Modeling Mechanical Reinforcement of Vegetation to Wall Stability: A Case Study of a Short Retaining Wall in Hong Kong

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Abstract

A numerical investigation is conducted to examine the effect of mechanical reinforcement of vegetation (trees and shrubs) on the enhanced factor of safety of gravity wall using the Rankine-Bell equation with common geotechnical checking on sliding and overturning. A case study in Hong Kong with a masonry wall and tree groups at the crest is selected for analysis. Results show that the root reinforcement could more than offset the surcharge from the weight of the vegetation and stabilize the wall in normal condition, but the detrimental effects outweigh the benefits under extreme gusts. Parametric studies have also been conducted to assess the sensitivity of wall stability to the variation of vegetation effect (root cohesion c_{r} and root zone h_{r}). A noticeable increase in factor of safety is observed and wall stability is more sensitive to the depth of root zone h_r than root cohesion c_r. Results of the current study encourage practitioners to consider the mechanical reinforcement of vegetation in geotechnical assessments of the stability of wall and it could be useful in solving conventional design problems of wall less than 3m and with less structural measures.

Keywords: Shallow Failure, Wall Vegetation, Root Reinforcement, Stability Analysis.

1 Introduction

Old stone retaining walls with vegetation are unique features in Hong Kong. Though they are of high preservation value, many of them are substandard as they were built in the old days and often situated in areas with many site constraints (Jim, 2012). Technical guidelines on slope mitigation often go with structural works for reinforcement as conventional practice, in which their properties are more controllable, and the slope is more robust in return. However, the urge for more environmentally friendly solutions is raising. There have been extensive research and engineering in providing a multitude of examples and protocols for representing and calculating the stabilizing effects of tree roots in slope stability models. Vegetative crib walls have been put into practice as a bio-engineering measure to improve the stability of a soil slope (Tardío & Mickovski, 2016). The presence of plants, living components, changes the soil conditions and even serve as structural members when they are well established. Better recognition and limitation of root-soil interactions shall enable engineers to choose the best additions for stability.

In Hong Kong, studies on stabilization and restoration with vegetation have been launched on natural terrain landslide sites in 2006 (GEO, 2008) while the use of bioengineering is mainly related to landscaping in man-made slopes (GEO, 2011a). Effect of wall trees on stability of masonry walls was examined in GEO Report No. 257 (GEO, 2011b) but the contribution of root reinforcement is neglected in the analysis due to the difficulty in quantifying the effect of roots. There is currently little

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information or specific case studies that can provide guidance on how to numerically assess the stabilizing effect of the roots behind the wall permeating the backfill.

In this paper, a case study of a 3m high masonry wall in Hong Kong with mechanical reinforcement of vegetation is investigated following the modified Wu model (So & Choi, 2021) on wall stability. Field data are collected for root reinforcement modeling and cross-reference with literatures. Conventional geotechnical assessments on sliding and overturning of retaining wall are performed. Parametric studies are carried out to evaluate the sensitivity of wall stability to the variation of vegetation effect (root cohesion c_r and root zone h_r).

2 Case Study

A masonry retaining wall located near the crest of the soil slope has a maximum retaining height ranging from 1.5m to 3.2m. A grassy sloping ground with mature trees (trunk diameter varies from 300mm to 750mm) with a spacing of 2m to 3m are located all along the back of the masonry wall (Plate 1). An existing box culvert and existing covered surface channel (Plate 2) were located just behind the masonry wall.

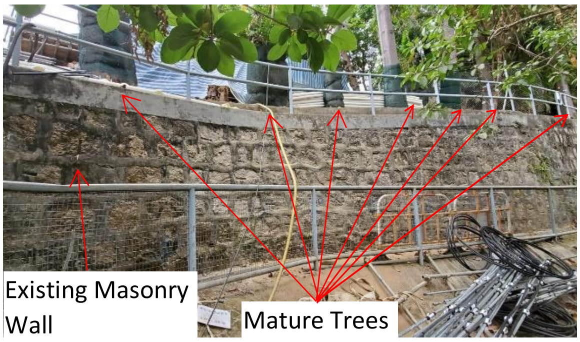

Plate 1 A tree group at the crest of the masonry wall

Plate 2 Crest facility at the study feature

Ground investigation revealed that the masonry wall is founded on loose-fill and retaining a fill slope at the crest. Stability analyses showed that the calculated minimum factors of safety are lower than the required minimum factor of safety from conventional checking of gravity walls. As the slope does not possess adequate factors of safety to meet the required safety standard, slope upgrading works are necessary.

Pit by pit excavation and backfilling with lightweight concrete and soil nailing with tie column were selected for different portions of the wall following their retaining height to cater for site constraints. During construction, intermingled roots of different individual trees were observed. The extent of soil replacement was much less in the presence of trees. Because of this, the feasibility of providing alternative means to effectively stabilize the wall while retaining the tree had been examined in detail but not forthcoming. In the absence of any other feasible mitigation measures, the removal of three trees/shrubs is necessary to upgrade the masonry wall to the current standard and to ensure public safety.

A post-construction review was carried out to determine the mechanical reinforcement of tree roots on the stability of the masonry wall. (Gray & Sotir, 1996) mentioned the mechanical effects as shown in Table 1. A single tree with the largest DBH at the crest area is selected for modeling and parameters required including the root cohesion, tree weight, and wind forces are presented.

Table 1. Influence of vegetation on slope stability (modified after Gray & Sotir, 1996)

Mechanical mechanism	Result	Influence
Reinforcement and anchorage by root	Increasing shear strength	+
Weight of trees surcharges the slope	Increasing normal and downhill force components	+/-
Vegetation exposed to wind	Transmits dynamic forces into the slope	-
Roots bind soil particles at the ground surface	Reducing susceptibility to erosion	+

3 Estimation of Root Cohesion

Methods in modeling the root reinforcement began with (Wu, 1976), (Waldron et al., 1977), and (Wu et al., 1979) in the late 70s, also known as “Wu and Waldron’s model” (WWM). The increased shear strength due to root reinforcement τ is commonly modeled via an additional term called “root cohesion”, c_r, into Mohr-Coulomb failure envelope equation.

$$\tau = c_r + c_s + \sigma \tan \phi \qquad (1)$$

where c_r is the additional “root cohesion”, c_s is the soil cohesion, σ is the normal stress on the shear plane and $\tan \phi$ is the slope of the failure envelope while ϕ is the soil friction angle.

When there is a soil movement like a translational shallow failure, soil shear stress is developed and roots crossing the failure plane are mobilized in tension. Figure 1 shows the mechanism of soil-root reinforcement and the fiber breakage model. The resulting additional shear strength can be predicted by:

$$c_r = (\sin\ \xi + \cos\ \xi \tan\ \emptyset') \cdot T_r \cdot RAR \qquad (2)$$

where ξ is the shear distortion angle of a root within the shear zone, T_r is the mean tensile strength of roots and RAR is the root area ratio, i.e., the sum of the total cross-sectional area of root (A_r) over soil (A_s). (Wu, 1976) proposed an average value of 1.2 for $(\sin \xi + \cos \xi \tan \emptyset')$, considering the roots are not oriented perpendicular to the slip surface.

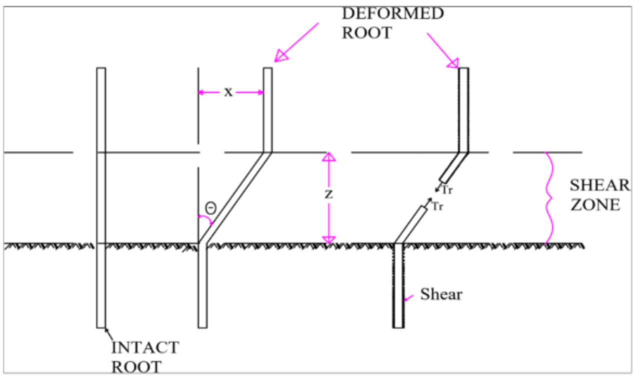

Figure 1: Fiber breakage model (adapted from Tsige et al., 2019)

(Leung et al., 2015) further narrowed the typical values to 1.15-1.17 with consideration of Hong Kong geological information. (So & Choi, 2021) proposed a presumed value of 1.15 for conservative use and this value is adopted in this study. Combining the above all and the root cohesion can be estimated as:

$$c_r = 1.15 \cdot T_r \cdot RAR \quad (3)$$

3.1 Rar Determination

There are generally two methods in obtaining the RAR values, namely the "core break" sampling (Schmid & Kazda, 2002) and the "profile wall" method (Böhm, 1979). As the site works included pit by pit excavation and backfilling with lightweight concrete right behind the wall, the latter method was selected for sampling. Root counting is performed with image processing on the trench profile wall photographs followed by counting pixels that contain roots in the image histograms in Photoshop (Eab et al., 2015). A profile of rooted soil down to 3m depth was exposed and several images were taken. However, it turned out the root distribution can hardly be recognized and rightly mapped with image processing in the presence of coarse roots and similar colors of roots and soil, though they provide anchorage effects. Manual data labeling was done instead for data correction.

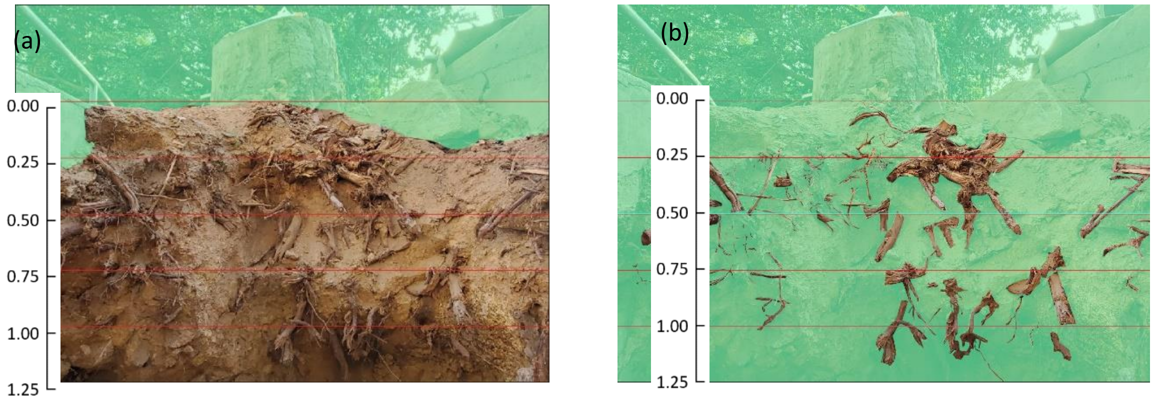

Figure 2: (a) rooted soil photograph taken from a 30m high species with a DBH of 750mm up to 1.25m depth

(b) processed image with manually filtered roots and a root area ratio from 1.95% to 8.22%

One tree sample photo with depth up to 1.25m is shown in Figure 2. For fitting in the modified Wu model, only the roots with diameters between 1mm to 10mm are counted and it is assumed to be 1/3 of total roots (Leung, 2014). RAR for a eucalyptus tree after discounting are 4.84%, 8.22%, 4.82%, 4.26%, 1.95% with an increment of 0.25m up to 1.25m along with the depth.

3.2 Tensile Strength Determination

In the view that no pull-out test / tensile strength test is conducted for the tree species on-site, a presumed value of 8MPa is adopted for our case (So & Choi, 2021).

3.3 Root Depth and Root Zone

Though a rough rule of thumb the mechanical reinforcement of roots is suggested to be limited to a zone about 1.5m from the surface (Gray & Sotir, 1996). On-site pit excavation revealed the eucalyptus tree could extend deep into the ground (observable up to 2.3m) (Plate 3). A maximum root depth of 2.25m is selected for modeling. The field result is comparable to the dataset of three 25-year old excavated Monterey pine trees with an average height of 30m and a mean stump diameter of 60cm (0.2m above ground), and their vertical roots penetrated 2.93m on average (Watson & O'Loughlin, 1990). Therefore, the rooted zone is assumed to be 1.7m (W) * 3m (L) * 2.25m (D) due to high stiffness structures at the back of the wall, limiting the spread of tree roots.

Plate 3 Exposed root system of a 30 m high eucalyptus tree and root depth = 2.3 m

It is not certain that the semi-empirical formula of calculating c_r can be used with RAR beyond 0.7%, though the field results were up to 8%. A uniform root architecture RAR value = 1.0% is considered for conservative use. Following Eq. (3), an average value of root cohesion with depth corresponded to c_r = 92.0 kPa. However, this value still appears to be larger than the typical c_r values recommended in Table 8 of Geoguide 1 (GEO, 2020) for in-situ completely decomposed granites. Therefore, the value is capped at a maximum of c_r = 15 kPa and used to simulate the effect of uniform roots on wall stability. Superposition effects from tree groups are suggested by (Docker, 2003) but they are ignored in this study for simplicity.

3.4 Tree Weight

The weight of vegetation is considered as a surcharge load and it would have a major influence on slope stability when the vegetation cover is heavy. It increases the slice weight and in turns increases the slice base normal and shear resistance. (Greenwood et al., 2004) suggests that DBH > 0.3m of a tree is a threshold value of considering a major implication of tree weight to slope stability. Some of the key indicators in determining the surcharge loads due to the weight of trees include the size, density, and species of vegetation. (Emadi-Tafti & Ataie-Ashtiani, 2019) summarised the surcharge loads reported by numerous researchers. GEO Report No. 257 (GEO, 2011a) recommends equations

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using biomass regression method with DBH as main parameters developed by (Jenkins et al., 2003) to determine the dry mass of trees and the species group of “hard ample/ oak/ hickory/ beech” was selected. There is also a 50% increase in tree truck density with moisture content. In this study, we adopted the equations suggested from GEO Report No. 257 (GEO, 2011a) for calculation.

$$\mathrm{b_m} = \mathrm{Exp}(\alpha_0 + \alpha_1 \ln DBH) \quad (4)$$

$$ratio = \mathrm{Exp}(\beta_0 + \beta_1 \,/\, DBH) \quad (5)$$

where $\mathrm{b_m}$ is the total aboveground biomass (kg) for trees 2.4cm DBH and larger, DBH is the diameter at breast height (cm) which measured at 1.3 m above the trunk base, α_0 = -2.0127, α_1= 2.4342, ratio = component to total aboveground biomass, β_0=-0.3065, β_1= -5.4240 for stem wood.

3.5 Wind Loading

Much of the masonry wall failure is associated with tree uprooting during hurricanes in Hong Kong GEO Report No. 257 (GEO, 2011a). Urban trees are often grown with many big branches, shallow roots, and shallow root plates (Ken James, 2020). When they are exposed to wind, an overturning moment is acted on the root plate. If the root anchorage is not strong enough, tree uprooting will happen. These additional dynamic forces will also be transmitted into the masonry walls, having an adverse effect on their stability. GEO Report No. 257 (GEO, 2011a) outlines the procedures in estimating the static and dynamic force of the wind acting on trees and in turn evaluate the stability of the wall tree. Herein the static drag force is only considered and estimated by the following equation with a conservative assumption that the wind flow is acting downslope.

$$\mathrm{F} = \frac{1}{2}\rho \mathrm{C_D} \mathrm{A} \mathrm{V}^2 \quad (6)$$

F= the wind force (newtons, N), ρ = the density of air (kg/m^3), $\mathrm{C_D}$= the drag coefficient (dimensionless), A= the frontal area (m^2), V= the wind velocity (m/s)

Wind velocity = 26m/s, a critical wind speed of tree failure as reported in GEO Report No. 257 (GEO, 2011b)

Frontal area of the truck = tree height * DBH =22.5m^2

Frontal area of the crown = 12m (spread of crown) * 15m (upper half of tree height) * 0.25 (an assumed reduction factor) = 45m^2

Drag coefficient of truck = 0.5, Crown=1.2

Uniform distributed load = Loading / Load spread area (extent of lateral roots = 1.7m (W) * 3m (L))

Table 2. Summary of the tree weight and the wind load for the eucalyptus tree

DBH (cm)	Height (m)	Tree spread (m^2)	root area	Tree Weight (kN)	Distributed load (kN/m/m)	Wind load (kN)	Distributed load (kN/m/m)	Moment (kNm/m)
75	30	5.1		64.5	12.64	27.03	9.01	218

4 External Stability

Same as typical retaining structure, bio-engineering structure is also checked along with existing geotechnical engineering standards (sliding and overturning) and expressed with factor of safety for their stability according to Geoguide 1 (GEO, 2020). Forces, i.e., self-weight, earth pressure from the backfill, hydrostatic pressure, loads from structures, which are acting on the wall are considered, and the wall is assumed as a monolithic structure. In this study, global factor is adopted for conventional checking, except in examining wind load with a partial factor in overturning moment checking. The resistance to sliding and overturning will be affected by the apparent cohesion from roots. The internal stability of masonry wall is ignored for conventional checking. Yet, it is worth mentioning that plant roots tend to avoid zones of stress and thus not disrupting or compromising the structural integrity of the wall (Gray & Sotir, 1996).

The apparent cohesion value calculated by Eq. (3) will be further incorporated into the calculation of active soil pressure on retaining wall following Bell's equation (for a cohesive backfill with a horizontal ground surface) and Rankine theory in the root zone, with a tension crack developing to a depth z_c. Negative earth pressures within this zone and cases of tension cracks filled with water are ignored in this study. Development of tension crack is confined to the root zone only if the critical depth is larger than the depth of root zone. Figure 3 and Figure 4 illustrate a modified wall geometry and the normal stress acting on the wall with the tree.

$$k_a = \frac{1-sin\phi}{1+sin\phi} \quad (7)$$

$$P_a = \sigma_z \cdot k_a - 2c\sqrt{k_a} \quad (8)$$

$$z_c = \frac{1}{\gamma\cdot}\left(\frac{2c}{\sqrt{k_a}} - q\right) \quad (9)$$

5 Modelling

A 3m high and 0.9m width masonry wall with the following assumptions is modeled as a typical example.

- 2D plane strain model
- The wall is with a vertical back and the ground surface is horizontal.
- Isotropic, homogenous soil layer
- The interface slope is horizontal.
- 1/3 water at retaining height to cater for the groundwater rise during a 1 in 10 years return period rainstorm.
- Wall friction is assumed to be 2/3 φ and base friction = 0.9 φ

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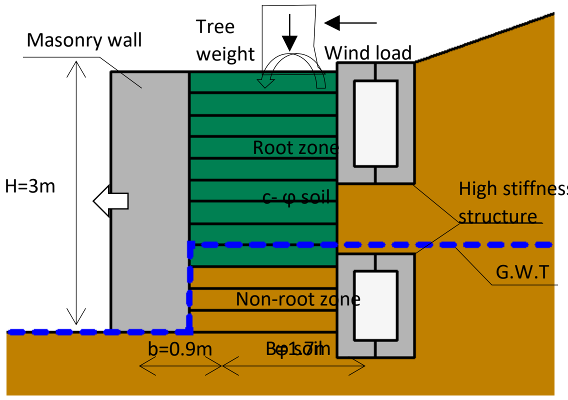

Figure 3: Typical example of a masonry wall with tree

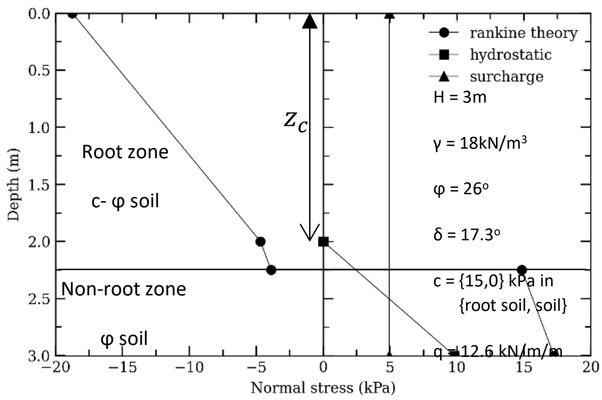

Figure 4: Illustration of the normal stress acting on wall

The external stability check is shown in Table 3.

Table 3. External stability check. Sliding and overturning safety factor formula adapted from Geoguide 1 (GEO, 2020)

Mode of Failure	No vegetation	With vegetation (Tree weight)	With vegetation (Tree weight and wind load)
FoS sliding	0.85	1.28	0.88
FoS overturning	1.06	3.09	0.08<1.0 (Partial Factor for wind load)

6 Results

The external stability analysis without vegetation gave results of FoS = 0.85 and 1.06 for sliding and overturning respectively, which is as expected for a slender wall with limited self-weight. When mechanical reinforcement and surcharge from tree weight are considered, it yields FoS = 1.28 for sliding and 3.09 for overturning which are a significant increase. The wall that was initially unsafe/marginal safe (FoS <1 and ~1) is now safer. However, when wind effect is considered, the FoS against sliding falls back to 0.88 and overturning even diminishes to 0.08. Wall failure by overturning is expected. In fact, many walls would fail, based on the stability analysis using field data, but remain intact for a long time. The root reinforcement should more than offset the surcharge from the weight of the vegetation (Gray & Sotir, 1996). The mechanical effect of vegetation is the major factor in stabilizing the wall.

7 Parametric Studies

It is of practical interest to demonstrate the effect of root reinforcement by FoS increment with respect to bare slope. Parametric studies were performed for depth of root zone h_r and apparent root cohesion c_r and applied in the typical example. Young trees and shrubs are considered which are with negligible weight and windthrow problems. Figure 5 and Figure 6 show how the value of FoS increment is influenced by h_r and c_r.

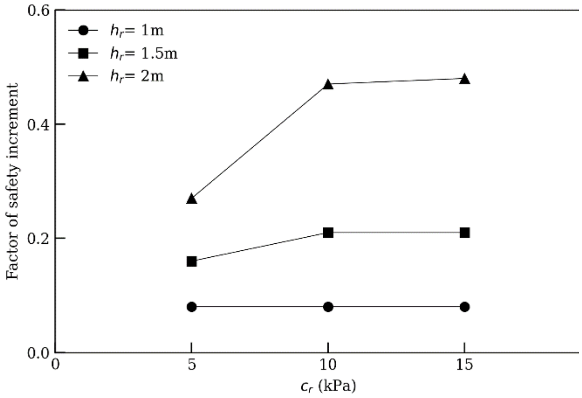

Figure 5: Factor of safety increments for the root zone with respect to bare slope against sliding

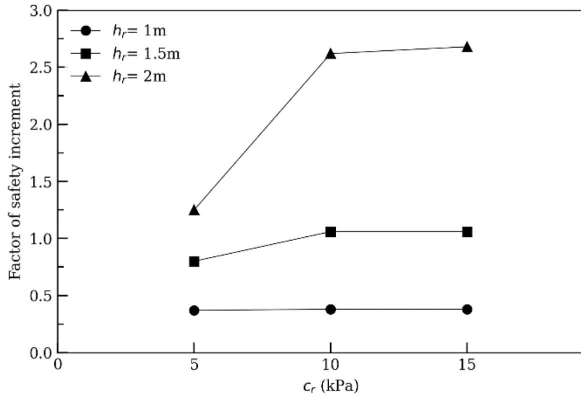

Figure 6: Factor of safety increments for the root zone with respect to bare slope against overturning

Both FoS increment against sliding and overturning follows similar trends. The FoS increments increase with increasing c_r at a gentle rate when c_r lies between 5 kPa and 10 kPa and remain constant when c_r goes beyond 10 kPa. Increments of 0.27 against sliding and 1.25 against overturning are observed at h_r= 1.0m and c_r= 15kPa. When c_r increases from 5 kPa to 15 kPa, the increment is increased by 78% for h_r = 2m and by 0% for h_r=1m against sliding, while overturing yields a FoS increment of 114% for h_r = 2m and 3% for h_r = 1m. Particular attention is drawn to the cases in which the increased FoS are almost constant. It is because the development of tension crack is limited by the depth of root zone and a further increase in root cohesion would have limited beneficial effects on wall stability.

8 Discussion

8.1 Stone Wall Failure Versus Tree Failure

Though the FoS against overturning under windthrown condition indicates there is an overturning failure, the tree is much likely uprooted rather than wall failure. A review of wall failure history in Hong Kong was conducted by (Jim, 2012). Reported cases of two recent stonewall tree failures indicated there were tree failures without damage to wall structure. The lack of joints or avenues for roots to penetrate the wall is considered as the fundamental cause of insecure root anchorage, and thus leading to tree overturning under extreme gusts. On the other hand, wall failures were mainly attributed to poor design, workmanship, maintenance, and sometimes associated with leaking pipes situated behind the wall.

8.2 Tree anchorage and lateral root

For fitting in Wu model, the contribution from coarse roots (diameter >10mm) is not counted in this study and they shall act as bending beams to counteract the shear force. For woody root species such as trees and shrubs, the majority of the total root mass are structural and coarse roots. 62% of the total roots are coarse roots (>5mm) in one study of a spruce tree reported by (Parr & Cameron, 2004). Structural analysis, i.e. using p-y models, can be used to estimate the root-soil interaction when the roots are subject to lateral loading (Meijer et al., 2019). The selection of prediction models on root reinforcement is discussed in (So & Choi, 2021). When considering engineering use of vegetation to stabilize the walls, roots must cut through the failure surface to provide a stabilizing effect.

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For a (45° + φ/2) active failure plane, woody plants with propensity of deep rooting and lateral spreading is advisable for maximizing the mechanical reinforcement of vegetation (Liang et al., 2020).

9 Future Work and Limitation

While the beneficial effects of roots are notable in wall stability, the following areas shall be considered in future works.

- Probabilistic study of root distribution on wall stability shall be examined given that the randomness of root depth and distribution. A dataset of maximum root depth for woody plant with fitted distribution indicates it is a lognormal distribution (Zhu et al., 2017). Deterministic analysis on uniform root length could not accurately capture the effect of mechanical reinforcement.
- In considering the mechanical effect of a single species, the increase in shear strength of soil is often exponentially reduced with depth. Root cohesion with a non-linear distribution would give a better estimation of root effect. Yet, much of the root reinforcement studies reveal the vegetation exhibit a central zone with the most contribution to soil strength in the first two meters. For woody plants with intervals, it would be more practical to model the root cohesion with a stepped function in shallow depth when examining the slope stability.
- Evapotranspiration is ignored in this study. Consideration of matric suction shall further increase the safety factor and prevent shallow landslides.

10 Conclusion

The effect of root reinforcement is conventionally neglected due to difficulties in quantifying the roots as suggested in GEO Report No. 257 (GEO, 2011a). However, consideration of the mechanical effect of roots could be effective, particularly in a congested site in reducing the use of structural measures in stabilizing retaining wall with physical constraints and construction difficulties at shallow depth. For example, tree roots could replace the top row of soil nails or otherwise, the tree roots would act as obstructions to the installation of soil nails if the root strengthening effect is ignored. A real case history showing the retaining wall with tree groups at the crest that was below the safety margin and substantial upgrading works were conducted to meet the statutory requirements. Application of mechanical reinforcement of tree roots to slope stabilization have been reviewed in a companion paper (So & Choi, 2021) and a post-construction review is conducted on tree roots effects on wall stability. The apparent root cohesion c_r has been incorporated in the wall stability analysis using Rankine-Bell equation. Deep-rooted trees are beneficial to wall stability when wind speeds are low. In one example the 2.25m deep-rooted trees provide 51% and 192% in FoS against sliding and overturning respectively. However, when windthrow failure is considered, the wall stability will drastically decrease. There is not much increase in FoS against sliding and FoS against overturning even drops to a very unsafe point. Parametric studies reveal that the wall stability is more sensitive to the depth of root zone h_r than root cohesion c_r. The development of tension crack is limited by the depth of root zone and further increase in root cohesion would have limited beneficial effects on wall stability. For engineering application in wall stabilization, shrubs with propensity of deep rooting and lateral spread are recommended to be used to minimize surcharge and windthrow problems while maximizing the mechanical reinforcement. The result of this post-construction review is encouraging and further investigation on the application of root reinforcement is recommended.

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