On the Application of Mechanical Reinforcement of Tree Roots to Slope Stabilization

Arthur K O So* & Ricky Y S Choi

Meinhardt Infrastructure and Environment Limited

*Corresponding author
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Abstract

The root strengthening effects on soil behind retaining walls may be quantified by a simplified equation $\Delta S = 1.2T_R(A_R/A)$ where ΔS, T_R and A_R/A are the shear strength increase, tensile strength of root and root area ratio respectively. However, this effect is ignored during stability analysis due to the possible significant variability of the potential beneficial effect and extreme difficulty in fully characterizing the tree roots and quantifying their effects. In this paper, advancements in the last few decades in biotechnical slope stability are reviewed. Representative models to quantify the mechanical effects of tree roots are studied. If other potential beneficial effects due to existence of roots and suction effect due to transpiration of tree are ignored, the term 1.2, root tensile strength and root area ratio may still be the three key parameters to the root strengthening effect in slope stability. However, for plants with larger structural roots where root bending rather than axial breakage is dominant, the roots may be considered using beam bending or p-y models. Based on the information commonly used for slope design and obtained from literatures, presumed values of two key parameters and a simple insitu measurement method invented by other are recommended.

Keywords: Biotechnical Slope Stabilization, Root-Soil-Slope Interactions, Mechanical or Root Reinforcement, Predictive Models, Root Architecture, Presumed Values, Parametric Studies

1 Introduction

Vegetation had been used as foundations, retaining walls and to stabilize slopes and embankments 4,000 years ago in ancient China (Smith and Snow 2008) and ancient Rome (Partov et al. 2016). The design and utilization at that time were basically empirical in nature. Despite the incorporation of vegetation effects onto slope stability analysis was introduced in 1960s (Greenway 1987), current practice in most part of the world still considers vegetation mainly for aesthetic purposes and erosion control. The engineering functions of plant roots have been generally ignored in the scientific analysis and design of slope stability. As in the GEO Report No. 257 (GEO 2011), the root strengthening effects on the soil behind retaining walls was quantified following a simplified equation $\Delta S = 1.2\ T_R\ (A_R/A)$ by Wu et al. (1979) where ΔS, T_R and A_R/A are the shear strength increase, tensile strength of root and the root area ratio (RAR) respectively. However, the Report concluded that this equation may be conservatively ignored during stability analysis due to the possible significant variability of the potential beneficial effect and the extreme difficulty in fully characterizing the tree roots and quantifying the strengthening effects of tree roots.

In this paper, the root reinforcement model by Wu et al. (1979) is examined. Advancements in the last few decades in the biotechnical slope stability, and in particular the soil variability and effect of

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vegetation are reviewed. Other representative models to quantify the mechanical effects of tree roots are studied. The key design parameters to the root strengthening effect in slope stability are identified. Based on the information commonly used for slope design and obtained from literatures, presumed values of two key parameters and a simple insitu measurement method invented by Meijer et al. (2019) are suggested. Hypothetical slope analyses and parametric studies are carried out.

2 Literatures Review

The Root Reinforcement Model of Wu et al. (1979): The model is based on the Mohr-Coulomb equation

$$S = c + \sigma_N \tan\phi \quad (1)$$

where S = soil shearing resistance, c = cohesion, σ_N = normal stress on the shear plane and ϕ = soil friction angle. Waldron (1977) first assumed that all roots extended vertically across a horizontal shear zones and the roots act like laterally loaded piles so that tension is transferred to the roots as the soil is sheared. The equation is therefore modified as

$$S = \Delta S + c + \sigma_N \tan\phi \quad (2)$$

and $$\Delta S = T_R (\sin\theta + \cos\theta \tan\phi) \quad (3)$$

where ΔS = increased shear strength due to the roots, T_R = tensile strength of roots and θ = angle to the shear plane. Gray (1974) reported that the results of several studies on root permeated soil showed that ϕ appeared to be affected little by the presence of roots. ΔS may therefore be considered as an increase in c or the apparent cohesion c_r. Sensitivity analysis by Wu et al. (1979) showed that the bracket $(\sin\theta + \cos\theta \tan\phi)$, or k' as termed by some researchers, is fairly insensitive to the normal variations in θ and ϕ with values ranging from 1.0 to 1.3. A value of 1.2 was therefore selected and the equation became-

$$\Delta S = 1.2\, T_R (A_R/A) \quad (4)$$

where AR/A is the root area ratio RAR. Thus, the root reinforcement simply depends on RAR and TR. Despite this model is simple to use, it may be over-simplified as it assumes that: i) the roots are well anchored and do not pull out when tensioned (fibre break), ii) the roots are perpendicular to the slip plane (perpendicular root), iii) the full tensile strength of all roots is mobilized when the soil shears, and therefore considers the forces acting in the root-soil matrix when all roots reach their maximum tensile stress. Furthermore, the variability in vegetations and effects of root architecture might have imposed uncertainty in the predictions. In order to have a better understanding of the biotechnical slope stability, advancements in the knowledge and technology in the last few decades are reviewed.

2.1 Slope Stabilization Function of Plants

Ng et al. (2019) and Bordoloi and Ng (2020) have attempted to provide a state-of-the-art for the vegetation in engineered slope stability by viewing the effect of inherent plant traits/parameters with that of its slope stability and protection functions. Their work reviews can be distinguished into three areas: 1) the plant-soil-atmosphere continuum, 2) an overview of the major stability functions provided by plant in slope, and 3) a new gap area and function scope in engineered vegetated slopes.

Figure 1 is a schematic representation of the stabilization functions provided by plant in slope which includes; namely, a) the root reinforcement, b) the hydrological reinforcement, and c) the interception. Both the root and shoot architecture affect these functions. The root reinforcement in turn includes: i) the tensile force mobilization and anchorage upon hard stratum, ii) the soil aggregation by root growth, and iii) the secretion of cohesive enzymes called mucilage.

For the purpose of this paper, only the mechanical reinforcement of root (shaded in Figure 1) is focused, but not other potential beneficial effects, such as the increase in soil aggregate stability by roots interweaving in the soil matrix, roots exudating organic matters to increase the soil structure, root caps secreting mucilage to bind the soil particles, and micro-organisms producing polysaccharides to enhaunce the formation of soil aggregates (Vannoppen et al. 2015). Suction effect due to transpiration of the tree is also ignored.

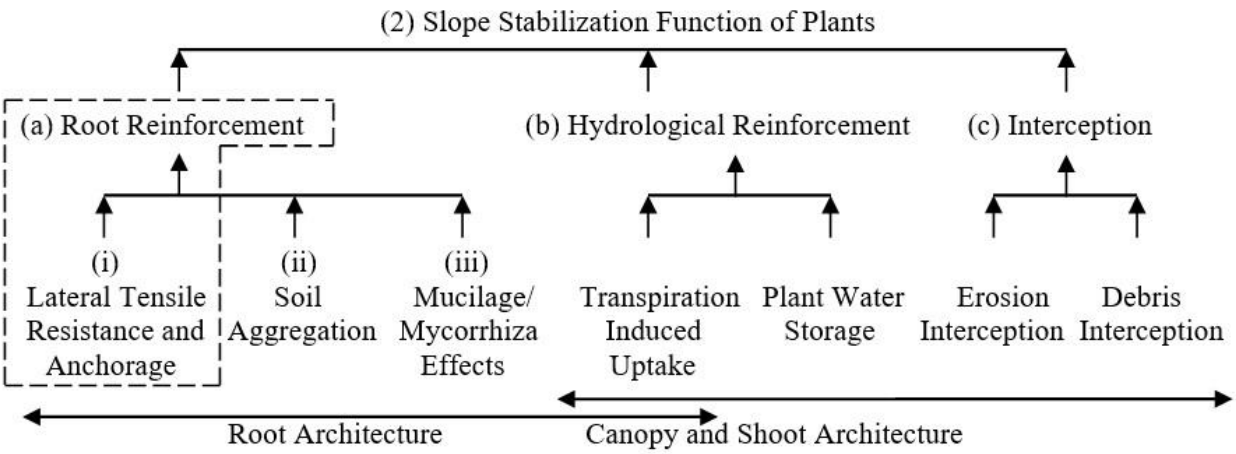


Figure 1: Schematic Representation of the Major Slope Stabilization Functions of Plants (modified after Bordoloi and Ng, 2020)

The incorporation of vegetation effects on slope stability resembles a reinforced soil slope analysis. It involves complicated interaction of two natural materials, unsaturated soils and plants, and crosses over the fields of unsaturated soil mechanics, plant science and ecological science. Table 1 is a summary of the basic parameters for the inter-dependent of the root-soil interactions to determine the mechanical strength (shear strength and Young's modulus) of rooted soil in slopes.

Table 1. Root-Soil Interaction in Terms of Basic Parameters that Govern the Mechanical Strength of Rooted Soil (modified after Bordoloi and Ng, 2020).

Root	**Soil**
Condition (Living/Dead)	Particle and Pore Size Distribution
Fine/Coarse Root Ratio	Matric Suction and Water Content
Micro-Fibrillary Angle	Stress History
Root Diameter	Density
Root Architecture (Sinuosity)	Mineralogical Content
Bio-Polymer Composition	Nitrogen Availability

2.2 Variability of Vegetation and Soil and their Effects to Roots

Vegetation may be classified as herbs (including grasses and ferns), climbers, shrubs, small trees (around 3m tall), medium trees (much taller than 3m with small crown) and large trees (taller than 10m with large crown) (GEO 2008). Different species have different root systems (tap root and fibrous root) and root architecture (uniform, triangular, exponential and parabolic), and properties of soil affect the spatial distribution and depth of the root system. Perry (1989) commented that the variation in root size from large woody to small non-woody, perennial to ephemeral, and absorbing to non-absorbing is continuous. This makes the sorting of roots into various category arbitrary, but classification and sorting are still essential to comprehending the pattern and integrated function of the total root system. Coppin and Richards (1990) reported that individual species vary in their rooting behaviour, but soil type and ground water regime strongly influence the root development. e.g. Roots in well-drained soils have to go deeper and exploit a much larger volume of soil than those in moister soils while a high groundwater level or a layer of densely compacted soil will force roots to spread laterally. The majority of roots are usually found within 300-400mm depth in herbaceous vegetation and up to 3m deep in vegetation dominated by trees and shrubs. Dobson (1995) reported that most roots are found close to the soil surface with 90% or more of all roots located in the upper 600mm. It is uncommon for trees to have roots deeper than 2m though exceptionally some small roots (a few mm in diameter) can extend to 5m or more.

Of the mechanical properties of roots, many researchers (e.g. Coppin and Richards 1990, Abernethy and Rutherford 2001, Simon and Collison 2002, Pollen and Simon 2005, Stokes et al. 2008, Leung et al. 2015 and Ji et al. 2020) reported an exponential decrease in root tensile strength with increasing root diameter. Regarding the root-soil interaction, Abe and Ziemer (1991) used a large shear box to shear across a vertical plane and found that the amount of root deformation increases as the number and size of roots decrease. Tobin et al. (2007) found that roots can stretch by 10-20% of their length before failure whilst most soils fail at strain around 2%. Based on in-situ field shear tests for different tree species, Docker and Hubble (2009) showed two modes of root failure: type 1 failure which occurs after reaching maximum shear resistance and diminishes as the displacement increases, and type 2 failure which occurs before reaching a maximum resistance with continuous increasing shearing resistance. Thomas and Pollen-Bankhead (2010) found that the root architecture has a significant impact on the loading curve shape and the peak load supported by a root bundle. Based on triaxial tests, Meng et al. (2020) showed that roots under low confining pressure can play a greater role in resisting the failure of rooted soil, and its ability is affected by root geometry (number, diameter and length) and distribution characteristics (root angle).

2.3 Measurement of the Mechanical Behaviour of Roots

The measurement of mechanical behaviour of roots started in 1970s (Wu 2007, Giadrossich et al. 2017). They may be distinguished into two main types of tests: 1) direct measurement of a specific behaviour of root and 2) combination of root and soil as a matrix. Tensile strength tests, compression test, buckling tests and pullout tests are in the former group and are for woody roots. They can be carried out on a single root or on a bundle of roots in the field or in the laboratory. Shearing of a block of rooted soil in field or a rooted soil column in the laboratory, direct shear test and rooted soil under compression are tests in the latter group. They are for finer roots of which the roots are part of the soil system and the effect of each one cannot be separated but can only be considered within a global behaviour. Some innovative methods are the X-ray computed tomography and digital volume correlation (Bull et al. 2019) and the Corkscrew extraction method (Meijer et al. 2019).

2.4 Predictive Root Reinforcement Models

The researches of root reinforcement began with direct shear tests performed on soil blocks containing roots, e.g. Endo and Tsuruta (1969), Wu (1976). Since then many models were developed which may be classified (e.g. Liang et al. 2020) into: 1) a continuum approach which considers root-soil matrix as a homogeneous material of increased strength or root cohesion, or 2) a root-soil interaction approach which considers roots as structural elements embedded in soil. The additional resistance in soil due to roots is introduced into stability calculations, which may be distinguished as: a) fibre pull out model, b) fibre break models, c) fibre bundle model, and d) beam bending or p-y model. Some representative models are given in Table 2.

Table 2. Some Representative Root Reinforcement Models

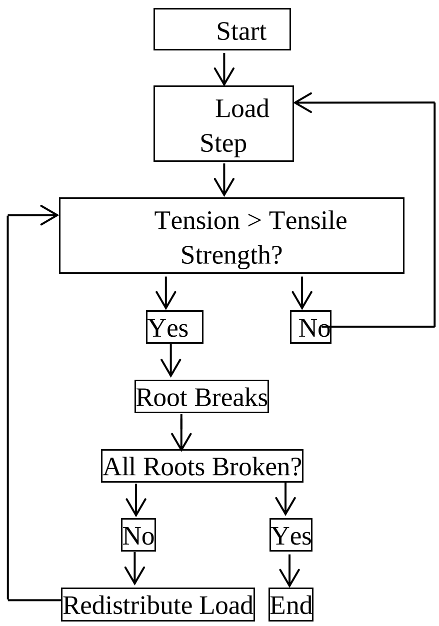
	Authors	Models
Fibre Pull-Out Model		
1.	Endo and Tsuruta (1969)	$S = (c + r) = W \cos\alpha \tan\phi$ where S = shear strength of root-soil, c = cohesion of soil, r = apparent cohesion, W = effective weight of soil, α = slope of failure surface, and ϕ = friction angle.
Fibre Break Models		
Perpendicular Root Reinforcement Models		
1.	Wu (1976)	$\Delta S = \tau_r (\sin\theta + \cos\theta \tan\phi) = 1.2\ T_R$ where ΔS = increase in shear strength, τ_r = shear stress parallel to shear zone, θ = shear strain, ϕ = friction angle of soil, and T_R = tensile strength of root.
2.	Waldron (1977)	$\Delta S = T_R (\sin\theta + \cos\theta \tan\phi)$ where ΔS = increase in shear strength, T_R = tensile strength of roots, θ = angle to the shear plane, and ϕ = friction angle of soil.
3.	Wu et al. (1979)	$\Delta S = 1.2\ T_R (A_R/A)$ where ΔS = increase in shear stress, T_R = tensile strength of roots, and A_R/A = amount of roots present in soil.
4.	Waldron and Dakessian (1981)	$T_{RS} = (4z\tau_b E_R/d)^{1/2} (\sec\theta-1)^{1/2} (A_R/A)$ where T_{RS} = mobilized tensile strength of stretched roots, z = thickness of the shear zone, τ_b = root-soil bond stress, E_R = tensile modulus of the root, D = root diameter θ = angle of shear distortion, and A_R/A = root area ratio.
5.	Abe and Ziemer (1991)	$\Delta S = \Delta S_t + \Delta S_p$ where ΔS_t = reinforced strength caused by tensile stress of root, and ΔS_p = shear strength applied to a root by earth pressure.
6.	Wu (2013)	T_R = breakage tensile strength or pull-out capacity, whichever the less.
Inclined Root Reinforcement Models		
1.	Gray and Leiser (1982)	$\Delta S \propto A_R/A = \Delta c_r$ where ΔS = increase in shear strength, A_R/A = root area ratio, and Δc_r = increase in apparent cohesion of soil.

<table>
<tr><td>2.</td><td>Gray and Ohashi (1983)</td><td colspan="2">$\Delta S = t_r [\sin\theta + \cos\theta \tan\phi]$ for perpendicular fibre

$\Delta S = t_r [\sin(90-\psi) + \cos(90-\psi) \tan\phi]$ for inclined fibre
where ΔS = increase in shear stress, $t_r = (A_R/A)\,\sigma_b$, A_R/A = root ratio area, σ_b = tensile stress developed in root at shear plane, θ = angle of shear distortion, ϕ = friction angle of soil, $\psi = \tan^{-1}\{1 / [k_1 + (\tan^{-1}\alpha)^{-1}]\}$, k_1 = shear distortion ratio = x/z
x = horizontal component of shear displacement, z = thickness of shear zone.</td></tr>
<tr><td>3.</td><td>Gray and Barker (2004)</td><td colspan="2">$\Delta S = k\,\beta\,(A_R/A)(\sin\theta + \cos\theta \tan\phi)$

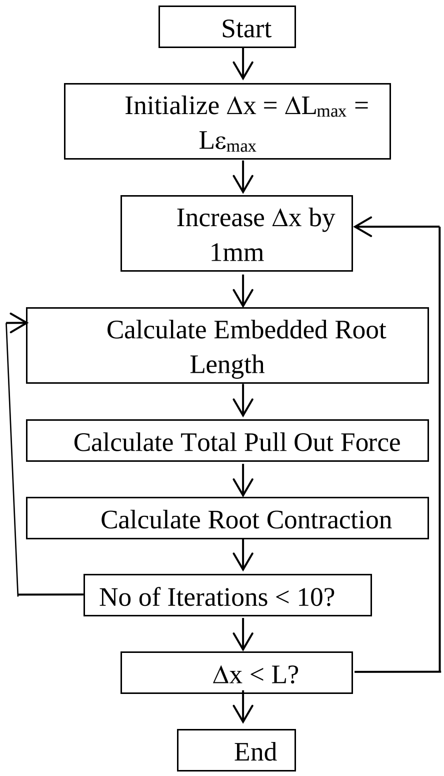
where $k = (4z\,\tau_b\,E_R/d)^{1/2}$, z = thickness of shear zone, τ_b = bond stress of root-soil, E_R = tensile modulus of root, d = diameter of root, $\beta = (\sec\theta - 1)^{1/2}$, θ = angle of shear distortion, A_R/A = root ratio area, and ϕ = friction angle of soil.</td></tr>
<tr><td colspan="4">Fibre Bundle Models (FBM)</td></tr>
<tr><td>1.</td><td>Pollen and Simon (2005)</td><td>a) Comments to the assumptions and limitations of the Wu et al. (1979) model which could over-estimate up to 50%.

b) Considered that when slopes fail, the root-soil matrix shears and the roots contained within the soil have different tensile strengths and thus break progressively with an associated redistribution of stress as each root breaks by iterations (see flow chart on the right).

c) Laboratory test data showed that the root tensile strengths decreased nonlinearly with increasing root diameter.</td><td>
</td></tr>
<tr><td>2.</td><td>Thomas and Pollen-Bankhead (2010)</td><td colspan="2">a) Used sensitivity analysis and fiber-bundle model (FBM) to examine assumptions underpinning root-reinforcement models.

b) Different methods for apportioning load between intact roots.

c) Monte Carlo approach to simulate plants growing on slopes and <u>floodplains</u>.</td></tr>
</table>

3.	Schwartz et al. (2010)	a) A more complicated pull-out based model by iterations, also named as the Root Bundle Model. b) It incorporated some features of the root geometry (root length, root diameter, root branching pattern and root tortuosity) and mechanics (maximum tensile strength, Young's modulus, root-soil interfacial friction, soil saturation) (see flow chart on the right). c) It contributed to the understanding the pull-out behavior of roots.	
4.	Ji et al. (2020)	This model is based on an energy approach whereby the root breakage is driven by the work that is yielded in soil shear movement and is dissipated by roots. The criterion determining the rupture of a root is only dependent on whether the work that it receives is greater than the energy to break the root in tension. The work equation shows that the root breakage is dependent on the load and displacement.	
Beam Bending or p-y Models			
1. 2. 3. 4.	Duckett (2014) Mao et al. (2014) Liang et al. (2015) Meijer et al. (2019)	These models use a set of transverse force-displacement (*p-y*) springs, which may be highly non-linear, to model the root-soil interaction in bending. They are computationally efficient and implicitly incorporate the effects of soil properties as well; however, further development would be required to generalize such analyses into analytical or finite difference-based models which are simple to use in practice.	

3 On the Application

3.1 Selection of Prediction Methods

The Wu and Waldron model (Wu 1976, Wu et al. 1977, Waldron 1977) and the RipRoot model (Pollen and Simon 2005) are widely used. They assume the roots being highly flexible with negligible bending stiffness. The roots will break in tension during shearing such that the additional strength provided by the roots is mainly a function of root properties, i.e., tensile strength of roots, root density and root orientations. However, the RipRoot model can model progressive failure as the weakest roots within the root system break first, with the load shared between different diameters of the roots. Thomas and Pollen-Bankhead (2010) permitted the load shared by: (i) equal load applied to individual roots regardless of root dimension, (ii) load apportioned by root diameter or (iii) load apportioned by root cross-sectional area. For plants with shallower, fine and fibrous root systems, the fibre breakage models are acceptable because the root diameters are more homogenous. However, it may not always work as roots are pulled out of the soil before breaking. Waldron and Dakessian (1981) proposed a pull-out-based model which is not widely adopted due to its dependence on root strain and is relatively difficult to estimate in practice. Schwarz et al. (2010) proposed a more complicated pull-out-based model or the Root Bundle Model, which incorporated some features of the root geometry and mechanics. Despite this, it is seldom used in engineering practice due to its complexity in the input parameters. Since most of these models assume root breaking such that the roots are well anchored and do not pull out when tensioned, the term “breaking” may be interpreted as by breakage, slippage or buckling. As such, the “interpreted breaking force” may be a more flexible term to consider other types of root failure depending on what the “ultimate” resistance is considered to be. For plants with larger structural roots where root bending rather than axial breakage may be more dominant, the roots may be considered as flexible cables for fine roots or bending beams for coarse/ structural roots subject to lateral loadings using the beam bending or p-y models. The surcharge and wind effects of shoot to slope stability can refer to GEO Report No. 257 (GEO 2011). Recommendations on the estimation of root reinforcement are summarized in Table 3.

Table 3. Summary of Suggestions based on Literature Reviews

Vegetation	Root Diameters (mm)	Approaches	Predictive Methods	Field or Laboratory Tests	Recommended T_R (MPa)
Herbs (including Grasses and Ferns) Climbers Shrubs Small Trees (around 3m Tall)	Generally thin or fine roots (<10mm)	Continuum approach combining root and soil as a matrix	Wu and Waldron model or RipRoot model k' = 1.15 to 1.18	Field: shear test, borehole shear test and vane shear test. Laboratory: shear test, triaxial test and compression test	3 - 18MPa for 10mm diameter roots, Suggested 8MPa for all roots with diameter < 10mm in mixed species
Medium Trees (much taller than 3m with Small Crown) Large Trees (Taller than 10m with Large Crown)	Fine and thin roots (<10mm) Coarse roots (>10mm)	Root-soil interaction approach considering roots as structural elements embedded in soil	Beam bending or p-y models for coarse roots	Field: pullout test Laboratory: tensile test and compression test	Tree species specific.

3.2 Determination of the Three Key Parameters in the Wu and Waldron Model

Leung et al. (2015) may be the pioneers to study the root effects of Hong Kong native plants on enhauncing slope stability. Despite many sophisticated models have been developed, the Wu and Waldron model was adopted likely due to its simplicity. The term ($\sin\theta + \cos\theta \tan\phi$) or k', tensile strength of roots and root area ratio are therefore the three key parameters. Based on four young shrubs and trees with height ranging between 1m and 1.5m, k' was determined varying from 1.15 to 1.18. The root class distribution was found varying probably due to species genetics and environmental factors such as soil moisture, and the roots of the studied trees extending deeper into the ground (up to 0.8m) as compared with the shrubs (up to 0.4m). Figure 2(a) shows that the average RAR lied between 0.03% and 0.14% for the top 0.1m soil and decreased with depth when all roots were considered, but could lie below 0.05% even close to the ground if only the roots of 1 to 10mm diameter were considered. Figure 2(b) shows that the conventionally adopted power decay relationship between T_R and root diameter was applicable for the studied species. The T_R was found having no significant difference within the studied species, but significant difference between the studied species. Despite this, the consolidated figure shows that T_R appears to fall within a band irrespective of the studied species with an average T_R = 8MPa for a root diameter = 10mm.

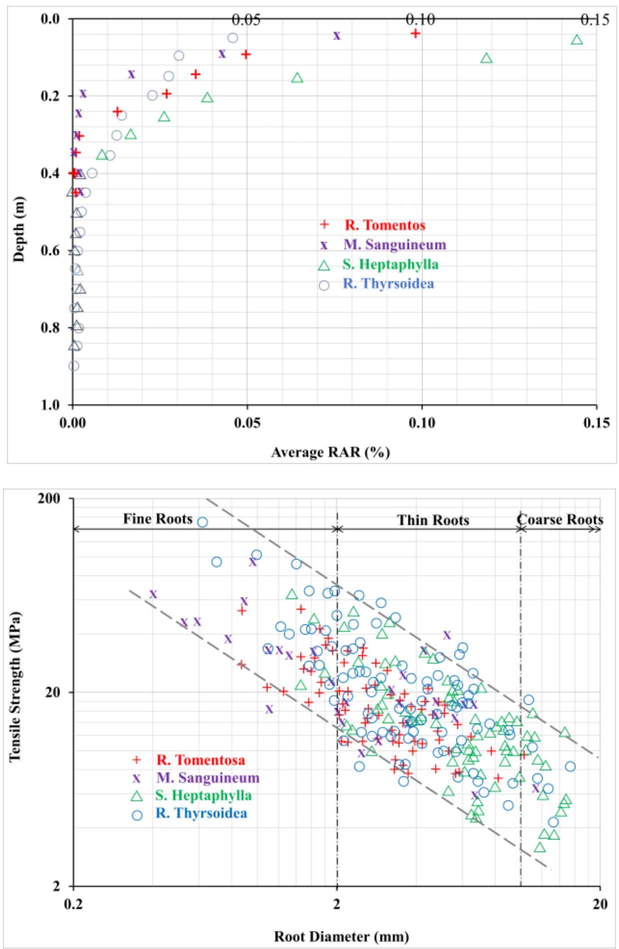


Figure 2:Variation of (a) Average RAR with Depth when All Roots are considered, and (b) Tensile Strength with Root Diameter of Four Native Species (after Leung et al. 2015)

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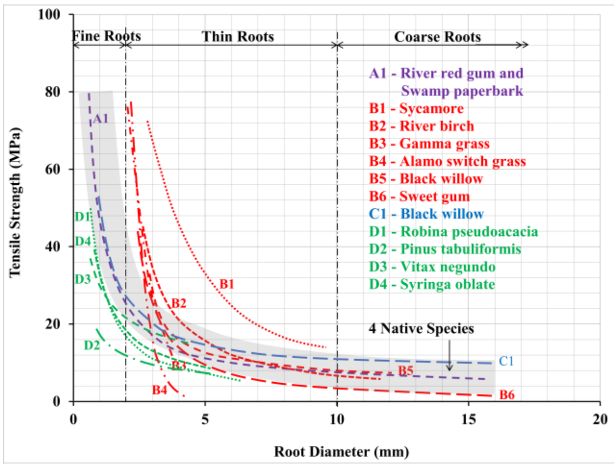
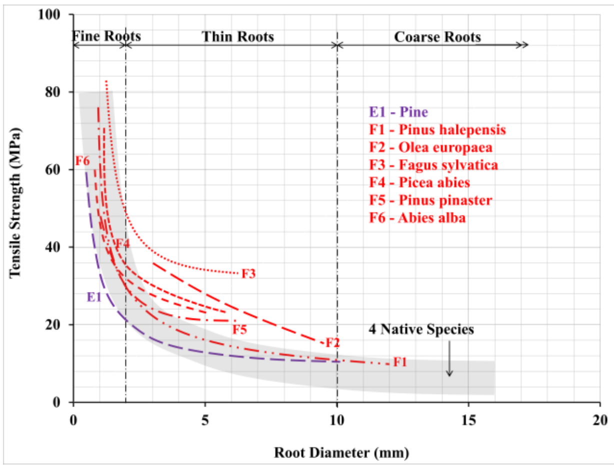
As shown in Figure 3, the obtained T_R and root diameter relationship of all studied species (modified to natural scale) also falls into the order compared to some reported European species. This may suggest that 8MPa may be a conservative design assumption for an average T_R of the fine and thin roots for slope covered with mixed native species. Thus, presumed values of k' = 1.15 and T_R = 8MPa may be conservatively used for fine and thin roots of less than 10mm irrespective of species as recommended in Table 3.



(a) Grasses to Medium Trees: A-series after Abernethy and Rutherford (2001), B-series after Simon and Collison (2002), C-series after Pollen and Simon (2005) and D-series after Ji et al. (2020)



(b) Large Trees: X-series after Pollen and Simon (2005) and Y-series after Stokes et al. (2008)

Figure 3: Variation of Tensile Strength T_R with Root Diameter of Four Native Species and Some European Species

The root depth and RAR are therefore the only significant variants which are unknown but can be determined by conventional field or laboratory tests (see Table 3). An innovative method invented by Meijer et al. (2019) using a corkscrew device to extract soil cores may also be considered as it can provide rapid estimation of T_R, root depth and RAR for mixed species on field. As shown in Figure 4, for each selected corkscrew sample, the total mass, volume and water content are measured. Root material is collected by careful washing of the extracted soil plug on a 2mm sieve. The root volume fraction can be calculated as the volume of roots over the measured volume of the extracted core. Assuming a uniform distribution of root orientations, RAR can be estimated as ½ of the measured root volume.

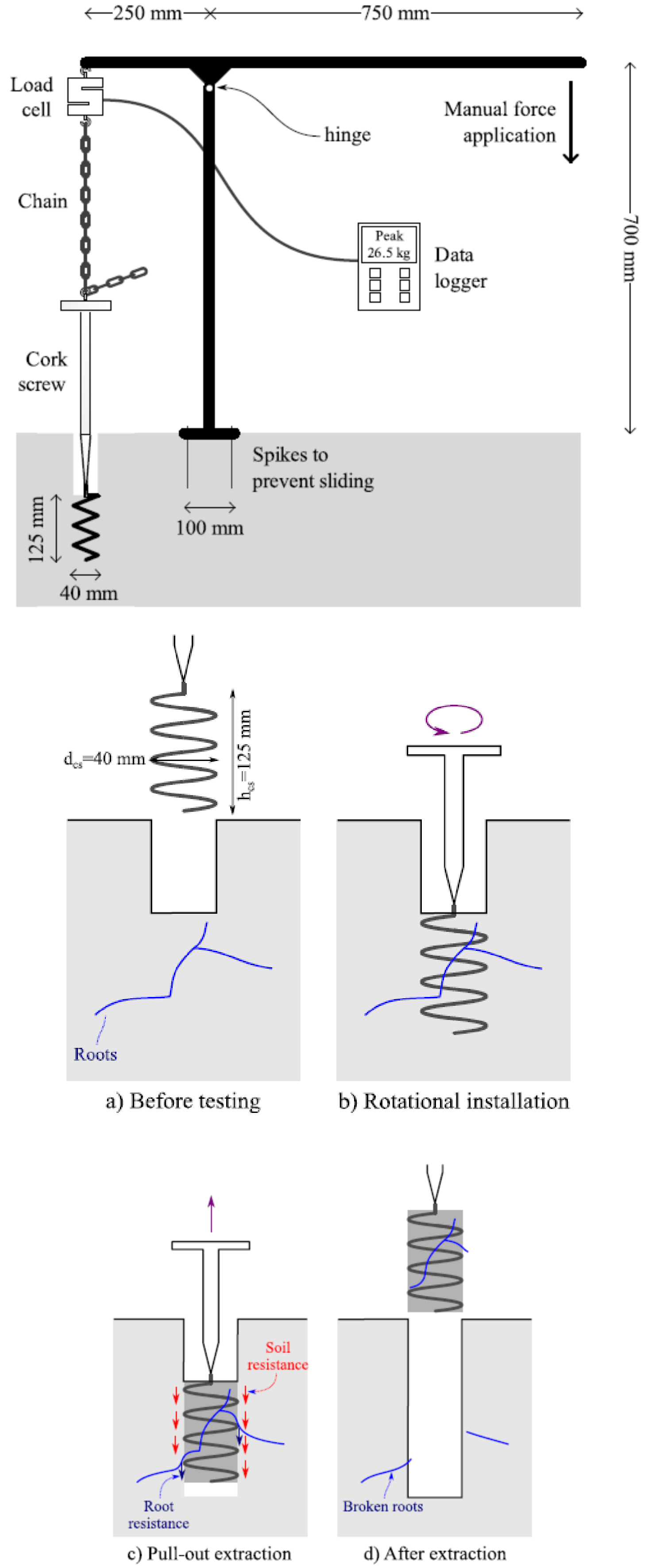


Figure 4: Schematic Corkscrew Measurement Setup and Test Procedures (after Meijer et al. 2019)

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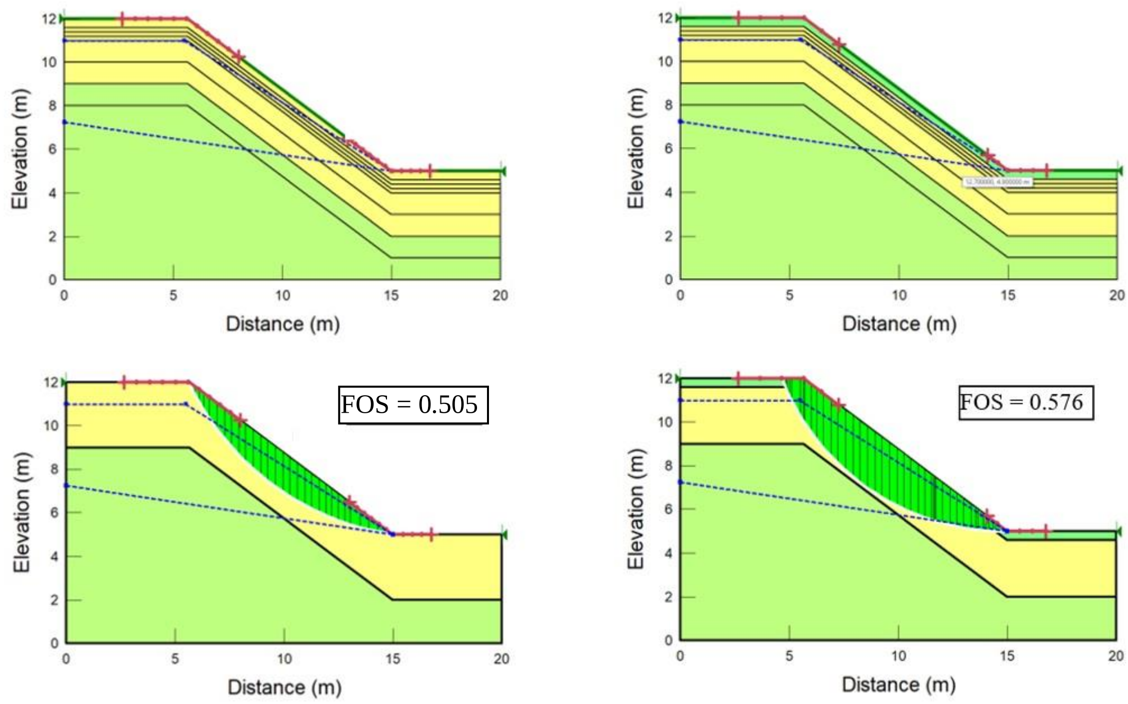
3.3 Slope Stability Analysis

As shown in Figure 5, a hypothetical slope model of 7m high at 37° angle and composed of 3m colluviums fill on the top and completely decomposed granite at the bottom is set up for demonstration. Presumed values k' = 1.15 and T_R = 8MPa are adopted, and conservative values RAR = 0.1% and root depth = 0.4m are assumed. The ΔS or apparent cohesion c_r is calculated equal to 1.15 x 8MPa x 0.1% = 9.2kPa. The design parameters of the slope with and without roots are summarized in Table 4. Soils are modelled according to the Mohr-Coulomb theory. The hydraulic condition is assumed to be hydrostatic with a fixed groundwater table at 1/3 slope height and a perched water table at 1m below the surface of top soil. Stability analysis is carried out by Morgenstern and Price method using the computer software SLOPE/W 2012. For a slope without vegetation, shallow slip appears at the crest of the slope and extends to the toe of slope giving a FOS = 0.505. When vegetation is added, the apparent cohesion renders the slip surface moving away from the crest of the slope and deeper into the top soil, thus resisting by a larger volume of soil and giving larger FOS = 0.576.

Table 4. Design Parameters for Slope Analysis (using k' = 1.15, T_R = 8MPa and RAR = 0.1%)

Soil Type	Thickness (m)	Unit Weight ? (kN/m³)	Cohesion c (kN/m²)	Friction Angle ?	Vegetation	Root Depth (m)	Average RAR (%)	ΔS (kN/m²)
Upper Soil (Fill)	3m	19.0	0	30°	Without	-	-	-
					With	0.4	0.1%	9.2
Lower Soil (CDG)	infinite	19.0	5	35°	-	-	-	-



(a) No Vegetation

(b) Uniform Vegetation Layer

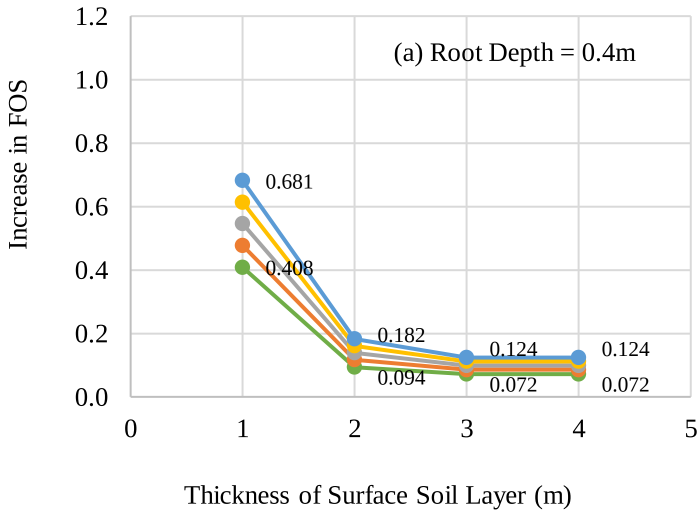
Figure 5: Hypothetical Infinite Slope Models

Sensitivity analyses are carried out for different RAR (0.125%, 0.15%, 0.175% and 0.2%), root depth (0.4m, 0.6m, 0.8m and 1m) and top fill thickness (1m, 2m and 4m). Figure 6(a) shows the effect of RAR to root strengthening with root depth = 0.4m. For RAR = 0.1%, the increase in FOS is 0.408 at fill thickness = 1m, and decreases markedly to 0.094 at fill thickness = 2m and then slightly to 0.072 at fill thickness = 3m and 4m. This is significant as it may imply that a marginally safe slope with shallow top soil can be upgraded to a safe slope with sufficient FOS even with RAR = 0.1%. Similar trends of increase in FOS are observed when RAR is increased from 0.1% to 0.2%. The increase in FOS and % increase corresponding to respective RAR for various fill thickness with root depth = 0.4m are summarized in Table 5. Largest increase in FOS with increased RAR occurs at fill thickness = 2m.

Table 5. Increase in FOS with increased RAR for Slope Model with Root Depth = 0.4m

Top Fill	1m		2m		3m		4m	
RAR (%)	Increase in FOS	Increase in %	Increase in FOS	Increase in %	Increase in FOS	Increase in %	Increase in FOS	Increase in %
0.1	0.408	-	0.094	-	0.071	-	0.072	-
0.125	0.477	17%	0.116	23%	0.085	19%	0.086	19%
0.15	0.546	34%	0.138	47%	0.099	36%	0.098	36%
0.175	0.613	50%	0.160	70%	0.110	54%	0.111	54%
0.2	0.681	67%	0.182	94%	0.124	72%	0.124	72%

Figures 6(b)-(d) show the effect of RAR to root strengthening with root depth increasing from 0.4m to 1.0m. Similar trends of increase in FOS are observed, of which a marked increase is observed at fill thickness = 1m. For RAR = 0.1% and fill thickness = 1m, the increase in FOS increases from 0.408 to 0.570, 0.962 and 0.992 when the root depth increases from 0.4m to 0.6m, 0.8m and 1.0m respectively, indicating the increase in strengthening effect is very prominent when the root depth about 0.4-0.6m, which is about half of the top soil thickness. Similar trends of increase in FOS with increased root depth are observed for different RAR.



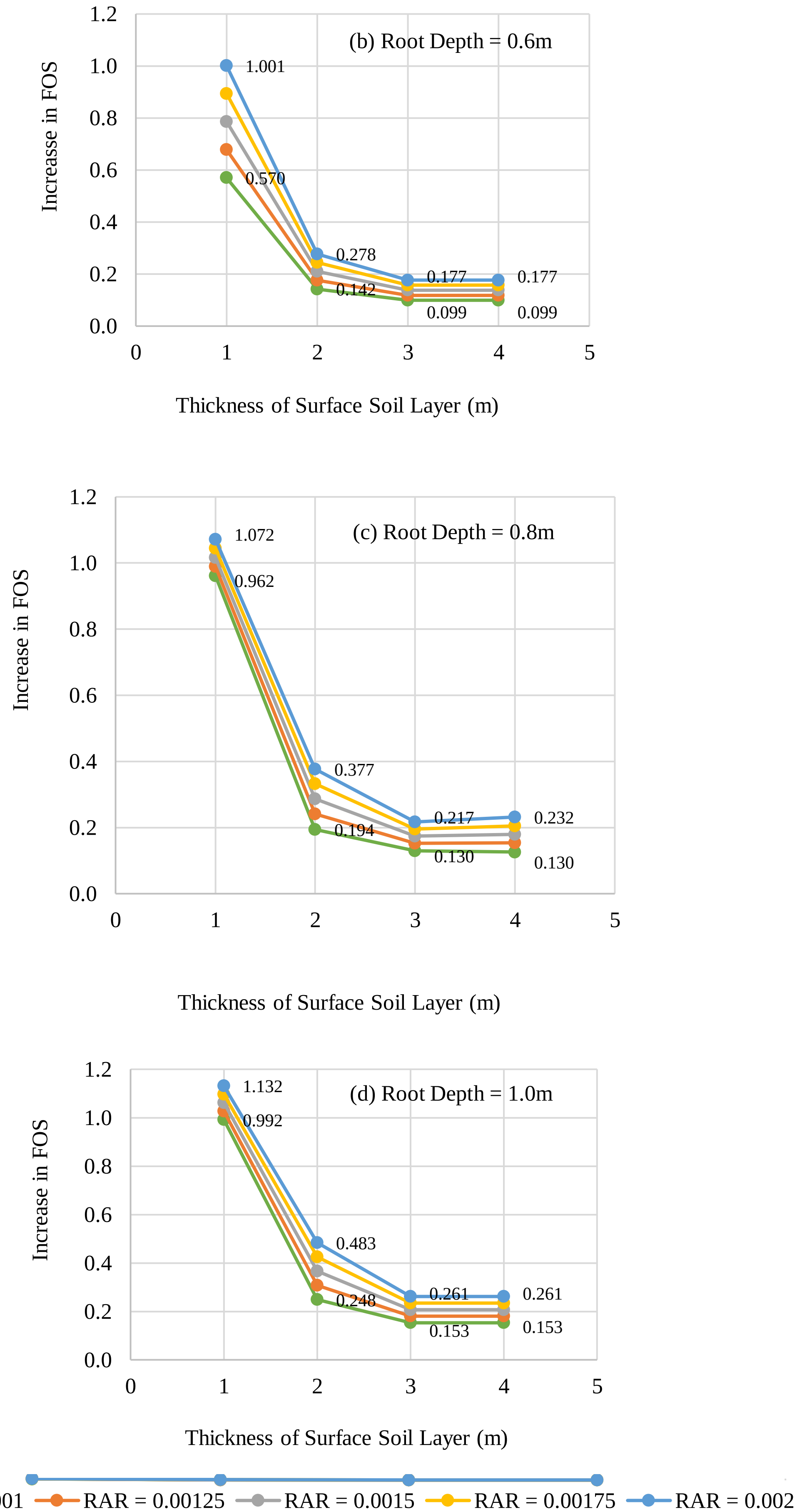


Figure 6: Sensitivity Analysis for Different RAR, Root Depths and Slope Heights

4 Conclusions

Current practice in most part of the world still considers vegetation mainly for aesthetic purposes and erosion control. The engineering functions of plant roots have been generally ignored in the scientific analysis and design of slope stability. This may be due to the lack of understanding of root functions and therefore the lack of confidence from engineers. The significant variability of the potential beneficial effect and the extreme difficulty in fully characterizing the tree roots and quantifying the strengthening effects of tree roots may be the crux. Despite many complicated and rigorous models are developed in the last decade to predict the root reinforcement, they are considered impractical to use due to the large number of inter-related controlling factors which resulted in low correlation coefficients, and mixed vegetations are always encountered in field.

An overview of the major stability functions provided by plant in slope is examined. Plant roots stabilize a soil slope by root reinforcement, hydrological reinforcement and interception. Root reinforcement can be in the form of lateral tensile resistance and anchorage, soil aggregation and mucilage effects. A lower bound approach is attempted such that it can provide an indication to the probability of the predicted strengthening likely exceeded. As such, only the mechanical reinforcement of root is considered but not other potential beneficial effects. Suction effect due to transpiration of the tree is also ignored. The Wu and Waldron model is recommended because of its simplicity. Root depth and RAR can vary largely and are therefore two key parameters dominating the strengthening effect. They can be determined on site. k' varies within a small range of 1.0 - 1.2 and is therefore not controlling. In the absence of test data, presumed value of 8MPa for T_R is suggested. It is determined from the strengths of many European, Chinese and 4 native species for root diameter of 10mm or less, which show that the majority of roots of these sizes for a vast number of species in different soils and climates can exceed. The presumed value can be fine-tuned when more local data are obtained.

However, for plants with larger structural roots (say > 10mm) where root bending rather than axial breakage is dominant, more sophisticated beam bending or p-y models can be adopted which require more input parameters to execute. A hypothetical slope stability analysis is carried out to demonstrate the practicality of the presumed values. Sensitivity analyses show that root strengthening can be significant for slope with shallow top soil even with RAR = 0.1%. The root depth and thickness of top soil affects the locus of the slip surface, and the strengthening appears to be most effective when the root depth is about half of the thickness of the top soil.

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