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Research Paper

Effect of Diameter, Root Moisture Content, Gauge Length and Loading Rate on Tensile Strength of Plant Roots and Their Contribution to Slope

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ABSTRACT

Root tensile strength is a crucial parameter for enhancement of soil shear resistance against failure. Mechanical stabilization of plant roots depends on the tensile strength properties of roots, friction properties, and root density and its network. The aim of the study is therefore, to conduct combined effect of various influential factors (diameter of the root, specimen length, testing speed, and root moisture variation) on the root tensile strength properties of plant roots. The root system of five selected plant species are studied. Intact and undamaged root specimens sampled and tested for root characteristics and tensile strength (Tr) at different root moisture content with different diameter classes. The result of the study further revealed that (a) testing speed has insignificant influence on plant root tensile strength (b) specimen length and plant root tensile strength showed a significant negative linear correlation (c) root diameter and tensile strength showed negative power function correlation (d) root moisture content had slightly negative correlation with root tensile strength. From five tested plant species, the highest tensile strength recorded in Salix subserrata followed by *Eucalyptus globules*. Therefore, *Salix subserrata* is a promising species for slope stabilization because of its root mechanical characteristics.

1. Introduction

Plant roots can enhance the stability of slopes in both dry and wet seasons (De Baets et al., 2008,; Yang Chen, Li & Zhang, 2016). The root system of plants have an important role in stabilizing slopes from failure by enhancing shear strength of soil (De Baets et al. 2008; Reinhold, Medicus, Fellin, & Zangerl, 2009).

Root micromechanical characteristics, at tissue and fiber stages, can affect behavior of root tensile strength (Genet et al., 2005**)**. The root tensile strength of roots increased with decreasing root diameters. In contrarily, the tensile breaking force has a linear relationship with root diameters. Roots of vegetation enhances soil shear strength by transferring shear stress built up in the soil in to root tensile forces. When the shear developed in the slope causes the roots to deform and causes elongation, provides enough interface friction and confining stress to lock root fiber on place and stop slippage (Abdi, 2014; Lateh, Bakar & Khan, 2011; Genet,

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Stokes, Fourcaud, & Norris, 2010; Osman & Barakbah, 2011; Yang et al., 2016). Root tensile strength affected by moisture, contents and diameter of the roots. Minor loss of root moisture can increase root tensile strength, but too much losses of moisture makes the root elongation, and results in reducing tensile strength (Yang, Chen, Li, & Zhang, 2016a; Yang et al., 2016b; Fan & Su, 2009). The root diameter has a strong correlation with root tensile strength, as root diameter reduces the tensile strength of the root also decreases. For instance, Yang et al., (2016) identified that the root of *Betula platyphylla* exhibits better tensile strength when both diameter and moisture content controlled under the laboratory condition.

The effect of environmental factors on the tensile strength of roots examined by (Genet et al., 2010; Saifuddin & Osman, 2014; Hales & Miniat, 2017; Yang et al., 2016; Chen, Wang, Yang, & He, 2014). Environmentally driven factors such as soil moisture conditions and air temperature contribute for the change of root tensile strength, amongst these factors moisture condition of the roots has significant effect on the root tensile strength. With relatively drier conditions, the roots possessed better tensile strength than wet conditions (Hales & Miniat, 2017; Genet et al., 2010).

Roots with high cellulose contents can resist shear stress than roots with low cellulose content (Zhang et al., 2014; Genet et al., 2005). The larger root has small cellulose contents than smaller roots per dry mass. This is because of the cellulose made of polymer chains are consisting highly resistant hydrogen bond. Therefore, roots with high cellulose are stronger in tensile strength than roots with low cellulose content.

The tensile strength of plant roots affected by different factors such as root traits, moisture condition of the roots (Pollen & Simon, 2004; De Baets et al., 2008,; Schwarz, Giadrossich, & Cohen, 2013; Greenwood, Norris, & Wint, 2006; Tardío & Mickovski, 2016; Gentile et al., 2010,; Holsworth 2014; Cebada, 2017). Factors such as testing speed, specimen length, loading direction and loading stress can influence root tensile strength (Ou et al., 2017; Lim et al. 2011). However, there are very few studies about the mechanism by which testing speeds and specimen length and root moisture content affect tensile strength of roots. Therefore, this paper focused on the effect of root traits, testing speed, and specimen length on the tensile strength of root.

2. Materials and Methods

2.1 *Root excavation techniques*

Five plant species comprising grass, shrubs and tree species (*Salix subserra* Willd), *Eucalyptus globules* Labill, *Chrysopogon zizanioides* (L.) Roberty and *Psidium guajava L. Pennisetum. Macrourum (Nees) Benth* selected based on their root characteristic and widespread distribution in and around the study area (Talema et al., 2017). The plant species selected from the area where the topography and temperature is the same. Manual excavation of plant roots with vertical projection carried out (De Baets et al., 2008). During excavation process of plant roots, attention taken to the root specimens. After excavation, the roots immediately packed in plastic bags to preserve their moisture contents. And then transported to Jimma Institute of Technology, Mechanical Engineering Laboratory, the root specimens preserved to relative humidity 65% and 20 °C to insure the same degree of preservation of biomechanical properties of the roots until root tensile strength test conducted. The root samples attached to clamping system to avoid root damage at clamping points, then 20mm/min constant rate of displacement applied (Habibah et al., 2014; Naghdi et al., 2013). When the tested root broken at the middle, the test was considered as valid.

2.2 Procedures to determine root area ratio (RAR)

The root area ratio (RAR) and tensile strength of individual roots of specimen used to assess the mechanical effects of the plant root (Watson et al., 2008;Temgoua, Kokutse, & Kavazovic, 2016; Zhang et al., 2014). The root area ratio is the ratio determined by dividing total area of roots by area of soil at which the roots intersects (Gentile, Elia, and Elia,2010). Root area ratio values determined using profile trenching method as a function of soil depth to determine root involvement to soil shear strength. The cross-sectional areas occupied by the roots determined for the soil depth interval of 0.2m. The values of RAR determined by counting the individual roots manually after the roots detached from the soil. The number of the roots and depth at which they occur taken and recorded for each species. RAR values obtained at the depth interval of 0.2m of all roots diameter over 0.25mm and less than 8.5mm. The root diameters crossing the soil profile measured by Vernier caliper.

2.3 Determination of root tensile strength (T_r)

Roots of five plant species chosen to test the tensile strength and apparent root cohesion for the proposed slope stability analysis. The plants are *Salix subserrata, Chrysopogon zizanioides, Eucalyptus globules, Psidium guajava, and Pennisetum macrourum.* The root tensile strength tests conducted for different root diameter ranges between 0.25mm and 6.5mm. To ensure an accurate reflection of the mechanical root properties, all plant root specimen, which collected from the field, placed in sealed bags. The tensile test done by using Testometrics, material-testing machine, England; Serial no. 500-517 with the test force ranges between 40KN-100KN (Figure, 1). Plant root tensile strength tested at different testing speed of 20mm/min, 50mm/min and 100mm/min, and at four different specimen length of 100mm, 150mm, 200mm and 250mm to examine the effect of testing speed and specimen length. Root diameters measured using digital caliper in three different points, and the mean diameter calculated to assign the representative value conforming to the breaking point of each sample. Tensile strength value of each root determined by the machine load cell and recorded with the data logger. The following formula used to calculate the tensile strength of plant roots.

Fig.1 Tensile strength testing machine and sample prepared for testing.

The influence of roots reinforcement on soil stated as a cohesion term (Gentile, Elia, & Elia, 2011; Noroozi & Hajiannia, 2015; Watson et al., 2008). In the Mohr-column failure criteria were the soil root composite shear strength calculated as follows:

$$S_r = c' + (\sigma - \mu) \tan\varphi' + \Delta S \quad (1)$$

Where *c′* is the effective cohesion of the soil, σ is the normal stress due to the weight of the water and soil of sliding mass, *u* is the soil pore–water pressure, φ is the effective friction angle of the soil and Δ*S* is the apparent cohesion provided by the presence of roots.

Assuming that soil friction angle not affected (Gentile et al., 2011) the additional cohesion provided by roots calculated as:

$$\Delta S = Tr\,(\sin\beta + \cos\beta\tan\varphi) \quad (2)$$

Where, T*r* is the average mobilized tensile strength of roots per unit area of the soil and β is the angle of root distortion in the shear zone. Sensitivity analyzes show that the values of ($\sin\beta + \cos\beta\tan\varphi'$) approximated as 1.2 for 30° < φ′ < 40° and 48° < β <72° (De Baets et al., 2008). Thus, equation simplified as:

$$\Delta S = 1.2 Tri \quad (3)$$

Where *Tri* is the tensile strength of an individual root (i) and (*Ari|A*) is the root area ratio or proportion of root cross-sectional area to soil cross sectional area A. From all selected plant species, a total of 2374 root samples collected and 650 found undamaged and tensile strength conducted. Out of 300 roots, 194 (29.85%) successfully tested. 456 specimens (70.15%) broken near or at the position of clamping, or slipped out clamps and thus could not use for analysis. Samples collected to conduct tensile strength of the roots at two different root moisture contents. The root reinforcement, Cr values calculated by considering the average tensile strength of roots at soil depth interval of 0.2m for all selected plant species. Tensile strength (Tr) along the soil depth at root diameter interval of 0.2mm.

2.4 Root moisture content determination

The root samples collected to determine tensile strength at two different moisture conditions. Namely, fresh and air dried moisture condition for each plant species. The fresh and air dried with a different diameter of the root samples weighted before and after oven dried. The moisture contents of the root samples from study area determined in the laboratory according to ASTM D2216 testing procedures. And using the recommendations given in this research work, an oven drying temperatures of I05°C used to dry the test samples. An appropriate amount of sample taken for the moisture content determination. Finally, the moisture contents for the root set of samples calculated using the normal procedures as shown in ASTM D2216.

2.5 Data analysis tools

The relationship between tensile strength and root diameter presented with a power relationship as indicated in (De Baets et al., 2008; Burylo et al., 2011; Fan and Lai, 2014; Norris and Street, 2005; Greenwood, Norris, and Wint, 2006), the tensile strength(Tr) decreases with increasing root diameter following the simple power law equation determined by:

$$Tr = \alpha .\, D^{-\beta} \quad (4)$$

Where, α and β are empirical values depends on plant species.

Analysis of data conducted using IBM statistics version 24. Pearson correlation used for non-parametric to investigate the significant of root number, Root Area Ratio (RAR) and root cohesion with plant species and soil depth. As the data not normally distributed. The level of significance between diameter and tensile strength, moisture variation and tensile strength of roots analyzed by one way analysis of variance (ANOVA). To measure the combined effect of specimen length and diameter on tensile strength, and test speed and diameter on tensile strength of roots, analysis of covariance (ANCOVA) applied. In which root diameter taken as covariate, gauge length and loading rate as independent variable, and root tensile strength as dependent variable.

3. Results and discussions

3.1 Root Area Ratio determination

The variation in root area ratio (RAR) with varying depth of soil for all plant species shown in Figure 1. RAR values increased until 0.6m depth and decrease, afterwards. For instance, the RAR values recorded until a maximum depth of 2.2m for *Salix subserrata.* The highest RAR values recorded within the range of 0.3m-0.6m for *Salix subserrata* and the minimum value is 0.038% at 2.2m soil depth for the same species. Similarly, for all plant species, generally it observed that reduction of RAR with increasing soil depth as depicted Table 1. The RAR distribution with depth also revealed the differences between species with increasing rooting depth.

Table 1. Summary of root characteristics for all plant species

plant species	Depth (cm)	Number of roots	RAR (%)	Tr, MPa	Cr,kPa
Salix subserrata	220	847	$2.02*10^{-1}$	41	9.9
Eucylptus globulus	180	441	$1.94*10^{-1}$	32	7.44
Chrysopogon zizanioides	100	398	$2.3*10^{-2}$	33	0.91
Psidium guajava	160	312	$9.4*10^{-2}$	38	4.27
Pennisetum macrourum	100	376	$3.0*10^{-1}$	23	0.84

Salix subserrata has strongest root reinforcement effect than other plant species, because of high value of root cohesion and tensile strength as shown in figure 1, with an average value of apparent cohesion of 9.90 kPa within 220cm soil depth of the species.

The relationship between root area ratio (RAR) and soil depth from Pearson correlation analysis shown in Table 2. The relationship between RAR and soil depth is represented by a second-degree polynomial model with strong negative correlation ranges (R^2=0.875-0.999). Similarly, root cohesion and RAR Have a strong positive correlation. As Cr decrease as RAR decreases with soil, depth increases as shown in Table 3.

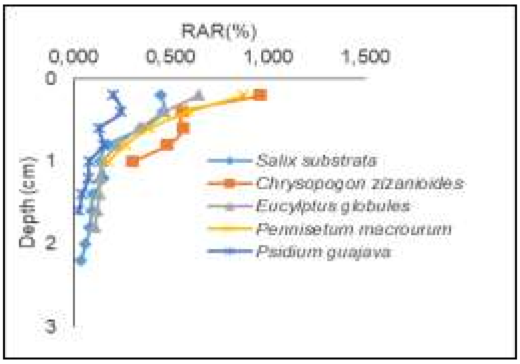

Fig. 1 Scatter plot for root area ration (RAR) values at different depths (mean ± standard deviation).

Table 2 Difference of Root area ratio (RAR) and root depth with species reveled by Pearson correlation is significant at 0.05 (2-tailed), RAR = Root area ratio, z = soil depth.

Plant species	Model	R^2	p
Ss	$RAR = 0.83z^2 - 3.1z + 3.05$	0.950	0.000
Eg	$RAR = 0.83z^2 - 3.1z + 3.05$	0.989	0.030
Pg	$RAR = 0.09z^2 - 0.82z + 1.1$	0.890	0 .001
Pm	$RAR= 0.30z^2 - 0.68x + 0.44$	0.999	0.002
Cz	$RAR = 0.19z^2 - 0.45z + 0.3$	0.875	0.000

The relationship between root area ratio (RAR) and soil depth from Pearson correlation analysis shown in Table 2. The relationship between RAR and soil depth is represented by a second-degree polynomial model with strong negative correlation ranges (R^2=0.875-0.999). Similarly, root cohesion and RAR Have a strong positive correlation. As Cr decrease as RAR decreases with soil, depth increases as shown in Table 3.

Table 3. Difference of Root area ratio (RAR) and root cohesion with species reveled by Pearson correlation.

Plant species	*Model*	R^2	P
Salix subserrata	$Cr = 3.46x^2 + 3.26x + 0.067$	1	<0.001
Eucalyptus globules	$Cr = 0.3167x - 1E-15$	1	<0.001
Psidium guajava	$Cr = 3E-1x^2 + 3.1x + 2E-15$	1	<0.001
Pennisetum macrourum	$Cr= 0.14x^2 + 4.34x + 0.0012$	1	<0.001
Chrysopogon zizanioides	$Cr = 5E-1x^2 + 0.36x + 2E-15$	1	<0.001

Correlation is significant at 0.05 (2-tailed), Cr = Root cohesion, x = RAR.

Figure 2 shows the relationship between root depth and root cohesion of all plant species. From Pearson, correlation confirmed that the higher Cr and RAR values in the soil, the better increase in soil reinforcement. As observed from Figure 2, grass (*Chrysopogon zizanioides, Pennisetum macrourum*) can reinforce soil up to 1m soil depth, however shrubs (*Salix subserrata* and *Psidium guajava*) and tree (*Eucalyptus globules*) can stabilize soil beyond one meter up to 2.2m soil depth. Among all selected plant species, *Salix subserrata* has better root cohesion value.

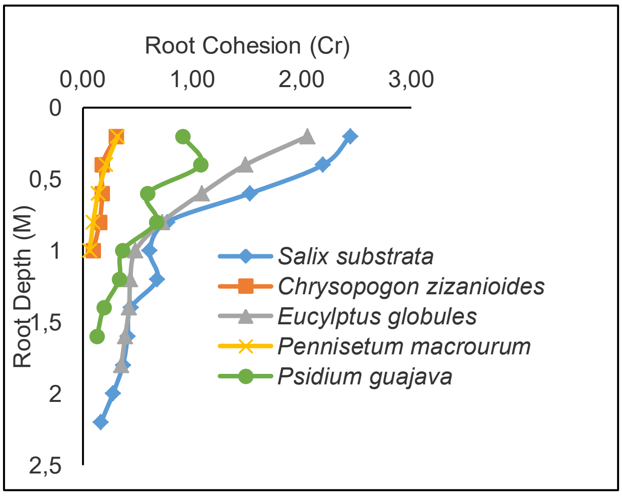

Fig. 2 Scatter plot for root cohesion (Cr) values at different depths (mean ± standard deviation).

3.2 Effect of Root Diameter on Tensile Strength

The effect of root diameter on the tensile strength at dry condition shown in Table 4. The tensile strength predicted by root diameter in all the experimental species. With a non-linear relationship between diameter and tensile strength. As observed, there is a decrease of tensile strength with increasing root diameter following power relationship. Values of α, β and statistical significance of the relationship shown in Table 4. From the regression analysis, the high value of α and the low value of β showed that the plant species had better tensile root strength (Figure 3 and Table 4). Therefore, from all selected plant species, *Salix subserrata* had high α (scale factor 53.798) and low β (decay rate,-0.871). Thus, this plant species had better tensile strength value than other plant species. The result of ANOVA showed that the root diameter properties were a significant influence on tensile strength of root for all plant species. For instance, Salix *subserrata* ($F_{(1, 20)}$ = 15.519, P<0.01, R^2= 0.647). This showed that the tensile strength of *Salix subserrata* highly affected by the diameter of root than other plant species. Similarly, from a statistical point of view, the correlation coefficient is significant for all plant species.

Table 4. ANOVA and Regression analysis of root diameter and tensile Strength for all plant species at dry condition Tr= tensile strength, D: root diameter for 20mm/min & 100mm gauge length

Plant species	model	R^2	F value	p value	Mean(Tr)
Salix subserrata	$53.798x^{-0.871}$	0.647	15.519	<0.01	41.85
Eucalyptus globules	$48.887x^{-0.551}$	0.712	14.321	<0.01	32.18
Psidium guajava	$36.338x^{-0.345}$	0.402	11.476	<0.01	38.47
Pennisetum macrourum	$30.216x^{-0.598}$	0.402	16.029	<0.01	23.13
Chrysopogon zizanioides	$18.883x^{-0.681}$	0.450	17.796	<0.01	33.08

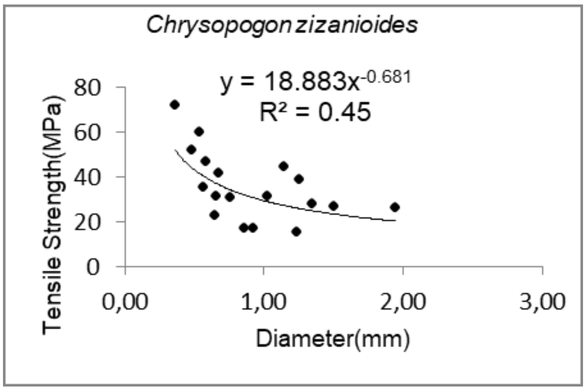

Fig. 3 Effect of root diameter on tensile strength at constant value of loading rate (20mm/min) and 100mm gauge length for all selected plant species.

3.3 Effect of Root Moisture Content on Tensile Strength

Table 5 shows the tensile strength well predicted by root diameter in all the selected plant species. With a non- linear relationship between diameter and tensile strength under various root moisture content. From ANOVA and regression analysis, except *Salix subserrata*, the root diameter properties were a significant influence on tensile strength of root for all plant species at moist condition. For instance, *Salix subserrata* (F (1, 20) = 13.685, P= 0.091, R^2= 0.328). The statistical significant effect of root moisture on tensile strength and parameters of α and β of power equation given in Table 5. From regression analysis, the species grouped from having strong roots (i.e. high α values and low β values) to having weak roots (I.e. low α values and high β values). The values of tensile strength and R^2 for all species were less than the value of dry condition. For instance, *Salix subserrata* had the tensile strength value obtained at most root condition was 39mpa less than the value of dry condition, (41.85mpa). The R^2 of *Salix subserrata* is

0.328 for saturated condition, which is less than 50%, this showed that the diameter of the root less correlated with tensile strength of the root at moisture condition. The low squared value showed that tensile strength of all plant species slightly affected by root moisture content. Rather it might affect by several controlling factors such as roughness and thickness of roots, chemical composition of roots, topography and soil properties. The study shows that there is a slight correlation between root strength and root moisture content. Since, *Salix subserrata* slightly affected by moist condition, the plant considered a water loving plant that could be suitable to stabilize the slope failures caused by an increase in ground water level.

Table 5. ANOVA and Regression analysis of root diameter and tensile Strength for all plant species at moist condition Tr= tensile strength, D: root diameter, root diameter for 20mm/min & 100mm gauge length

Plant species	model	R^2	F value	p value	Mean(Tr)
Salix subserrata	$35.625x^{-0.741}$	0.328	13.685	0.091	39
Eucalyptus globules	$31.618x^{-0.698}$	0.452	10.687	<0.01	32
Psidium guajava	$23.478x^{-0.418}$	0.437	9.658	0.015	27
Pennisetum macrourum	$22.680x^{-0.426}$	0.394	13.981	<0.01	19
Chrysopogon zizanioides	$16.214x^{-0.541}$	0.362	18.695	<0.01	30

3.4 Effect of Gauge Length on Root Tensile Strength

The effect of gauge length of roots on tensile strength shown in Table 6. From ANCOVA analysis, the tensile strength of roots significantly decreased with increasing gauge length. For instance, for gauge length of *Salix subserrata* ($F_{1,22}$ = 45.489, p = <0.001; $F_{1,22}$ = 18.837, p = <0.001; $F_{1,22}$ = 21.643, p = <0.001; $F_{1,22}$ = 19.097, p = <0.001;) for 100, 125, 150, and 200mm gauge length respectively. The mean tensile strength values of *Salix subserrata* are 41.85, 36.15, 35.25, and 34.47mpa for 100, 125, 150, and 200mm gauge length respectively. Similarly, the result of the analysis shows that root gauge length significantly affects the root tensile strength of all five selected plant species.

The result shows that gauge length has strong negative linear correlation with root tensile strength for all selected plant species (Tr = -0.0689L + 46.627, R^2 = 0.7738; Tr = -0.0271L + 31.207, R^2 = 0.9563; Tr = -0.0237L + 36.49, R^2 = 0.9069; Tr = -0.0356L + 23.591, R^2 = 0.8114, Tr = -0.0271L+ 31.207, R^2 = 0.9563, where Tr is root tensile strength and L is gauge length). For *Salix subserrata, Eucalyptus globules, Psidium guajava, Pennisetum macrourum, and Chrysopogon zizanioides* respectively. The tensile strength of roots decreased significantly as the gauge length increased.

Table 6. ANCOVA results of roots tensile strength affected by different gauge length at 20mm/min loading rate

Size		S.subserrata	E. globules	P. guajava	P. macrourum	P.zizanioides
100 mm	F	45.489	36.826	23.651	38.484	118.230
	p	<0001	<0001	<0001	<0001	<0001
	T	41.85	32.18	38.47	23.13	33.08
150 mm	F	18.837	37.700	17.684	19.722	86.132
	p	<0001	<0001	<0001	<0001	<0001
	T	36.15	28.33	33.25	19.67	32.58
200 mm	F	21.643	33.077	14.658	17.998	51.736
	p	<0001	<0001	<0001	<0001	<0001
	T	35.25	27.48	32.65	18.56	30.78
250 mm	F	19.097	24.322	26.325	9.539	43.111
	p	<0001	<0001	<0001	<0001	<0001
	T	34.47	25.62	31.95	16.94	26.05

The regression analysis and fitting curves of root tensile strength for all plant species over root diameter with different gauge length. The root tensile strength affected by the diameter of the root as the gauge length increased and their relationship is a negative power function. Better tensile strength recorded at 100mm root gauge length for all plant species. At this gauge length, all selected plant species gave better values scale factor (α), and low value of decay rate (β). This result showed that increasing gauge length could increase the possibility of encountering defects, such as flow in the roots, and decreased the tensile strength.

3.5 Effect of loading rate on Root Tensile Strength

The effect of diameter on tensile strength of roots at a different loading rate for five-selected plant species shown in Table 8. The analysis of covariance (ANCOVA) performed with a root diameter as covariate, loading rate as independent variable, and tensile strength as dependent variable. To eliminate the influence of root gauge length, constant gauge length 100mm taken. ANCOVA results showed that little difference in tensile strength between different loading rates and slightly significant differences in tensile strength observed based on root diameter. At the loading rate of 20mm/min, the diameters of roots significantly influence the tensile strength of roots.

The results of root area ratio (RAR) values found to be highest in the first and second layers of soil. The values of RAR in this study is agreement with the findings of (Habibah, Nazi, and Ghassem,2014; Cebada, 2017; Temgoua, Kokutse, and Kavazovic, 2016; Naghdi et al., 2013; Gentile, Elia, and Elia, 2010, ; Stokes et al., 2009; Yun Wang Chok, 2008).

4. Results and discussions

The RAR values significantly decreased with soil depth and the highest root distribution observed in the upper 60cm soil depth for all plant species. The study shows that the highest RAR values for grasses (*Chrysopogon zizanioides* and *Pennisetum macrourum*) located in the second soil depth (20cm). Thus, these two grass species would be more suitable for very shallow soil depth slope than middle of the slope along the road. Whereas, the highest RAR values for shrubs and trees (*Eucalyptus globules, Psidium guajava and Salix subserrata*) found in third and fourth layers of soil profile. Similarly, (Habibah, Nazi, and Ghassem, 2014) and (Alam et al. 2018) reported a maximum RAR at the third layer. The average number of roots decreased with increasing soil depth. Table 1 and Figure 1 shows that the RAR values increases with increasing root diameter and thus RAR values are sensitive to root diameter, which is similar result with (Burylo, Hudek, and Rey, 2011; Mahannopkul and Jotisankasa, 2019; Chirico et al., 2013; Yun Wang Chok, 2008; Nyambane and Mwea, 2011).

The increase in loading rate had a minor effect on root tensile strength for roots at a constant gauge length for all selected plant species. It is in agreement with (Ou et al., 2017) in this study loading rate influences the effect of diameter on root tensile strength. Particularly, for the roots with 100mm gauge length, the diameter had significant effect on the tensile strength at the loading rate of 20mm/min. However, the effect decreased at the loading rate of 100mm/min and 200mm/min. this result suggested that further increased of loading rate have negligible effect on tensile strength of roots. Moreover, Gauge length and root tensile properties significantly correlated the negative linear correlation between gauge length and tensile strength observed. Increasing gauge length could increase the possibility of encountering defects, such as flow in the roots, and consequently decreased the tensile strength.

Root tensile strength values decreased with increasing diameter of roots as studied by different authors and described by power law equation (Naghdi et al., 2013; Lateh, Avani, and Bibalani, 2014; Cebada 2017). In the power law, the parameters rely on the plant species and environmental conditions. In specific plant species, the highest values of α and the lowest value of *β* shows that the plant species produces the highest tensile strength against shallow slope failure, as described by (Centenaro et al., 2018; Boldrin, Leung, and Bengough, 2016; Gentile, Elia, and Elia, 2010). The values of *α* (scale factor) and *β* (decay coefficient) for each plant species fall in the range of values found in previous studies. Several grass species characterized by low decay factors and higher decay coefficients (Reubens, 2010, Gentile, Elia, and Elia, 2010; Stokes et al., 2009). For shrub species, the values of α and β ranging from 4.4 to 91.2 and from -0.52 to -1.75 respectively, reported (Mahannopkul and Jotisankasa, 2019; Ehsan Abdi et al., 2010). For tree species, decay coefficient reported in literature (Alam et al., 2018) ranged from -0.52 to -0.11 and higher scale factor reported (from 18.4 to 60.15). From our study, the (scale factor) ranges -0.324 to -0.551, and *β* (decay coefficient) ranges 36.338 to 53.798 for trees and shrubs. Whereas, the (scale factor) grasses ranges -0.598 to 0.681 and *β* (decay coefficient) ranges 18.883 to 30.216 (Table 7). The analysis of variance revealed that roots of shrubs and trees species were the most resistance to tensile stresses and can stabilize slope failure better than grass species.

Smaller diameter roots have more tensile strength, because cellulose is more optimal for resisting failure in tension and enhances reinforcement effect (Yun Hang Chok, 2008; Genet et al., 2005; Zhang, Chen, and Jiang, 2014). As the diameter of roots increased the content of cellulose declines. The difference in cellulose content among the roots shows, cellulose is the main governing parameter for tensile strength of roots. The elongation of roots based on the chemical contents of root fibers, Roots with high cellulose content can resist against to applied force (Zhang, Chen, and Jiang, 2014). This study articulated that the smallest roots were the most resistant in tension, and tensile strength increased with the decrease in root diameter. Which is consistent with the results of (Zhang, Chen, and Jiang, 2014; Habibah, Nazi, and Ghassem, 2014).

The tensile strength of highly affected by different environmental factors. Moisture content of root and diameter of the root are among factors that affects tensile strength properties (Ishak, Ali, and Kassim 2013). In this study, root tensile strength tests conducted within particular species for two different moisture conditions, roots tested for lower root moisture contents are significantly stronger than those with high root moisture conditions (Table 4 and 5). As the concentration of water increases in the cell wall of roots weakens the strong bond of between fibers (Ishak, Ali, and Kassim, 2013; Lateh, Avani, and Bibalani, 2014). All tested plant species have different tensile strength at different moisture condition Therefore, there is non- linear relationship between root tensile strength and root diameter at varied root moisture contents. The laboratory observations demonstrated that roots can lose their strength in rainy season. For instance, the percentage variation of tensile strength of *Salix subserrata* between saturated and dry conditions is 5.51%. This showed the tensile strength of *Salix subserrata* less affected by root moisture content. Similarly the percentage decreased in tensile strength of *Eucalyptus globules, Psidium guajava, Pennisetum macrourum,* and *Chrysopogon zizanioides* are 7.69%, 25.89%, 25.79% and 8.27% respectively. Therefore, this plant species is water loving plant, that can more appropriate to stabilize the slope failures caused by high groundwater level and followed by *Eucalyptus globules* when compared with selected plant species.

5. Conclusions

The number of roots and RAR shows a great variability with soil depth for all five selected plant species. The highest values of root number and RAR observed between 0.2 and 0.6m from the surface for all plant species. As the depth of the soil profile increase, there is a significant decrease in RAR and cohesion of root.

The highest root cohesion observed in *Salix subserrata and Eucalyptus globules* and thus, these two plant species are promising in reinforcing slope failure as deep as 2m. Whereas, grasses (*Chrysopogon zizanioides* and *Pennisetum macrourum)* are only efficient up to 1m deep slope.

The effect of different factors on root tensile strength conducted. The individual effects of diameter, gauge length, loading rate and root moisture content on root tensile strength evaluated and compared with tensile strength of different plant species.

Tensile strength correlated with diameter at different gauge length, loading rate and root moisture content using power regressions. Root tensile strength test showed a negative power relationship with root diameter.

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