeper depths because of root-water uptake. For box T, the measured initial suctions were higher than those in the other two boxes, particularly at 30 and 140 mm depths. As compared to bare box B, the observed higher suctions retained in the two vegetated boxes G and T were likely attributed to the changes of water retention ability of soils, due to the presence of plant roots (Scanlan and Hinz 2010).

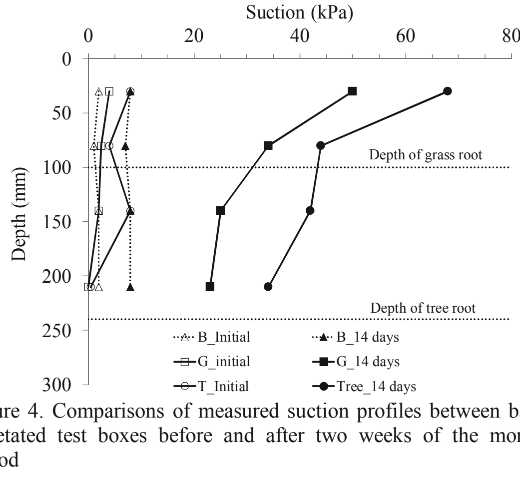

Figure 4. Comparisons of measured suction profiles between bare and vegetated test boxes before and after two weeks of the monitoring period

After two weeks of testing, suctions recorded at all depths in bare box B increase by nearly the same amount of 6 kPa, suggesting that there was again unit gradient downward flow. The downward water flow during the monitoring period in box B was expected because surface evaporation was greatly minimised by covering the soil surface using the plastic sheet (see Figure 1). On the contrary, uniform suction distributions are not observed in both vegetated boxes G and T. It can be seen that there are significant increases in soil suctions at all depths in these two boxes, particularly within plant root zones in shallower depths. This is not surprising because hydraulic gradient near soil-atmosphere interface is much higher than that in deeper depths. Measured suctions at all depths in box G are higher than those in Box B. When grass is present, the peak induced suction due to grass root-water uptake (i.e., 50 kPa) is found to be six times higher than that in bare box B (i.e., 8 kPa) at 30 mm depth. Although measurements at 140 and 210 mm depths were made outside the root zone of grass, suctions at these depths are also influenced by the root-water uptake happened in shallow depths. As identified by Ng et al. (2012), vertical influence zone of induced suction in soil vegetated with grass could be as deep as four times of grass root depth.

For box T, suctions recorded at all depths are higher than those in the bare box B. When the tree is present, the peak suction induced at 30 mm depth (i.e., 67 kPa) is found to be almost eight times higher than that in bare box B (i.e., 8 kPa). This is attributed to tree transpiration by intercepting 50 % of incoming radiant energy (see Figure 3) and also soil evaporation by receiving remaining energy fallen on soil surface. It is important to recognize that the observed distribution of suction in box T is consistent with that of RAI shown in Figure 2. The amount of suction induced is found to increase with an increase in RAI proportionally. For a tree having a higher RAI, this means that a larger surface area of tree roots is available for root-water uptake to induce higher suctions.

When compared to box G, it can be seen that suctions recorded at all depths in box T are about 34 % higher (see Figure 4). This is likely because the root diameter and root depth of the tree are larger and deeper than those of grass, respectively. As compared to short, fine grass roots, the characteristics of tree roots are more favorable for root-water uptake. At deeper depths of 140 and 210 mm, the measured suctions in box T are expected to be higher than those in box G. This is because suction measurements at these two depths were made within the tree root zone in box T, but those in box G were outside the root zone of grass.

6 SUMMARY AND CONCLUSIONS

In this study, a series of laboratory tests were carried out to explore the effects of two different plant types (grass and tree) on induced suction and its distribution in compacted silty sand in an atmospheric controlled plant room. Measured induced suction in vegetated soils were compared and correlated with energy distribution and plant characteristics.

After two weeks of testing, peak suctions (i.e., 50 kPa and 67 kPa) induced in silty sand vegetated with grass and tree are found to be at least six and eight times higher than that (i.e., 8 kPa) in bare soil, respectively. The additional suction induced in vegetated soils is attributed to plant transpiration through energy interception by plant leaves. For the tree having a LAI of 4.6, the maximum amount of energy interception by tree leaves is up to 50 % of the incoming energy supplied in the atmospheric-controlled room. It is important to recognize that the measured vertical distribution of suction in vegetated soil depends on RAI. The magnitude of suction induced is found to be directly proportional to RAI. When RAI is higher, higher surface area of tree roots is available for root-water uptake to take place and higher suction is hence induced.

When comparing soil vegetated with grass and tree, peak suction induced by tree is 34 % higher. This is because root diameter and root depth of the tree are larger and deeper than those of grass (which has finer and shorter roots), respectively. As expected, these characteristics of tree roots are more favorable than those of grass for root-water uptake.

7 ACKNOWLEDGEMENTS

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