Assessing the effect of Alnus roots on hillslope stability in order to use in soil bioengineering

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ABSTRACT: The role of plant roots in stabilizing slopes is obvious, but the amount of the effect is varied in different species. The purpose of this study was to evaluate the effect of alder (*Alnus subcordata)* roots on hillslope stability. The profile trenching method was used to obtain root characteristics and a standard Instron testing machine was used for determining the tensile strength of roots. Direct shear test with undisturbed samples was used for determining the soil strength parameters. Using the results of biotechnical characteristics and the *Wu* model, the reinforcement effect was calculated. Using the reinforcement values and soil strength parameters and Slip4Ex program, factor of safety with and without vegetation was calculated. The obtained results indicated that the root density and number of roots decreased with increasing depth and the average root area ratio was 0.071% ± 0.01. Tensile strength decreased with increasing diameter of roots following the power function with an average of 16.29 ± 3.10 MPa. The minimum and maximum of reinforcement were 0.55 KPa and 110.76 KPa, respectively. The results of this paper augment the knowledge about biotechnical characteristics of root systems of Alder species and indicate that this species increases the factor of safety about 16.79%.

Keywords: biotechnical properties of root; soil reinforcement; factor of safety

Human activities have adverse effects on slope stability around man-made structures such as forest roads. One of the common methods to stabilize slopes is to use vegetation. Researchers demonstrated the role of plant roots in stabilizing slopes and preventing soil erosion (Gray, Sotir 1996; Norris et al. 2006; Genet et al. 2008). Roots work effectively with the help of hydrological and mechanical factors (Nilaweera, Nutalaya 1999). Hydrological factors such as evapotranspiration reduce the amount of water in soil and thus increase the slope stability (Wu 1984). Mechanical factors such as distribution and tensile strength of roots (Nilaweera, Nutalaya 1999) increase the shear strength of soil. For measuring root distribution, the root area ratio (RAR) should be calculated (Abernethy, Rutherfurd 2001). Actual determination of RAR for a plant is essential in order to calculate the factor of safety (FOS) (Danjon et al. 2008) and root tensile strength is an important index for determining the soil reinforcement (genet et al. 2005). Many studies have been conducted to evaluate the mechanical properties of plant roots (Bischetti et al. 2005; Tosi 2007; Abdi et al. 2010; Burylo et al. 2011; Vergani et al. 2012) but these parameters are affected by species and site conditions (Schmidt et al. 2001; Schmid 2002).

Measuring the amount of increased slope stability by different species at the same site and one species at different sites is a key component of bioengineering, therefore the aim of this study was to evaluate the effect of *Alnus subcordata* roots on stabilizing roadside slopes. This species is native, pioneer and fast growing but despite potential capabilities for bioengineering purposes, it has not been investigated in Iran until now.

MATERIAL AND METHODS

Site study

The study was conducted in district No. 1 of Tanian forests, in the west part of the Hyrcanian forests, Northern Iran.

The study area was located between 37°15' and 37°16'N, and between 49°4' and 49°8'E. The study area is situated at an altitude between 100 and 1,400 m a.s.l., on a slope from 30% to 60%. The total surface area is 2,204 ha. In general, the relative humidity is high; with the annual rainfall varying between 1,500 and 2,000 mm per year. The season from June to September is relatively dry and warm. These forests were previously composed of mixed deciduous species including hornbeam, oak, maple, and beech with alder, ironwood, Caspian locust, and date plum, but it has been damaged as a result of harvesting. However, it has been reforested with local species such as *Quercus castaneifolia* (oak), *Acer pseudoplatanus* (Sycamore maple), *Fraxinus excelsior* (European ash), and *Alnus subcordata* (Caucasian alder) and also poplar and coniferous trees. In this study, the focus was on Alder that was about 15 years old.

Investigation of plant and soil characteristics

In this study, eight alder trees were randomly selected. Root sampling was carried out in September 2011. The number of roots, root area ratio, tensile strength of roots, root reinforcement, soil shear strength and factor of safety were investigated. For determining the factor of safety, Slip4Ex program was used and the data was analysed by SPSS 13 statistical software (J. Greenwood, Nottingham Trent University, UK).

Root number and RAR

A profile trenching method was used for measuring the RAR. In downslopes where roots have a larger positive impact on the factor of safety (Ji et al. 2012), a profile was dug at a distance of one meter from each sample trees. Each profile was divided into 10-cm layers (Abdi et al. 2009). The number and diameter of roots were measured and the root area was calculated by assuming the circular cross-section of roots. RAR was estimated by dividing the root area aggregate by the soil area in each layer. The following equation was used to calculate RAR:

$$\mathrm{RAR} = \sum \frac{\pi r^2}{A}$$

where:

πr^2 – root area in each layer (mm^2),

A – soil area in each layer (mm^2).

Root tensile strength (TS)

Field and laboratory tests are common methods for investigating tensile strength, while in this study a laboratory test was used. Root samples were collected from a depth of about 30 cm (Cofie, Koolen 2001). Then sampled roots were washed with water and put into plastic bags with ethylene alcohol solution at 15% (Meyer, Göttsche 1971). Collected roots were tested for less than a week after sampling (Bischetti et al. 2005). The samples were live and protected from decay because the live roots have higher tensile strength than decaying roots (Schmidt et al. 2001). Samples of about 15 cm in length were selected (Cofie, Koolen 2001). Sample diameter was measured at three different positions along the length of the roots and average root diameter was obtained. The root tensile strength was measured with a standard Instron 4486 universal testing machine (Instron, Bucks, UK) with the constant strain rate of 10 mm·min^{-1}. Only samples which broke about in the middle of the root length were accepted (Bischetti et al. 2005).

Root reinforcement

The common model for estimating the effect of root reinforcement was mentioned by Wu (1976) and Waldron (1977). This model shows that tensile strength, density and depth of root depends on species, environment and variability of vegetation properties (i.e. age, health etc.) (Bischetti et al. 2005). The model is as below:

$$C_r = K \times t_R \qquad (2)$$

where:

C_r – shear strength increases due to the presence of roots,

t_R – mobilizes the tensile strength of roots per unit of soil surface,

K – coefficient between 1 and 1.3,

K was calculated as below (Wu 1976):

$$K = (\sin\theta + \cos\theta\tan\phi) \quad (3)$$

where:

ϕ – the soil particle friction angle.

De Baets et al. (2008) reported that θ is 40–50 degrees, therefore we assumed 45 degrees in this study.

Mobilized root tensile strength per unit surface (t_R) is obtained from the following equation:

$$t_R = T_r a_r \quad \text{(Bischetti et al. 2005)}$$

where:

T_r – root mean tensile strength,

a_r – root area ratio.

Taking into account root diameter variation, this formula is changed as follows (Bischetti et al. 2005):

$$t_R = \sum_{i=1}^{N} T_{r_i} \frac{Ar_1}{A} \quad (4)$$

where:

i – the diameter class (cm),

N – the number of classes.

The roots were divided into four diameter classes and tensile strength was calculated for each class. Root reinforcement for up to 1-cm diameter was calculated, but for investigating the RAR variation with depth, all roots were calculated.

Soil direct shear test

To determine the soil cohesion value and friction angle, eight undisturbed samples without root soil were taken from 50–65 cm depths. The samples were kept in plastic bags and carried to a laboratory. Direct shear test was performed in three replications with the frame size of 5.08 × 5.08 × 1.79 cm, normal stress of 10, 20, and 30 kPa, precision of 0.01 mm and unsaturated tested. The speed of lateral displacement was 1.08 mm·min^{-1} when the failure occurred while the peak shear force was noticed.

Factor of safety (FOS)

The slope stability is usually expressed by factor of safety. FOS is a number with threshold value which shows the capability of slope to remain stable or not (Genet et al. 2008). This value is calculated by dividing the resistance to load. The slope is stable if FOS is > 1 and unstable if FOS is < 1, also if FOS is between 1 and 1.3, it is necessary to monitor (Mulder 1991). The position of a tree on the slope affects FOS. When the tree is at the bottom of the slope, FOS is higher than when the tree is on the top or in the middle of the slope (Genet et al. 2010). In this study the trees were at the bottom of slope. FOS was calculated with and without plant root presence in the soil by the Slip4Ex program, which was developed by J. Greenwood, Nottingham Trent University, UK. This program is based on a limit equilibrium method and calculates the FOS by different methods; we used the Janbu method. FOS increase with plant roots presented in the soil (FOS_r) was determined as follows:

$$FOS_r = 100 \times ((\text{FOS with root} - \text{FOS without root})/(\text{FOS without root})) \quad \text{(Genet et al. 2008)}$$

RESULTS

Root number and root area ratio

The obtained results showed that the root number and RAR generally decreased with increasing depth and maximum rooting depth was 1 m. Minimum and maximum RAR was calculated to be 0.0002% and 0.488%, respectively. Root number and RAR pattern are shown in Figs 1 and 2.

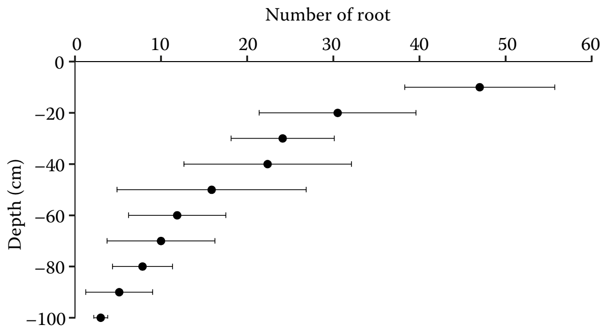

Fig. 1. Scatter plot for root number at different depths (mean ± standard deviation)

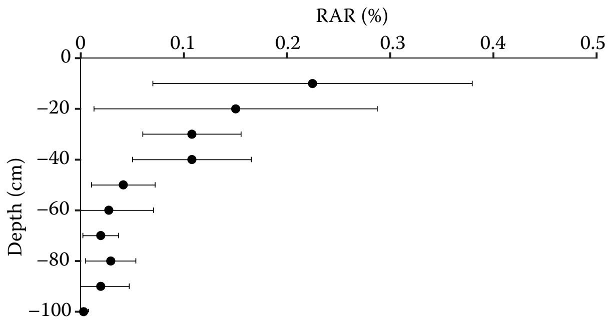

Fig. 2. Scatter plot for root area ration (RAR) values at different depths (mean ± standard deviation)

Table 1. Information of TS test

TS (MPa)			Root diameter (mm)		
Mean ± SE	min	max	mean ± SE	min	max
16.29 ± 3.10	3.32	114.48	1.14 ± 0.11	0.17	3.12

Table 2. Tensile strength power equation coefficients and correlation between diameter and tensile strength of roots

Number of samples	α	B	R^2	r
39	11.36	–0.75	0.40	0.52

Root tensile strength

Overall, 39 tensile strength tests were successfully performed on the root samples. The information on root tensile strength tests is shown in Table 1. According to the obtained results, the required force for root failure increased with increasing root diameter and constituted polynomial models (Fig. 3).

Tensile strength was obtained by dividing the root failure force by the surface area of each sample (Abdi et al. 2010). The results showed that tensile strength decreases with increasing diameter and the relationship between these two variables follows a negative power function (Fig. 4). The coefficients of the equation and the correlation coefficient between the diameter and the tensile strength are shown in Table 2.

Root reinforcement

Root reinforcement was calculated for roots of up to 10 mm in diameter and its distribution with depth was determined (Fig. 5). The minimum and maximum of reinforcement was 0.55 kPa and 110.76 kPa, respectively, and the lowest value was at the last depth and the highest value was at the first one with the highest number of roots.

Soil direct shear

Regarding the results of direct shear test of undisturbed soil, the cohesion value and friction angle were 0.0031 kPa and 30 degrees, respectively.

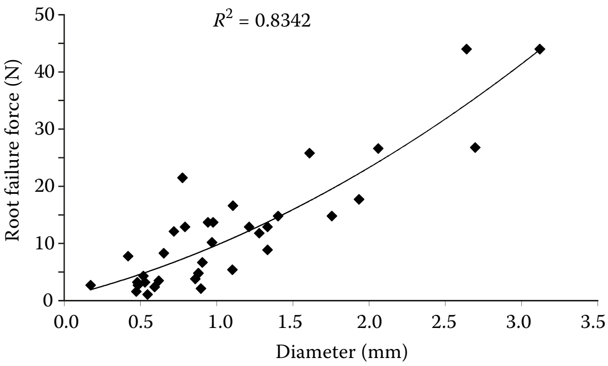

Fig. 3. Correlation between required forces for root failure and diameter, which is a polynomial function

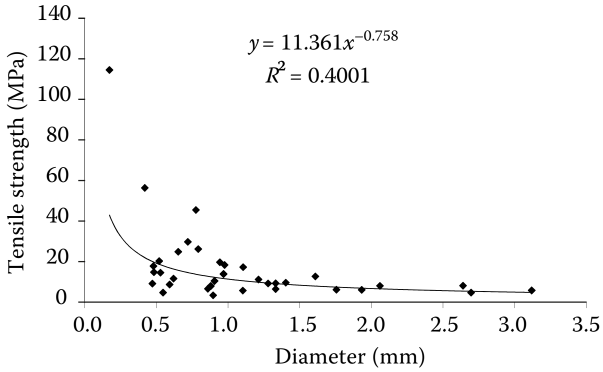

Fig. 4. Correlation between root tensile strength and diameter, which is a power function

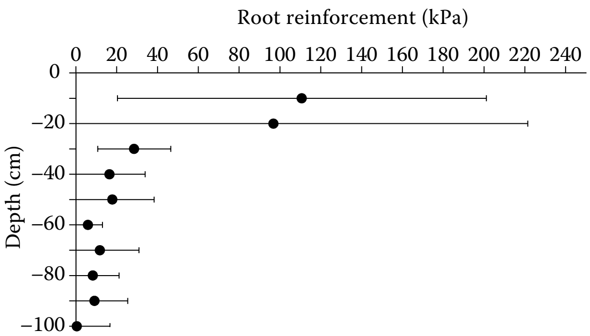

Fig. 5. Root reinforcement with roots present at different depths (mean ± standard deviation)

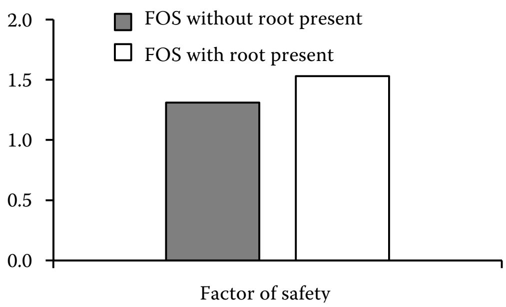

Fig. 6. Factor of safety (FOS) with and without plant roots present in the soil

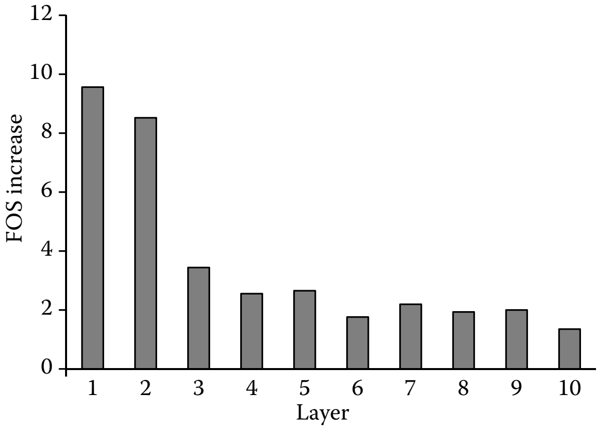

Fig. 7. Increased factor of safety (FOS) in the particular layers of soil

Slope stability

FOS was calculated 1.53 with vegetation and 1.31 without vegetation (Fig. 6). In other words, FOS increases up to 16.79% due to the presence of roots. FOS in different layers was calculated by assessing the amount of reinforcement for each layer and using the Slip4Ex program. Fig. 7 shows the FOS increase variation in the particular layers of soil.

DISCUSSION

Number and RAR

The results of this study showed that RAR values decreased with increasing depth and maximum RAR values were located in the upper layers. Some researchers reported the same results (Bischetti et al. 2005; Abdi et al. 2010; Comino, Marengo 2010; Burylo et al. 2011). It occurs due to lower nutrients and aeration, and the presence of more compacted lower layers (Bischetti et al. 2005). Average RAR value was 0.071 ± 0.01%. Bischetti et al. (2005) reported that the average RAR value for their study varied from 0.1% to 0.35%. However, for investigating the variation of RAR with depth, they considered diameters ranging from 1 mm to 10 mm but the present study considered all roots (with a minimum diameter of 0.01 and maximum diameter of 21.77 mm). The results of roots number also showed that this value decreased with increasing depth as a logarithmic function. The decreasing root number with increasing depth was documented by Abdi et al. (2010). More than 90% of the roots of this species were located at a soil depth above 80 cm. Measuring this depth is useful (Simon, Collison 2002) and it varied in different species (Simon, Collison 2002; Abdi et al. 2010).

Root TS

In this study root diameter and tensile strength showed a power relationship based where thinner diameters have greater tensile strength. The obtained result is consistent with the findings of many researchers (Gray, Sotir 1996; Bischetti et al. 2005; Tosi 2007; Abdi et al. 2009; Burylo et al. 2011; Ji et al. 2012). The mean tensile strength of investigated species was 16.29 ± 3.10 MPa, which was similar to previous studies (Morgan, Rickson 1995; Norris et al. 2008). These comparisons are sensitive to the number and diameter of samples (Tosi 2007) and also the tensile strength variation may be related to changes in the lignin/cellulose ratio that is influenced by season and abiotic factors such as mechanical stress (Plomion et al. 2001) and more cellulose will result in more powerful roots (Genet et al. 2005). Bischetti et al. (2005) showed that a species has higher tensile strength when α is higher and β is smaller in the tensile strength equation and Nilaweera (1994) reported the coefficient ranges for broadleaved tree species α (between 29.1 and 87.0) and β (between –0.8 and –0.4). In the present study α (11.36) does not follow the range suggested but β (–0.75) is in the above-mentioned range. Bischetti et al. (2005) reported alder in Valdorena with $\alpha = 34.76$ and $\beta = -0.69$, Abdi et al. (2009) reported hornbeam species with $\alpha = 34.24$ and $\beta = -0.45$ and also Abdi et al. (2010) observed ironwood with $\alpha = 33.05$ and $\beta = -0.37$ in the Hyrcanian region and Vergani et al. (2012) reported five broadleaved species in the Alpine region with α ranging between 14.83 and 26.39 and β from –0.46 to –0.2. The R^2 correlation between root diameter and root tensile strength was medium (0.40). This result is comparable with the study of Bischetti et al. (2005) for the species *Alnus viridis* with R^2 of 0.34. Although it seems low R^2 due to the low number of tests, Burylo et al. (2011) reported *Quercus pubescens* R^2 of 0.73 with 14 tests.

The analysis showed that required force for root failure increased with increased root diameter and this relationship was a polynomial regression and Schmidt et al. (2001), Tosi (2007), Comino and Marengo (2010) also reached the same conclusion.

Root reinforcement

The highest reinforcement value in this study occurred at the first depth which contains the highest number of roots. Comino and Marengo (2010) reported that the highest shear strength increase for all species studied at the depth occurred when there were highest numbers of roots. The amount of root reinforcement was reported 1–150 kPa (Abernethy, Rutherfurf 2001; Schmidt et al. 2001; Bischetti et al. 2005, 2009; Genet et al. 2008) which depends on the vegetation type, environmental factors and soil depth (Vergani et al. 2012). In the present study minimum reinforcement (0.55 kPa) does not follow this range due to the fact that the last depth had a very low root number.

Factor of safety

Evaluating the soil FOS without plant presence showed that this area needs monitoring. Unsaturated direct shear test was used to calculate FOS and the test evaluated the strength parameter of soil to be high (Genet et al. 2010), which showed a critical situation in the study area. Increasing slope stability influenced root of plant in this study, which is consistent with the results of other studies (Tosi 2007; Genet et al. 2008).

CONCLUSIONS

In order to stabilize the unstable slope area by a bioengineering method, different species must be investigated and the best species should be selected to stabilize that area. This study showed that number, density, reinforcement and FOS of alder roots decrease with depth increase and most reinforcement occurred in the place with the highest density of roots. The present study also showed that the thicker diameter roots have lower tensile strength, although it requires more force for failure. Generally, this species increases the FOS and results in the stability of the region.

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