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Effect of the root biotechnical characteristics of *Alnus subcordata*, *Paulownia fortunei* and *Populus deltoides* on the soil mechanics

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Abstract: The effect of root reinforcement depends on the biotechnical characteristics of the root system including the tensile strength of individual roots, the root density and the distribution of the root system in the soil. This research was conducted in the Hyrcanian forest in Iran, where shallow landslides are frequent due to road construction. The effect of the root biotechnical characteristics of *Alnus subcordata*, *Paulownia fortunei* and *Populus deltoides* each one in 2-, 10- and 15-year-old plantations was assessed. The profile trenching method was used in this study to obtain the root area ratio of individual species by counting the number of roots and measuring the root diameter. For each species, single root specimens were sampled and tested for tensile tests in the laboratory using the standard Instron apparatus. The natural moisture content (two weeks after rainfall), Atterberg limits, shear strength of the soil were determined for plantations, stable and unstable sites. Results of this study indicated that plastic index and internal friction angle decreased with increasing root diameter rate. Moreover, internal friction angle and cohesion increased with increasing root area ratio and root diameter and density index. Tensile strength of roots decreased with increasing stand age. The highest and the lowest tensile strengths among species were observed for *Paulownia fortunei* and *Populus deltoides*, respectively. The findings of this research contribute to expanding the knowledge of root biotechnical properties of some tree species and to the choice of the most appropriate species for improving plastic index and shear strength in landslide prone areas.

Keywords: tensile strength; shear strength; Atterberg limits; root density; slope stabilization

Slope instability is one of the crucial problems in forest management practices especially in a transportation network. Vegetation can improve the shear strength of slopes prone to instability through root reinforcement (Avani et al. 2014). Effects of roots on increasing the soil shear strength depend on root tensile strength, morphological characteristics of the root system and the soil-root cohesive strength (Davoudi, Fatemi 2016). Determination of root tensile strength can provide the necessary data for analysing root-soil relations. Tensile strength of plant roots varies in a wide range and has been reported from thousands to millions of MPa (Davoudi 2009). Most roots directly affecting the soil shear strength are about 10 mm in diameter and less than 100 mm in diameter (Voottipruex

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et al. 2008). Tree roots improve soil mechanical properties (soil shear strength, soil cohesion and Atterberg limits) through a variety of mechanisms including hydrological and soil moisture modification. The root cohesion is added directly to the soil cohesion for the soil elements that are reinforced by plant roots (Chok et al. 2015).

The amount of reinforcement mainly depends on the density and tensile strength of the roots. Davoudi (2009) investigated the variation of shear strength of soil in relation to willow root density. The results reveal that in spite of a slight decrease by 8% in the internal friction angle, the appearance cohesion of clay soils increases significantly by up to 130%. The mixture of the soil samples with 4% of grass roots increased its unconfined compressive strength and shear strength by 93.3% and 68.5%, respectively. The permeability of soil was generally increased by the application of grass roots (Gobinath et al. 2015). Genet et al. (2006) showed that young trees provide greater soil cohesion than older trees because of an increased root area ratio (*RAR*). An increase in the *RAR* of young trees may be due to a higher planting density. Voottipruex et al. (2008) reported that vetiver grass roots increased the soil strength 1.5 times and *Acacia* tree roots increased the soil shear strength 3 times. Abdi (2014) found that the root distribution of Oriental beech generally decreased with increasing soil depth and the mean root strength value was 38.23 ± 1.19 MPa for 0.35–5.60 mm diameter range.

Soil is strong in compression but weak in tension. Conversely, roots are weak in compression but strong in tension (Pollen-Bankhead, Simon 2009). Roots in soil produce a reinforced matrix in which stress is transferred to the roots during loading of soil (Thorne 1990). Numerous long roots growing almost vertically downwards are able to penetrate and reinforce the soil that might be prone to surficial failure (Mickovski, Van Beek 2009). Schwarz et al. (2015) showed that the presence of 10 roots with diameters ranging from 6 to 28 mm in a rectangular soil profile 0.72 m by 0.25 m increased the compressive strength of the soil by about 40% (2.5 kN) at a displacement of 0.05 m, while the apparent stiffness of the rooted soil was 38% higher than for the root-free soil.

In northern forests of Iran, tree species for landslide control are often chosen according to environmental adaptability, ease of availability, ability of soil stabilization and commercial importance. Moreover, in bioengineering soil stabilization techniques it is necessary to know which trees enhance the mechanical reinforcement of soils (Wynn et al. 2004). In order to assess soil reinforcement by tree roots, root distribution and tensile strength data with soil depth in different species and ages is necessary. The environmental conditions and genetic characteristics of trees can also influence the root tensile strength (Hosseini et al. 2013). The changes in biotechnical characteristics of root system over time have been investigated scarcely (Genet et al. 2006). Therefore we carried out a study on the changes of biotechnical characteristics of root system and soil mechanics in 2-, 10- and 15-year old plantations of *Alnus subcordata*, *Paulownia fortunei* and *Populus deltoides* in an area where shallow landslides are frequent. The result of this study is useful to choose appropriate species for soil stabilization.

MATERIALS AND METHODS

Study area

The study area is located in Bahramnia forestry plan in the north of Iran (36°44'N, 54°23'E) at 650 m a.s.l. The managed forest area covers 1,713.3 ha. The forest is mixed deciduous which was established on brown forest soil with mostly sandstone as bedrock. Clay-loam silty texture and weathered stones are spread across the region. The climate is moderate and moist. The mean annual precipitation varies from 528 mm to 817 mm while precipitation is lowest in July and August. The total length of forest roads in district I was 30.3 km. These roads were constructed in 1989. In our study area, a single-tree selection method is carried out in timber compartments at 10-year intervals. Two periods of operations have already been done in district I. The tree species are *Parrotia persica*, *Carpinus betulus*, *Fagus orientalis*, *Quercus castaneifolia* and *Zelkova carpinifolia*. The mean of tree density per hectare was 214.92 and the canopy cover was 75–85%.

Biotechnical measurements of root system

In May 2017, three sites including stable site, plantations and unstable site were monitored. 2-, 10- and 15-year-old plantations of *Alnus subcordata*,

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Table 1. Root biotechnical characteristics of *Alnus subcordata*, *Paulownia fortunei* and *Populus deltoides* in 2, 10, 15 year-old stands

Age (year)	Species	*RD* (mm)	*TS*	*RDR*	d_{50} (mm)	*RAR*	*RDDI*
	Alnus subcordata	5.3[b]	24.9[b]	2.02[b]	2.4[a]	0.180[a]	0.364[a]
2	*Paulownia fortunei*	7.0[a]	35.5[a]	3.60[b]	3.0[a]	0.130[a]	0.468[a]
	Populus deltoides	5.0[b]	22.9[b]	12.23[a]	3.3[a]	0.020[b]	0.245[a]
	Alnus subcordata	5.5[a]	12.4[b]	5.57[b]	3.2[a]	0.160[a]	0.891[a]
10	*Paulownia fortunei*	6.2[a]	32.2[a]	4.76[b]	3.5[a]	0.060[b]	0.286[b]
	Populus deltoides	3.4[b]	9.9[b]	14.15[a]	2.5[a]	0.010[b]	0.141[b]
	Alnus subcordata	6.2[a]	7.3[b]	5.35[b]	2.9[b]	1.191[a]	6.372[a]
15	*Paulownia fortunei*	6.3[a]	26.5[a]	5.08[b]	4.3[a]	0.110[b]	0.559[b]
	Populus deltoides	4.6[b]	6.8[b]	21.58[a]	3.8[a]	0.008[c]	0.173[b]

RD – root diameter, *TS* – tensile strength, *RDR* – root diameter rate, d_{50} – diameter to what 50% of roots were equal to or lower than it, *RAR* – root area ratio, *RDDI* – root diameter and density index, different letters in a column show a significant difference between species in each stand based on Duncan test at $P < 0.05$

Paulownia fortunei and *Populus deltoides* were selected to determine the effect of trees age on biotechnical characteristics of root system. All plantations were close to each other on the same type of soil (silty loam), at the same altitude (400–500 m), and slope gradient (50%). Four trees from each plantation were selected randomly to determine root tensile strength (*TS*), root area ratio, root diameter and root diameter and density index (*RDDI*). Root biotechnical characteristics of *Alnus subcordata*, *Paulownia fortunei* and *Populus deltoides* in 2-, 10-, 15-year-old stands were recorded (Table 1). Root samples were collected at four directions around the tree using the profile trenching method (Abdi et al. 2011). The distance of sampling from each tree was 0.50 m. In the sampling process one trench of one meter in depth was dug around a tree. All roots were counted and then divided into diameter classes of 0.001–1, 1–2, 2–5, 5–10 and > 10 mm. The diameter of roots was measured with a digital calliper. 10 roots of 20 cm in length were randomly collected from each diameter class, direction and layer of the trench wall. All roots were kept in a plastic bag with 15% ethanol to preserve their moisture content (Lateh et al. 2014a). Tensile strength tests were carried out using a standard Instron apparatus. *RAR* or root area index is an amount of rooting mass in the soil (Bischetti et al. 2005). The root area ratio in each layer was calculated by Equation 1:

$$RAR = \frac{\sum_{i=1}^{n} \frac{\pi}{4} d_i^2}{A} \quad (1)$$

where:

d_i – diameter of root i_{th},

n – total number of roots in each layer,

A – area of soil in each layer (Comino, Marengo 2010; Avani et al. 2014).

Root diameter and density index (*RDDI*) in each layer was calculated by Equation 2 (Davoudi 2009):

$$RDDI = RAR \times RDR \quad (2)$$

where:

RAR – root area ratio,

RDR – root diameter rate.

Root diameter rate that was calculated for each layer by Equation 3:

$$RDR = \frac{d_{50}}{d_{max}} \times 100 \quad (3)$$

where:

d_{50} – diameter to what 50% of roots were equal to or lower than it,

d_{max} – maximum root diameter which is observed on the trench wall.

Measurements of soil mechanics

In Atterberg limits analysis, the liquid limit (*LL*) was determined using the usual multipoint method. In this method several samples were used in the Casagrande analysis. The number of drops of the cup required to close the groove and the soil moisture content (%) when the groove is closed for each sample were measured. Then, the flow curve of soil

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was designed in Excel (Microsoft) using three points. The liquid limit is the water content corresponding to closure at 25 drops. The moisture content, as determined in Equation (4), is the Plastic Limit (*PL*):

$$PL = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \quad (4)$$

where:
W_2 – weight of the can (g) + wet soil (g),
W_3 – weight of the can (g) + dry soil (g),
W_1 – weight of the empty can (g).

The Plasticity index (*PI*) of soil is the numerical difference between its liquid limit and its plastic limit (Equation 5):

$$PI = LL - PL \quad (5)$$

where:
LL – liquid limit,
PL – plastic limit.

The shear parameters of soil were measured according to the standard DIN 18137 by means of the grain size fraction < 0.5 mm using a box shear apparatus. After consolidating each sample for a minimum of 150 min, normal stresses (σ) of 10, 20, 40, and 80 kPa were incrementally applied to obtain the shear strength, the angle of internal friction (Φ), and the cohesion (*C*) (Equation 6):

$$SS = C + \sigma tan\Phi \quad (6)$$

where:
C – cohesion,
σ – normal stress on the failure plane,
Φ – angle of internal friction,
SS – shear strength.

The friction angle and cohesion can be determined as Equation (7) and Equation (8):

$$\Phi = tan^{-1}\left(\frac{SS}{\sigma}\right) \quad (7)$$

$$C = \frac{\sigma_1 - \sigma_3 tan^2\left(45 + \frac{\Phi}{2}\right)}{2\tan\left(45 + \frac{\Phi}{2}\right)} \quad (8)$$

where:
Φ – angle of internal friction,
SS – shear strength,
σ – normal stress on the failure plane,
σ_1 – major principal effective stress at failure,
σ_3 – minor principal effective stress at failure.

Statistical analysis

Statistical analyses were conducted using SPSS (Version 13.0, SPSS). To test whether the differences between the treatments were statistically significant ($P < 0.05$), one-way analysis of variance (ANOVA) and the Duncan multiple comparison procedure were performed. Pearson correlation coefficient was used to find relationships between parameters.

RESULTS AND DISCUSSION

The results of ANOVA revealed significant differences between species and stand ages. The highest and the lowest tensile strengths among species were also observed for *Paulownia fortunei* and *Populus deltoids*, respectively. The results indicated that the root density and number of roots

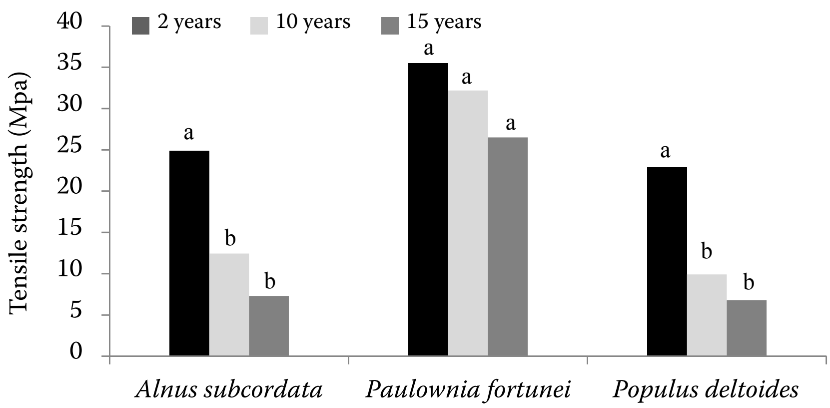

Fig. 1. Comparison of tensile strength between different species at different stand ages

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decreased with increasing *Populus deltoides* stand age, except for *Alnus subcordata* and *Paulownia fortunei* (Table 1). Moreover, the tensile strength of roots decreased with increasing stand age (Fig. 1). Abdi et al. (2011) investigated the root tensile strength of beech, hornbeam and ironwood. The highest and the lowest tensile strengths were observed for beech and ironwood, respectively.

The results showed that tensile force increased following a power law with increasing root diameter. But tensile strength increased following a power law with decreasing root diameter (Fig. 2). Based on the results, the magnitude of α in the relation between diameter and tensile strength in 2- and 10-year-old stand decreased from *Populus deltoides* to *Alnus subcordata* and *Paulownia fortunei*. In 15-year-old

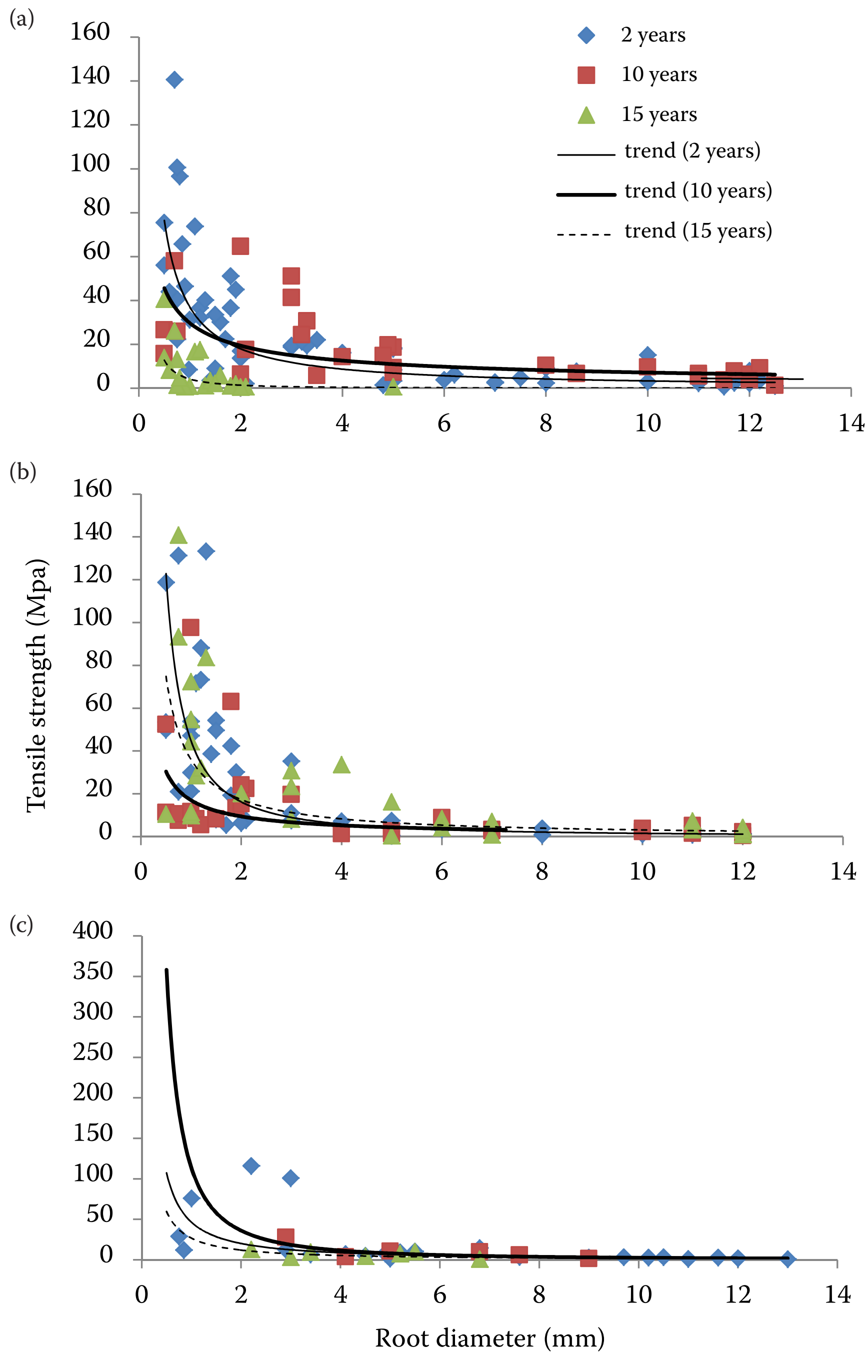

Fig. 2. The relationship between diameter and tensile strength of roots for (a) *Alnus subcordata,* (b) *Paulownia fortunei* and (c) *Populus deltoides* L.

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Table 2. Coefficients of tensile strength-root diameter equations and their coefficients of determination

Species	Stand age (year)	α	β	R^2
Alnus subcordata	2	37.05	–1.04	0.634
	10	29.71	–0.61	0.459
	15	4.188	–1.60	0.409
Paulownia fortunei	2	44.63	–1.46	0.795
	10	16.97	–0.84	0.487
	15	35.94	–1.05	0.550
Populus deltoides L.	2	46.46	–1.20	0.585
	10	113.6	–1.65	0.470
	15	26.64	–1.16	0.253

α, β – empirical coefficients

stand, the magnitude of α decreased from *Paulownia fortunei* to *Alnus subcordata* and *Populus deltoides.* Meanwhile β increased from *Alnus subcordata* to *Paulownia fortunei* and *Populus deltoides* (Table 2). Genet et al. (2008) investigated the effect of the age of *Cryptomeria japonica* D. Don and stand structure on slope stability. Results showed that root density (*RD*) was highest in the 9-year-old stand, but root tensile strength was lowest. In the 30-year-old stand, *RD* was low but a higher root tensile strength compensated for the decrease in *RAR*. Young trees have a greater *RAR* due to a higher planting density (Genet et al. 2006).

Root biotechnical characteristics of trees vary by species. In this study laboratory root biotechnical tests have been conducted to analyse the root system properties in different species at different sites. The plant root system affords further cohesion to the soil (Lateh et al. 2014b). In this study it was detected that soil cohesion in *Alnus subcordata* L. stand was higher than in other stands. The soil-root matrix increases the soil shear resistance. Therefore trees increase the slope stability (Lateh et al. 2014a). The results revealed that the plastic limit, internal friction angle and the appearance cohesion of soils in *Alnus subcordata* L. stand were significantly higher than in *Paulownia fortunei* and *Populus deltoides* L. stands (Table 3).

It was reported that the root density in *Alnus subcordata* decreased with increasing depth. Tensile strength decreases with diameter of roots following a power function with an average of 16.29 MPa (Maleki et al. 2014). In a study in Kenya, the root reinforcement effect of shrubs (*Atriplex halimus*), grasses (*Pennisetum clandistenum* and *Themeda triandra*), and tree ferns (Asparagus species) was assessed. Findings showed that maximum *RAR* values were located within 0.1 m for all the species. Shrub species showed high *RAR* values at a depth between 0.1 and 0.3 m. Root tensile strength decreases with increasing root diameter. The maximum root tensile strength value recorded was 39 N/mm^2 for grass (Nyambane, Mwea 2011). In *Quercus persica* with root diameter range of 1.0–5.5 mm and tensile force range of 1.3–411.3 N the tensile strength range was 0.93-1217.39 MPa. The relationships between root diameter and tensile force and strength were positive and negative power laws, respectively. Mean strength was higher in winter than in summer (Kazemi et al. 2014).

Table 3. Soil geotechnical characteristics in 2, 10, 15 year-old stands of *Alnus subcordata* to *Paulownia fortunei* and *Populus deltoids* L.

Age (year)	Site	*LL* (%)	*PL* (%)	*PI*	Φ (Degree)	*C* (kPa)
0	Unstable	34.2	19.1	15.1	42.2	8.2
2	*Alnus subcordata* L.	31.4	21.1	10.3	40.8	10.9
	Paulownia fortunei	34.3	25.8	8.5	26.4	10.0
	Populus deltoids L.	32.7	24.1	8.6	24.0	9.0
10	*Alnus subcordata* L.	39.4	26.4	13.0	42.8	14.9
	Paulownia fortunei	29.2	19.5	9.7	28.9	9.1
	Populus deltoids L.	29.7	21.6	8.1	25.5	8.1
15	*Alnus subcordata* L.	32.9	21.8	11.1	43.0	16.3
	Paulownia fortunei	33.1	24.3	8.8	32.5	7.9
	Populus deltoids L.	38.0	32.6	5.4	27.1	7.2
–	Stable	51.1	44.7	6.4	25.1	17.5

LL – liquid limit, *PL* – plastic limit, *PI* – plasticity index, Φ– angle of internal friction, *C* – cohesion

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Table 4. Pearson correlation coefficients between root and soil properties

Variable	1	2	3	4	5	6	7	8	9	10
	Age	*PI*	*LL*	Φ	*C*	*TS*	*RDR*	*RD*	*RAR*	*RDDI*
1	1									
2	-0.09^{ns}	1								
3	0.21^{ns}	0.07^{ns}	1							
4	-0.13^{ns}	0.85^{**}	0.22^{ns}	1						
5	0.08^{ns}	0.83^{**}	0.27^{ns}	0.92^{***}	1					
6	-0.57^{*}	0.02^{ns}	-0.38^{ns}	-0.13^{ns}	-0.30^{ns}	1				
7	0.31^{ns}	-0.73^{*}	0.26^{ns}	-0.64^{*}	-0.49^{ns}	-0.59^{*}	1			
8	-0.07^{ns}	0.33^{ns}	0.07^{ns}	0.34^{ns}	0.32^{ns}	0.62^{*}	-0.71^{*}	1		
9	0.34^{ns}	0.43^{ns}	-0.01^{ns}	-0.63^{*}	0.78^{*}	-0.36^{ns}	-0.31^{ns}	0.33^{ns}	1	
10	0.40^{ns}	0.40^{ns}	0.01^{ns}	-0.58^{*}	0.76^{*}	-0.41^{ns}	-0.23^{ns}	0.30^{ns}	0.99^{***}	1

PI – plasticity index, *LL* – liquid limit, Φ– angle of internal friction, *C* – cohesion, *PL* – plastic limit, *TS* – tensile strength, *RDR* – root diameter rate, d_{50} – diameter to what 50% of roots were equal to or lower than it, *RAR* – root area ratio, *RDDI* – root diameter and density index; *,**,*** significant at $P < 0.05$, $P < 0.01$ and $P < 0.0001$; ns – not significant

Lateral roots of *Carpinus betulus* are able to provide a tractive force of up to 167.4 N over a vertical cross-section area of 20–50 cm^2 and increase the shear strength of soil by 24.5% (Habibi Bibalani et al. 2009). Results of this study indicated that *PI* and ϕ decreased with increasing *RDR*. Moreover, *C* increased with increasing *RAR* and *RDDI*. Tensile strength of roots decreased with increasing stand age (Table 4).

CONCLUSIONS

The measurement and calculation of *RDDI*, mean root diameter, *RAR*, tensile strength and soil geotechnical factors in different conditions have been carried out for determining the best species for soil stabilization. The tensile strength tests showed that trees in juvenile stage give excellent results. *Alnus subcordata* had a dense network of root systems that significantly increased *RAR*. Maximum tensile strength and *RAR* were detected in almost two years after planting of *Paulownia fortunei*. The results obtained show that the strength properties of the soil samples were improved by the increase in root density. So, maximum shear strength was detected for *Alnus subcordata* L. Although our study has demonstrated the importance of tree age and species effects on slope stability, many questions still remain to be answered. The effect of slope hydrology, stand density and rising water table in these zones is not known yet.

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