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Interplay Between Ecology and Unsaturated Soil Mechanics for Bioengineered Landfill Covers and Slopes

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Abstract. The negative impact of climate change calls for additional sustainable and environmentally friendly techniques to be developed for the improvement of the engineering performance of civil infrastructure, such as landfill covers and slopes. Bioengineering using vegetation can be considered and promoted as a low-cost, aesthetically pleasant solution for greening landfill covers and improving shallow slope stabilisation. The mechanical effects of vegetation as soil reinforcement have been extensively studied, but the hydrological effects of vegetation on soil shear strength and water permeability are unclear. This study therefore presents an interdisciplinary research programme consisting of laboratory and field tests and centrifuge modelling. The programme explores the hydrological effects of plants on the performance of final landfill covers and slope stabilisation. Results show that suction induced by plants under a novel vegetated three-layer landfill cover is preserved better than that under a bare cover even after an extreme rainfall event with a return period of greater than 1000 years in Hong Kong. The laboratory tests and field trials demonstrate that the vegetated three-layer landfill cover system using recycled concrete can effectively minimise percolation at humid climate even without a geomembrane. Novel artificial root systems are developed for the centrifuge model tests. Heart-shaped roots have stronger pull-out resistance and higher preserved suction (hence higher soil shear strength) compared with tap- or plate-shaped roots. The heart-shaped root architecture is thus the most effective type in producing stabilisation effects on slopes.

Keywords. Soil bioengineering, vegetation, matric suction, landfill cover, slope stability

1. Introduction

Bioengineering using vegetation can potentially offer an environmentally friendly, cost-effective and aesthetically pleasant solution for greening landfill covers and improving shallow slope stabilisation. Although vegetation has been used in slope protection for decades, its purpose has mainly been aesthetic [1] probably because the mechanisms of soil–plant–atmosphere interaction have not been fully understood. Thus, the current

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design practice does not scientifically integrate the engineering function of plant roots into the analysis and design of landfill covers and slope stability.

Plant roots can provide mechanical reinforcement to slope stabilisation [2, 3]. The mechanical effects of root reinforcement have been extensively quantified experimentally and theoretically in the past decades [2, 4, 5]. By contrast, the hydrological effects of plants have received insufficient attention, as stated by Ng [6]. These hydrological effects refer to the increase in soil shear strength and the reduction in water permeability caused by enhanced soil suction [7]. The key to using plants for these purposes is to understand the fundamentals of unsaturated soil mechanics and soil–plant–atmosphere interactions, which are interdisciplinary subjects involving atmosphere science, soil science, botany, ecological and geotechnical engineering.

In this study, an integrated and complementary research approach is reported to investigate plant hydrological effects on the performance of final landfill covers and the stabilisation of shallow soil slopes. Firstly, a series of laboratory column tests was conducted to quantify transpiration-induced soil matric suction in a novel vegetated three-layer landfill cover using recycled crushed concrete without the use of a geomembrane. Two plant species commonly found in Hong Kong were studied. Secondly, a full-scale field trial was performed to investigate the influence of vegetation on the performance of the novel vegetated three-layer landfill cover for two years. Finally, novel artificial model root systems were developed for geotechnical centrifuge tests to study the combined mechanical and hydrological effects of different root architectures on hydrology, slope stability and failure mechanisms. The influence of root architectures on slope deformation and failure mechanism was identified. Additional details of the laboratory, field and centrifuge model tests and findings were given by Ng et al. [7].

2. Fundamentals of unsaturated soil mechanics

Relevant theories of unsaturated soil mechanics are introduced to improve our understanding of soil–plant–atmosphere interaction. For simplicity, the shear strength of unsaturated soil, τ_f, may be expressed in terms of water content and soil matric suction as follows [8]:

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\left[(\tan\phi')\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\right] \tag{1}$$

where c' is the effective cohesion; σ_n is the normal stress; u_a and u_w are the pore–air pressure and pore–water pressure, respectively; ϕ' is the effective friction angle; θ is the volumetric water content; θ_s is the saturated volumetric water content; θ_r is the residual water content. The difference between u_a and u_w (i.e., $u_a - u_w$) is called matric suction. Advanced theories, such as effects of state-dependent dilatancy on the shear strength of unsaturated soil, were provided by Chiu and Ng [9], Ng and Menzies [10] and many others. According to Eq. (1), plant-induced matric suction would increase soil shear strength due to a reduction in water content (and an increase in soil matric suction). The laboratory findings of Ng and Zhou [11] showed that matric suction can increase the tendency of soil dilation, thereby improving soil shear strength.

Unlike water permeability in saturated soils, that in unsaturated soils not only depends on the void ratio (e) but is also governed by the degree of saturation or the water content, which in turn affects matric suction in the soils. The relationship between water permeability and matric suction can be expressed as follows [12]:

$$k(\psi) = k_s \left[\frac{\int_{In(\psi)}^{b} \frac{\theta(e^y) - e(\psi)}{e^y} \theta'(e^y) dy}{\int_{In(\psi_{ave})}^{b} \frac{\theta(e^y) - \theta_s}{e^y} \theta'(e^y) dy} \right] \tag{2}$$

where ψ is the matric suction; $b = \ln(10^6)$; k_s is the saturated water permeability; y is a dummy variable for the integration of ψ; θ' is the first derivative of function θ. Water permeability generally reduces with increasing matric suction. Given that pore air is not conducive to liquid water movement in unsaturated soils, an increase in suction (i.e., a reduction in water content) leads to a decrease in water permeability. Eqs. (1) and (2) show that plant-induced suction not only increases soil shear strength but also reduces water permeability, thereby decreasing rainfall infiltration and hence potentially helping preserve a large amount of soil suction in unsaturated landfill covers and soil slopes. The hydrological effects of plant root–water uptake was not fully recognised until comprehensive research was conducted in the recent few years (e.g., Ng et al. [13, 14, 10]; Ni et al. [15, 16, 17]; Ng [8]).

3. Hydrological effects of vegetation on matric suction in landfill covers

To improve the effectiveness of a traditional landfill cover with capillary barrier effects (CCBE) in humid regions, Ng et al. [18] proposed an all-weather three-layer landfill cover system comprising a fine-grained layer underlying the traditional two-layer CCBE. Recycled construction waste was also proposed as cover materials for landfills to reduce cost and achieve environmental sustainability [19, 20]. The new three-layer landfill cover was vegetated with plants. In this study, the effects of plant roots on the hydrological performance of the three-layer landfill cover system during drying and wetting were studied.

One-dimensional soil column tests were conducted in a plant room at Hong Kong University of Science and Technology (HKUST) to quantify the effects of evapotranspiration (ET, which is the sum of soil evaporation and plant transpiration) on suction in the novel landfill covers in this study. Three columns were used, each with an inner diameter of 300 mm and a height of 1500 mm (Figure 1). Each column was compacted with completely decomposed granite (CDG), fine recycled concrete aggregate (FRC) and coarse recycled concrete aggregate (CRC) overlying completely decomposed volcanic rocks (CDV). The selected grass species (*Cynodon dactylon*, G) and shrub species (*Schefflera arboricola*, S) are native to southern China, including Hong Kong [20]. Bare soil (B) was used as reference. All the three columns were subjected to daily irrigation with a constant amount of water of 200 mL per day for 4 months. After drying, 48 h ponding with a constant water head of 100 mm (equivalent to a rainfall of more than a 1000-year return period in Hong Kong; [21]) was applied. Soil matric suction was measured continuously during the drying and wetting periods.

A three-dimensional full-scale test was conducted in the Xiaping landfill site in Shenzhen, China to evaluate the field performance of the novel three-layer cover system that uses recycled crushed concrete without the use of a geomembrane (Figure 2; [19]). The field test plot was located in a humid subtropical climate region with approximately

80% of rainfall occurring between May and September. Unsieved CDG and CRC were used for the top and intermediate layers, respectively, and sieved CDG was used as the lowest layer. One section was transplanted with *C. dactylon*, whereas the other section was left bare (Figure 2). Water percolation was measured for two years (June 2016 to June 2018) by using a lysimeter installed at the bottom of the landfill cover.

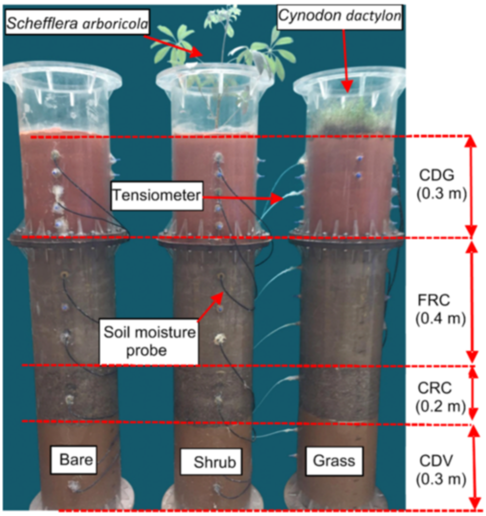

Figure 1. Overview of the three columns.

Figure 2. Front view of the Xiaping landfill site in Shenzhen, China.

3.1. ET-induced soil matric suction

Figure 3 shows the laboratory test results and compares the suction response under the bare and vegetated three-layer landfill covers. Suction under the vegetated covers was up to 95% higher than that under the bare cover due to ET before ponding. Compared with grass, shrub induced an additional 25%–30% suction in the FRC and CRC layers. After 48 h of ponding, suction in the top CDG and FRC layers was reduced to nearly zero. For the bare cover, suction in the bottom layer of CDV decreased from 52 kPa to 3 kPa during ponding. Percolation was observed under the bare cover, with a total of 35 g of water, which was equivalent to 0.5 mm water depth in the column. By contrast, for the vegetated covers, large amounts of suction (52 kPa for the grass and 57 kPa for the shrub cover) were maintained in the bottom layer of CDV. According to a comparison of the two vegetated cover systems, suction maintained under the cover with shrub in the FRC, CRC and bottom CDV layers was higher than that under the cover with grass by 2–6, 6 and 5 kPa, respectively. No percolation was observed under the covers with shrub and grass. Therefore, the vegetated three-layer cover system using recycled concrete aggregate can effectively minimise water infiltration under extreme rainfall events (more than 1000-year return period).

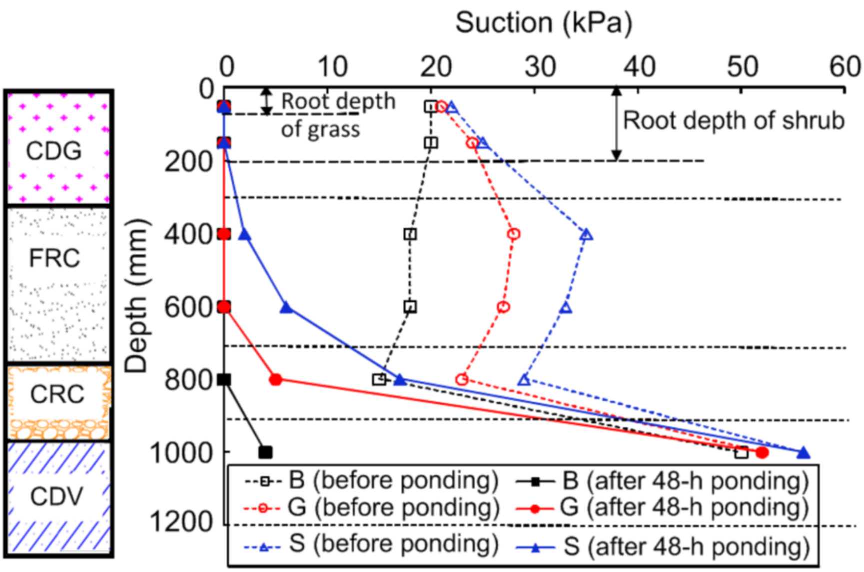

Figure 3. Suction distributions before and after ponding.

3.2. Root effects on water percolation in vegetated landfill covers

Figure 4 shows the cumulative percolation in the bare and grass-covered three-layer landfill covers in Shenzhen, China, from June 2016 to June 2018. The lines correspond to cumulative percolation at three different locations in the slope (i.e., crest, middle, toe). The cumulative rainfall depth of about 4900 mm for two years is also provided in the figure for reference. At the end of the monitoring period, percolation results were approximately 47 and 37 mm for the bare and grass-covered landfill covers, respectively. The difference was likely because of the presence of grass roots, which induced higher soil suction and hence reduced water permeability [7], thereby leading to decreased percolation. The cumulative percolation amount in the bare (47 mm) and grass-covered (37 mm) three-layer landfill covers met the recommended design criterion of 60 mm for two years [22]. These results demonstrated the effectiveness of grass in reducing excessive water percolation in the novel three-layer landfill cover system, which uses recycled crushed concrete and does not have a geomembrane in humid climates.

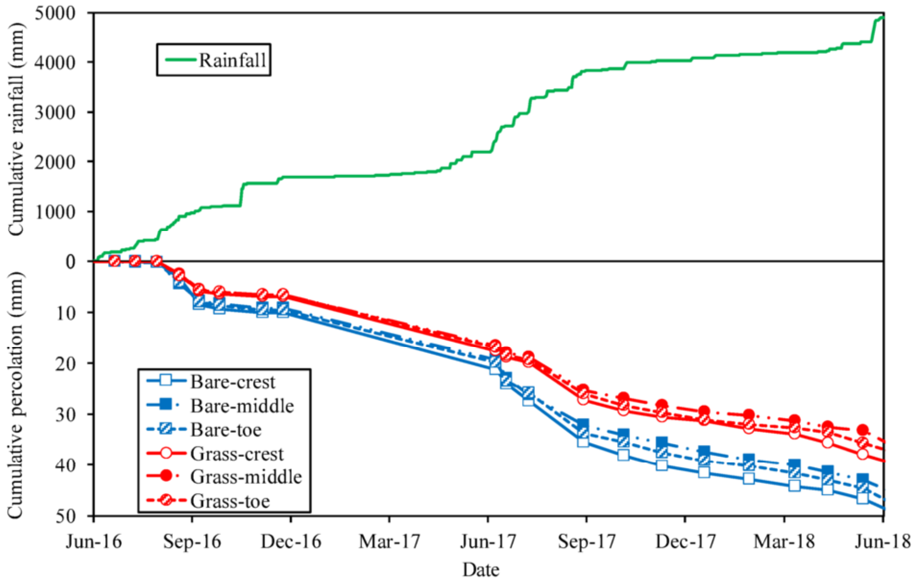

Figure 4. Cumulative percolation in the bare and grass covered three-layer landfill cover system.

4. Hydromechanical effects of plant roots on slope stability and failure mechanisms

Although the mechanical effects of plant roots on slope stability have been reported [4, 23], the combined hydromechanical effects remain unclear. Therefore, novel artificial root systems were developed for geotechnical centrifuge model tests to study the combined mechanical and hydrological effects of different root architectures on hydrology, slope stability and failure mechanisms [24, 25, 7, 26]. All dimensions reported in this section are in prototype scale unless stated otherwise.

4.1. Principle and properties of the novel root model

Figure 5 shows the artificial root models of the three different architectures (tap, heart and plate) created by Ng et al. [24]. They were developed on the basis of the idealisation and simplification of real roots retrieved from three species that are commonly used for slope rehabilitation and ecological restoration in tropical and subtropical regions, namely, *Schefflera heptaphylla, Rhodomyrtus tomentosa* and *Melastoma sanguineum* [27]. These artificial root models are made of a porous material called cellulose acetate (CA), whose tensile strength and elastic modulus are fairly close to those typically identified in real roots [28]. In the design of Ng et al. [24], these root models connect with a vacuum system, which includes a vacuum chamber that is partially filled with de-aired water. Through the vacuum source connected to the chamber, different vacuum pressures can be applied to the CA; hence, different vacuum pressures up to −100 kPa can be induced in the water reservoir. Given that the CA is in contact with soil, any applied vacuum (and hence reduction in total head inside the root model) would enable water to flow from the soil to the chamber through the filter. The decrease in soil moisture would then induce soil suction. Leung et al. [26] showed that the distribution of root area ratio with root depth is reasonably captured by the three root models, given the natural variability of plants in fields. Additional details of the test results and interpretation can be found in Ng et al. [7].

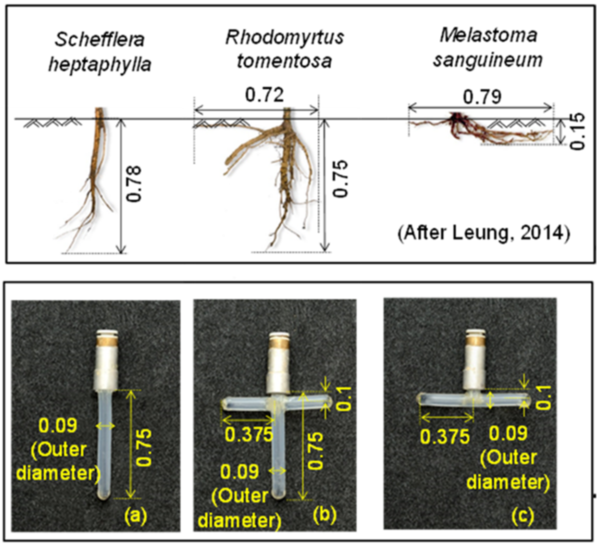

Figure 5. Idealisation and simplification of plant roots with different root architectures (unit: m; converted to prototype scale).

4.2. Root architecture effects on pore water pressure after rainfall

Figure 6 shows a typical centrifuge model setup. Three centrifuge tests were conducted to compare the contributions of three different root architectures, namely, tap, heart and plate, to the hydrology and stability of 45° model slopes made of CDG. Each model slope was supported by 15 artificial roots and subjected to a five-day simulated transpiration by the root system, followed by an intense 8 h rainfall event with a constant intensity of 70 mm/h (equivalent to a rainfall of 1000-year return period in Hong Kong; [21]). Six pore pressure transducers were installed to monitor the suction (negative pore water pressure, PWP) in each slope. All tests were performed at 15 g in the geotechnical centrifuge facility at HKUST. The soil properties, model setup, instrumentation and test procedures are detailed in Leung et al. [26] and Ng et al. [7].

Figure 7 compares the measured PWP profiles of the three model slopes with different root architectures during rainfall. Before rainfall, suction within the depths of the tap- and heart-shaped roots increased substantially during the transpiration process. The heart-shaped root could induce higher suction because it had two branches. For the plate-shaped roots, which did not have any taproot component, suction was noticeable only at a depth of 0.3 m. After a 2 h rain with a constant intensity of 70 mm/h (equivalent to a return period of 10 years), suction at all depths in all types of roots was reduced as expected. In the case of the heart-shaped roots, slightly higher suctions of 2–3 kPa were retained within the root depth. As the rainfall continued for another 6 h with the same intensity (equivalent to a return period of 1,000 years), a positive PWP of approximately 2 kPa resulted within the root depth. However, the plate-shaped roots showed the highest positive PWP amongst the three root types. This finding suggests that any transpiration performed by this type of root does not quite effectively help reduce the PWP below the root depth under extreme rainfall.

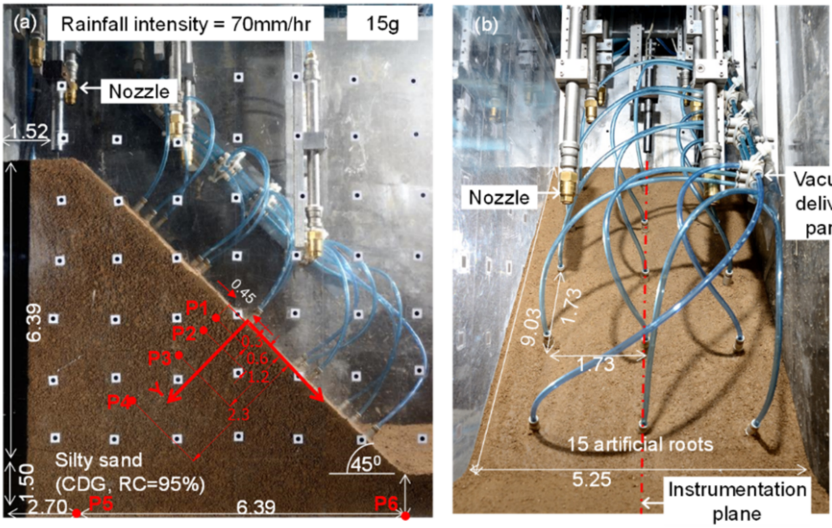

Figure 6. (a) Elevation and (b) side views of the centrifuge model package and instrumentation (all dimensions are in metres and in prototype scale).

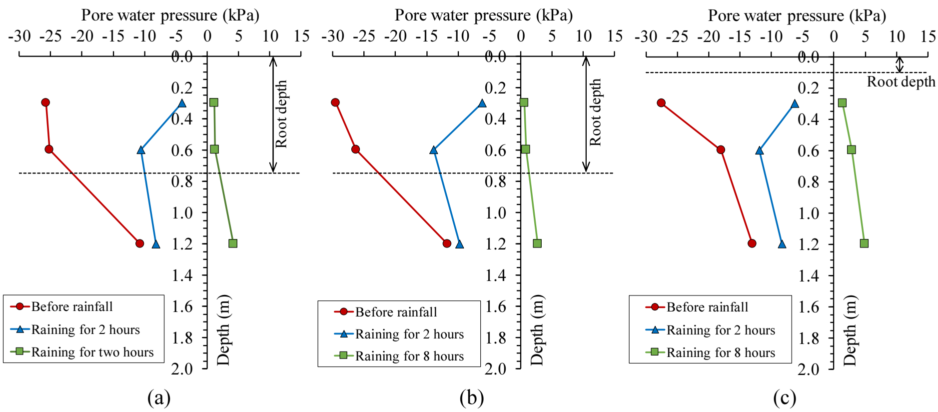

Figure 7. Distribution of measured and computed pore water pressure along various depths before and after rainfall in the slope models supported by (a) tap-, (b) heart- and (c) plate-shaped roots.

4.3. Effects of root architecture on pull-out resistance

Apart from hydrological reinforcement via plant transpiration, the pull-out resistance of plant root systems contributes substantially to the mechanical reinforcement of slopes

[29, 30]. Figure 8 compares the relationships between pull-out force and displacement of the tap-, heart- and plate-shaped architectures. All pull-out tests were conducted after 8 h of rainfall, when the soil was saturated (Figure 7). After peaking, the pull-out force in all three cases decreased as the soil–root contact area reduced continuously during the pull-out process. The peak resistance of the heart-shaped root (3.9 kN) was slightly higher than that of the tap-shaped root (3.5 kN). Moreover, the postpeak behaviour of the former architecture was more brittle, given that less pull-out displacement was required to mobilise the same amount of resistance in the former than in the latter. Given the similar positive PWP induced after 8 h of rainfall (Figs. 7(a) and (b)), the difference in pull-out behaviour between these two architectures was primarily attributed to the mechanical reinforcement given by the two branches of the heart-shaped root model. By contrast, the plate-shaped root architecture was not effective against pull-out force. This is because (i) the peak pull-out resistance (1.2 kPa) was three to four times lower and (ii) the postpeak load displacement response was much more brittle than those of the two former architectures. The major reason was that for this root architecture, the two horizontal branches located at much shallower depths failed to provide considerable pull-out resistance. The heart-shaped root architecture therefore had the highest pull-out resistance due to its multiple branching.

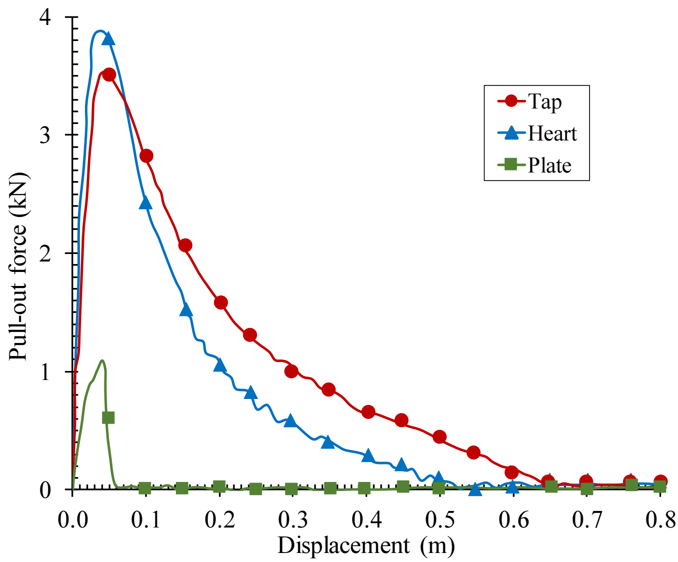

Figure 8. Comparison of the pull-out behaviour of tap-, heart- and plate-shaped root models [31].

4.4. Effects of root architecture on slope stability and failure mechanisms

On the basis of the measured PWP response (Figure 7) and pull-out resistance (Figure 8), the combined hydromechanical effects of the plant roots on slope stability and failure mechanisms were studied. In accordance with the back-analysed PWP responses, slope stability analysis was conducted using SLOPE/W [32] to determine the factor of safety (FOS) in each case. The artificial roots were modelled as a beam element to capture the elastic axial and bending responses [25, 7]. The computed FOS results are shown in

Figure 9. Before transpiration, the FOS was similar for the three slopes and exceeded 1.0 (i.e., the slopes were stable.). When suction was created by simulating transpiration, the FOS of each slope increased but not substantially (less than 4%) because transpiration affected mainly the PWP in the top 1.2 m of each slope. After the 8 h rain, the FOS of the three slopes dropped significantly, following a reduction in PWP upon infiltration. Despite the reduction in FOS, all slopes remained stable, as observed in the model tests. The FOS values of the slope supported by the heart-shaped roots were 16% and 28% higher than those of slopes supported by the tap- and plate-shaped roots, respectively. The greater stability provided by the heart-shaped roots came from the substantial suction preserved after rainfall and their higher mechanical pull-out resistance compared with that of the two other root architectures (Figs. 7 and 8). If the transpiration effects before the rainfall event were ignored, then the values of FOS after rainfall in all the cases would decrease below 1.0. Regardless of the root architecture, neglecting the effects of transpiration on slope stability resulted in a significant underestimation of FOS of up to 50%.

Two more centrifuge tests were conducted for steeper model slopes (i.e., 60°) vegetated with tap- and heart-shaped root models to study the role of root architecture in the slope failure mechanism. The two slopes were continuously subjected to an 8 h extreme rainfall event with a constant intensity of 70 mm/h (equivalent to a rainfall with a return period of 1000 years in Hong Kong) until failure. A comparison of the postfailure geometries between the two slopes in Figure 10 suggested that a shallower slip was formed and a smaller volume of soil failed when the slope was reinforced with heart-shaped roots in comparison with the tap-rooted slope. The runout distance from the heart-shaped slope toe was approximately 9% (4.3 m versus 4.7 m) shorter than that from the tap-shaped one, suggesting that the heart-shaped roots were more effective for stabilising slopes and reducing runout distance in comparison with the tap- and plate-shaped roots.

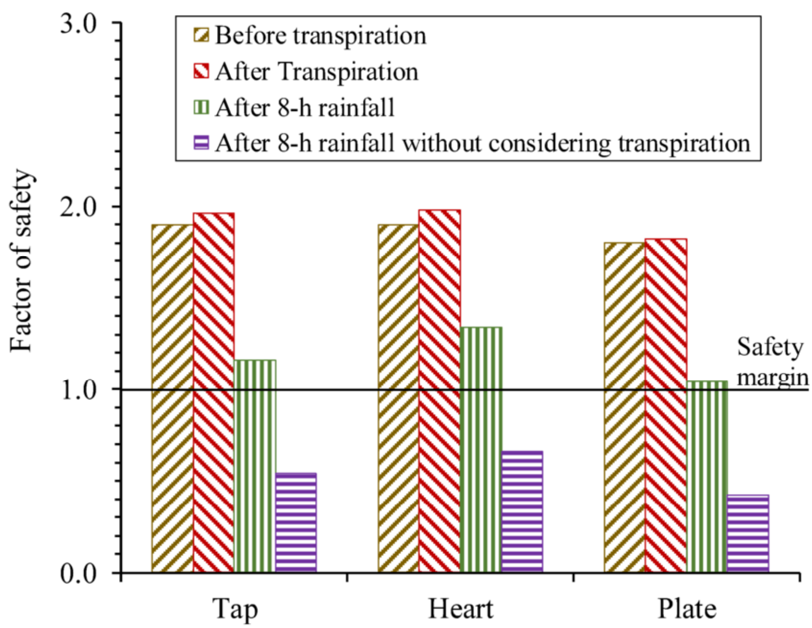

Figure 9. FOS of slopes supported by different root architectures.

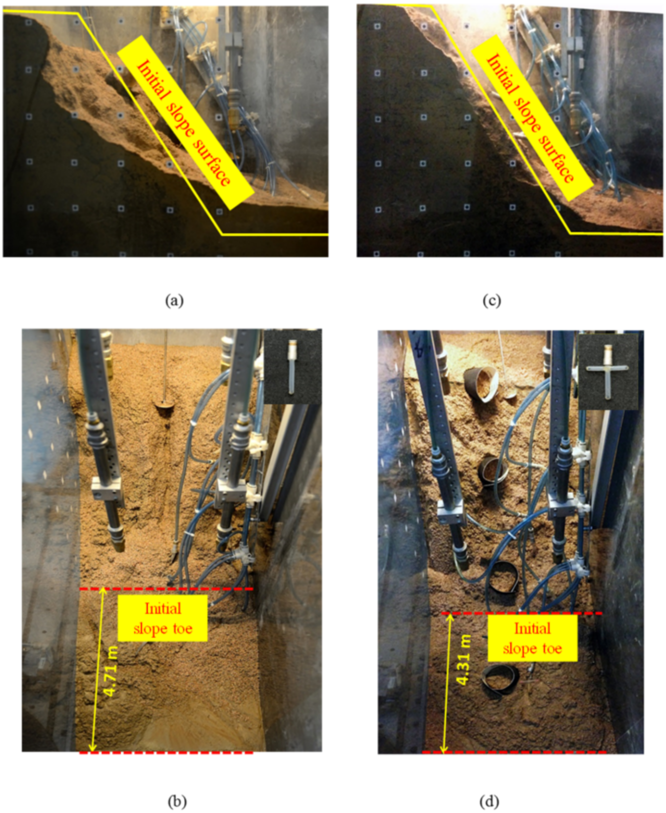

Figure 10. (a) Side view and (b) plan view of a 60° steep slope reinforced by tap-shaped roots; (c) side view and (d) plan view of a 60° steep slope reinforced by heart-shaped roots.

5. Conclusions

Sustainable and ecologically bioengineered landfill covers and slopes that use plants were studied through an interdisciplinary research programme. Three different plant species were studied. The species included tree (*S. heptaphylla*), shrub (*S. arboricola*) and grass species (*C. dactylon*) native to southern China. After 48 h of ponding (equivalent to a rainfall with a return period greater than 1000 years in Hong Kong), suction maintained under the novel vegetated three-layer landfill covers was higher than that under the bare cover. The shrub was more effective than the grass in preserving soil matric suction after intense rainfall. With the presence of plant roots, percolation in vegetated landfill covers was decreased significantly. Therefore, the vegetated three-layer landfill cover system, which uses recycled concrete and does not have a geomembrane, can effectively minimise infiltration and percolation in humid climates.

Novel artificial root systems with different idealised root architectures were developed to study the combined hydrological and mechanical effects of plant roots on slope stability in centrifuge model tests. The centrifuge experiments were conducted in the geotechnical centrifuge facility of HKUST. Findings showed that the heart-shaped roots were more effective in providing stabilisation effects in that they preserved higher suction (hence higher soil shear strength and lower water permeability) and exhibited stronger pull-out resistance compared with the two other root types during rainfall due to multiple branching. The FOS was greatly improved (up to 50%) when plant hydrological effects were considered. Therefore, vegetation should be an excellent alternative for developing sustainable and ecologically engineered landfill covers and slopes around the world.

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References

[1] N.J. Coppin, I.G. Richards, Use of Vegetation in Civil Engineering. Construction Industry Research and Information Association/Butterworths, London, UK, 1990.
[2] T.H. Wu, W.P. McKinnell, D.N. Swanston, Strength of tree roots and landslides on Prince of Wales Island, Alaska, *Canadian Geotechnical Journal* **16** (1979), 19–33.
[3] A. Stokes, C. Atger, A.G. Bengough, T. Fourcaud, R.C. Sidle, Desirable plant root traits for protecting natural and engineered slopes against landslides, *Plant and Soil* **324** (2009), 1–30.
[4] N. Pollen, A. Simon, Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model, *Water Resources Research* **41** (2005), W07025.
[5] D. Boldrin, A.K. Leung, A.G. Bengough, Root biomechanical properties during establishment of woody perennials, *Ecological Engineering* **109** (2017), 192–206.
[6] C.W.W. Ng, Atmosphere-plant-soil interaction: Theories and mechanisms, *Chinese Journal of Geotechnical Engineering* **39** (2017), 1–47.
[7] C.W.W. Ng, A.K. Leung, J.J. Ni, *Plant-Soil Slope Interaction*. Taylor & Francis, USA, 2019a. ISBN 978-1-13-819755-8
[8] S.K. Vanapalli, D.G. Fredlund, D.E. Pufahi, A.W. Clifton, Model for the prediction of shear strength with respect to soil suction, *Canadian Geotechnical Journal* **33** (1996), 379–392.
[9] C.F. Chiu, C.W.W. Ng, A state-dependent elastoplastic model for saturated and unsaturated soils, *Géotechnique* **53** (2003), 809–829.
[10] C.W.W. Ng, B. Menzies, *Advanced Unsaturated Soil Mechanics and Engineering*, Taylor & Francis Group, London, UK, 2007.
[11] C.W.W. Ng, R.Z.B. Zhou, Effects of soil suction on dilatancy of an unsaturated soil. In Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering. Osaka, Japan, 2005, 559–562.
[12] D.G. Fredlund, A. Xing, S. Huang, Predicting the permeability functions for unsaturated soils using the soil-water characteristic curve, *Canadian Geotechnical Journal* **31** (1994), 533–546.
[13] C.W.W. Ng, K.X. Woon, A.K. Leung, L.M. Chu, Experimental investigation of induced suction distributions in a grass-covered soil, *Ecological Engineering* **52** (2013), 219–223.
[14] C.W.W. Ng, A.K. Leung, K.X. Woon, Effects of soil density on grass-induced suction distributions in compacted soil subjected to rainfall, *Canadian Geotechnical Journal* **51** (2014a), 311–321.
[15] J.J. Ni, A.K. Leung, C.W.W. Ng, Investigation of plant growth and transpiration induced suction under mixed grass-tree conditions, *Canadian Geotechnical Journal* **54** (2017), 561–573.
[16] J.J. Ni, A.K. Leung, C.W.W. Ng, Modelling soil suction changes due to mixed species planting, *Ecological Engineering* **117** (2018), 1–17.
[17] J.J. Ni, A.K. Leung, C.W.W. Ng, Unsaturated hydraulic properties of vegetated soil under single and mixed planting conditions. *Géotechnique* (2019), https://doi.org/ 10.1680/jgeot.17.T.044.
[18] C.W.W. Ng, J.L. Coo, Z.K. Chen, R. Chen, Water infiltration into a new three-layer landfill cover system, *Journal of Environmental Engineering ASCE* **142** (2016a), 04016007.
[19] C.W.W. Ng, R. Chen, J.L. Coo, J. Liu, J.J. Ni, Y.M. Chen, L.T. Zhan, H.W. Guo, B.W. Lu, A novel vegetated three-layer landfill cover system using recycled construction wastes without geomembrane, *Canadian Geotechnical Journal* (2019b), https://doi.org/10.1139/cgj-2017-0728.

[20] C.W.W. Ng, B.W. Lu, J.J. Ni., Y.M. Chen, R. Chen, H.W. Guo, Effects of vegetation types on infiltration rate in three-layer landfill cover with recycled concrete, *The Journal of Zhejiang University-Science*-A **20** (2019c), 1–9.
[21] C.C. Lam, Y.K. Leung, Extreme rainfall statistics and design rainstorm profiles at selected locations in Hong Kong. Royal Observatory, Hong Kong, 1995.
[22] USEPA (U.S. EPA), Solid waste disposal facility criteria, Technical manual EPA530-R-93-017, Washington DC, 1993.
[23] R. Sonnenberg, M.F. Bransby, P.D. Hallett, A.G. Bengough, S.B. Mickovski, M.C.R. Davies, Centrifuge modelling of soil slopes reinforced with vegetation, *Canadian Geotechnical Journal* **47** (2010), 1415–1430.
[24] C.W.W. Ng, A.K. Leung, V. Kamchoom, A.Garg, A novel root system for simulating transpiration-induced soil suction in centrifuge, *Geotechnical Testing Journal* **37** (2014b), 1–15.
[25] C.W.W. Ng, V. Kamchoom, A.K. Leung, Centrifuge modelling of the effects of root geometry on the transpiration-induced suction and stability of vegetated slopes, *Landslides* **13** (2016b), 1–14.
[26] A.K. Leung, V. Kamchoom, C.W.W. Ng, Influences of root-induced soil suction and root geometry on slope stability: a centrifuge study, *Canadian Geotechnical Journal* **54** (2017), 291–303.
[27] B.C. Hau, R.T. Corlett, Factors affecting the early survival and growth of native tree seedlings planted on a degraded hillside grassland in Hong Kong, China, *Restoration Ecology* **4** (2003), 483–488.
[28] A. Stokes, C. Mattheck, Variation of wood strength in tree roots, *Journal of Experimental Botany* **47** (1996), 693–699.
[29] L.J. Waldron, S. Dakessian, Soil reinforcement by roots: Calculation of increased soil shear resistance from root properties, *Soil Science* **132** (1981), 427–435.
[30] A.R. Ennos, The anchorage of leek seedlings: The effect of root length and soil strength, *Annals of Botany* **65** (1990), 409–416.
[31] V. Kamchoom, A.K. Leung, C.W.W. Ng, Effects of root geometry and transpiration on pullout resistance, *Géotechnique Letters* **4**(2014), 330–336.
[32] Geo-Slope International Ltd., Stress-Deformation Modeling with SIGMA/W, An Engineering Methodology, 4th edn., 2009.
[33] F.T.Y. Leung, The use of native woody plants in slope upgrading in Hong Kong. PhD thesis, The University of Hong Kong, Hong Kong, China, 2014.