Quantifying the effects of root reinforcement of Persian Ironwood (Parrotia persica) on slope stability; a case study: Hillslope of Hyrcanian forests, northern Iran

Ehsan Abdi\textsuperscript{a,*}, Baris Majnounian\textsuperscript{a}, Maria Genet\textsuperscript{b}, Hassan Rahimi\textsuperscript{c}

\textsuperscript{a} University of Tehran, Department of Forestry, Karaj, Iran
\textsuperscript{b} Université Bordeaux I, US2B, 33405 Talence Cedex, France
\textsuperscript{c} University of Tehran, Department of Irrigation Engineering, Karaj, Iran

Abstract

Forest vegetation is known to enhance the stability of slopes by reinforcing soil and increasing its shear resistance through root system. The effects of root reinforcement depend on the morphological characteristics of the root system, the tensile strength of single roots, and the spatial distribution of the roots in soil. In the present study the results of research carried out in order to evaluate the biotechnical characteristics of the root system of Persian Ironwood (Parrotia persica), in northern Iran are presented. Profile trenching method was used to obtain root area ratio (RAR) values for uphill and downhill sides of the individual trees. For each species, single root specimens were sampled and tested for their tensile strength. It was found that root density generally decreases with depth according to an exponential law. Maximum RAR values were located within the first 0.1 m, with maximum rooting depth at about 0.65 m. RAR values ranged from 0.001% at lower depths to 1.39% near the surface, at upper 0.1 m depth. Significant differences of RAR values, rooting depth and root cohesion between uphill and downhill were observed, however, the differences were not significant for number of roots (ANCOVA). Downhill profiles had higher RAR values, rooting depth and root cohesion. In general, root tensile strength tends to decrease with diameter according to a power law, as observed by other researchers. Downhill roots were significantly stronger in tensile strength than uphill ones. Inter-species variation of tensile strength in downhill roots was also observed. The resulting data were used to evaluate the reinforcing effects in terms of increased shear strength of the soil, using Wu/Waldron Model. The root reinforcement provided by Persian Ironwood is about 46.0 kPa in the upper layers and 0.3 kPa in the deeper horizons. The results of Spearman test revealed a significant correlation between RAR and \( c \) and that best followed by a power law. The results presented in this paper contribute to expanding the knowledge on biotechnical characteristics of Persian Ironwood on slope reinforcement.

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1. Introduction

The number of catastrophic incidents caused due to slope instability has increased in recent years around the world, including northern regions of Iran. Slope failure and shallow landslides are a serious problem in Hyrcanian forests, where bare soils are vulnerable to failure during intensive rainstorms. Specifically, in forest roads where the trees have been clear cut, the slopes are prone to landslides. Land degradation due to landslides has catastrophic human, environmental and financial consequences. In forest regions, shallow landslides may destroy the roads and cut off wood extraction process with sever economical consequences. In some places, even protective engineering structures such as gabion walls could not prevent progressive slope failures to forest roads (such as in the study area, Fig. 1). Eco-engineering has recently been defined as the long-term, ecological strategy to manage a site with regard to natural and man-made hazards (Stokes et al., 2008). Eco-engineering methods are particularly suited to natural slopes, where management is long-term and the site is large-scale (Norris and Greenwood, 2008). It is generally accepted that plant roots provide reinforcement to a soil matrix due to the different material properties of soil and roots (Greenway, 1987).

Generally, soil is considered as to be a material strong in compression but weak in tension (Pollen, 2007). Conversely, roots are
weak in compression but strong in tension, providing potentially key reinforcement to landslide-prone hillslopes. Thus, the presence of roots in the soil produces a reinforced matrix in which stress is transferred to the roots during loading of the soil in a way that is similar to the reinforcement of concrete structures by steel and fiberglass (Thorne, 1990; Pollen, 2007). Several factors can affect the root reinforcement of a soil, including root density and tensile strength of the roots (Greenway, 1987) as well as the spacing of the plants/trees and the soil depth (Watson and Marden, 2004).

Knowledge of a range of root-wood tensile strengths and root density provides key information that is often required in root-soil assessment analysis, and can be useful when selecting plant species for erosion control (Pollen, 2007). Root area ratio (RAR) has been used as an indicator of root density by many authors (Burke and Raynal, 1994; Abernethy and Ruthefurd, 2000; Schmid and Kazda, 2001; Simon and Collison, 2002; Bischetti et al., 2005; Greenwood et al., 2006; Sun et al., 2008; Genet et al., 2008). RAR and tensile strength of the roots are the most important factors governing soil stabilization (Stokes, 2002; Genet et al., 2008, 2010). RAR and tensile strength have also been considered as the main biotechnical properties of plants (Gray and Sotir, 1996). In the present study, the effect of hydrological effect on root reinforcement has been not considered as it was not the objective of the study. However, it should be taken as an important factor in slope stability as the recent works by Simon and Collison (2002) and Pollen (2007) have shown. Both RAR and tensile strength are influenced by species, root type (size, order) and site characteristics such as soil type, climate, land use management, associated vegetation communities, spatial variability of vegetation properties (density, age), etc. (Gray and Sotir, 1996; Lindström, 1990; Nilaweera and Natalaya, 1999; Operstein and Frydman, 2000; Schmidt et al., 2001; Genet et al., 2008).

Estimates of root reinforcement of soils have commonly been attained using simple perpendicular root models such as Wu/Waldron model that calculates root reinforcement as an additive factor to soil strength. This model is widely used in evaluation of vegetated hillslope stability (Gray and Sotir, 1996; Schmidt et al., 2001) and estimates additional cohesion due to root presence using root tensile strength and root cross-section per unit area of soil (RAR) (Gray and Sotir, 1996; Greenway, 1987; Schiechtl, 1980). Some authors have shown that Wu/Waldron model may overestimate the root reinforcement effect (e.g. Abernethy and Ruthefurd, 2001; Pollen, 2007). The root reinforcement model of Wu/Waldron is based on the Coulomb equation in which soil shearing resistance is calculated based on cohesive and frictional forces as follows:

\[ S = c + \sigma_N \tan \varphi \]  \hspace{1cm} (1)

where \( S \) is soil shearing resistance (kPa), \( \sigma_N \) is the normal stress on the shear plane (kPa), \( \varphi \) is soil internal friction angle (degrees), and \( c \) is soil cohesion (kPa). Wu et al. (1979) extended Eq. (1) for root-permeated soils, by assuming that all roots extend vertically across a horizontal shearing zone, and the roots act like laterally loaded piles, and therefore, tension is transferred to them as the soil is sheared. The modified Coulomb equation becomes:

\[ S = c + c_r + \sigma_N \tan \varphi \]  \hspace{1cm} (2)

where \( c_r \) is increased shearing strength due to roots (kPa). In Wu/Waldron model, the tension developed in the root as the soil is sheared is resolved into a tangential component resisting shear and a normal component increasing the confining pressure on the shear plane. \( c_r \) can be represented by:

\[ c_r = K t_R \]  \hspace{1cm} (3)

where \( t_R \) is the mobilized root tensile strength per soil unit area; \( K \) is a factor taking into account the randomness of the orientation of the roots with respect to the failure plane. The value of \( K \) in most cases varies between 1.0 and 1.3 (Waldron, 1977; Wu et al., 1979). \( K \) can be represented by:

\[ K = \sin \theta + \cos \theta + \tan \varphi \]  \hspace{1cm} (4)

where \( \theta \) is the angle of shear distortion in the shear zone, and \( \varphi \) is the soil internal friction angle (°).

The mobilized root tensile strength per soil unit area \( (t_R) \) can be written as:

\[ t_R = T_r \frac{d}{A_r} \]  \hspace{1cm} (5)

where \( T_r \) is the average tensile strength per average root cross-sectional area; \( A_r \) is the root area ratio computed as \( A_r/A \), where \( A \) is the total cross-sectional area of all roots and \( A \) is the area of soil in the sample count.

Root tensile strength is affected as much by species as by differences in size (Bischetti et al., 2005). The generally accepted form for the relationship between root tensile strength \( (T_r(d)) \) and diameter \( (d) \) is a simple power function as follows (Bischetti et al., 2005; Gray and Sotir, 1996; Mattia et al., 2005):

\[ T_r(d) = \alpha d^{-\beta} \]  \hspace{1cm} (6)

where \( \alpha \) and \( \beta \) are empirical constants depending on the species type.

To account for the variability in root size, Eq. (5) must then be rewritten as:

\[ t_R = \sum_{i=1}^{N} \frac{T_r A_r}{A} \]  \hspace{1cm} (7)

where \( i \) indicates the diameter class and \( N \) is the number of classes.

Despite the large number of studies investigating the plant roots (Kramer and Boyer, 1995; Keyes and Grier, 1981; Jackson et al., 1996), most of them are focused on eco-physiologic behavior of vegetation and do not provide useful data regarding root reinforcement. Such studies, in fact, deal with nutrient and organic matter input to the soil, soil fertility maintenance and carbon sequestration, as a consequence, they only consider small diameter roots (<1–2 mm) in the upper soil layers (Reubens et al., 2007). However, in the recent years the interest in understanding of the role of vegetation on stability slopes and shallow landsliding are increased and the number of studies on this issue is increasing (Abernethy and Ruthefurd, 2001; Bischetti et al., 2009; Genet et al., 2008, 2010;
Roering et al., 2003; Reubens et al., 2007; Schmidt et al., 2001; Zhou et al., 1998). Nevertheless, due to the complexity of reinforcement mechanisms, variety of species and environments and spatial variability of factors governing the processes, such work can be considered eminently site-specific and more experimental data are still needed for a better understanding and generalization of the phenomenon (Mattia et al., 2005).

Persian Ironwood is a natural and native species in Hyrcanian forests. It is common plant, especially on steep and disturbed terrains, thus it can be employed as a bioengineering species to be used to enhance the stability of slopes adjacent to forest roads. However, there is lack of information regarding its biotechnical properties needed for assessment of its contribution to soil reinforcement and slope stability. As Hyrcanian forests are classified as hilly and mountainous, thus, biotechnical properties of Ironwood in hilly conditions are needed for such assessment. There are currently few studies are available on root density distribution (e.g. Di Iorio et al., 2005; Chiatante et al., 2007) and root strength distribution on slopes (e.g. Schiechtlf, 1980; Stokes, 2002). Therefore, the main objective of the present study is to expand the knowledge on both root strength and root density of Ironwood in hilly conditions and to evaluate its contribution to soil reinforcement of slopes.

2. Materials and methods

2.1. Site details

The Hyrcanian forests fall within the provinces of Gorgan, Mazandaran and Gilan, and slopes from the Alborz Mountains of northern Iran northward to the southern shores of the Caspian Sea. The Alborz Mountains rise as high as 5600 m above the sea level and form an effective barrier to rain clouds, making the region one of the wettest in Eurasia.

The study was conducted in an educational and experimental forest of University of Tehran (Kheyrud Forest). It is located on the northern slopes of Albourz Mountains, about 7 km east of Noshahr port. Patom is the lowest district of the forest with an area of about 900 ha which extends from 40 to 900 m above the sea level.

The selection system management is followed to ensure sustainable development and yield of the forest. Ground skidding is used to transport woods from stands to depots, where the woods are loaded and shipped by means of trucks. The extracted woods from three districts should be be transported via Patom district, which would be like a bottle neck. Therefore, occurrence of shallow landslides in this district may halt extraction of wood from the whole forest. Estimation of the number of landslides causing closure of roads in forested areas or the costs imposed on the local authorities by such events have not been thoroughly carried out in Iran. Sarikhani and Gorgi (2004) studied the possibilities of stabilizing landslides in Patom district (including the area in the present study) in part of a road network called “Poplar switchback” where the most severe problems have occurred up to now. In 1994 a series of landslides have caused the closure of roads in this area. The administration had decided to construct a new road segment with a length of 800 m to replace the damaged segment. The repair works cost about $38,000 for the management unit. Sarikhani and Gorgi (2004) stated that maintenance and reinforcement of the existing segment would have less than constructing the new segment. In another incident in 2004 a gabion wall was constructed to stabilize the hillslope of the road (Fig. 1) but after some years progressive failure ruined the gabion and a new gabion wall was constructed with a cost of $9000 in 2009 (Kheyrud Administration, 2009, personal communication).

Many areas in this forest are characterized by the presence of shallow translational slides. These slides involve the superficial layers of the slopes, in many cases less than 1 m deep and extend into the bedrock, where vegetation can exert a beneficial effect on stability through the reinforcing action of lateral root reinforcement. The site has relatively thin soil mantle, underlain by calcareous bedrock (Jura, Cretaceous) that contains discontinuities and cracks which are penetrable by roots (Majnounian and Etter, 1993). Thus the roots act in the same way as toe piles (Tsukamoto and Kusakabe, 1984). The slides normally involve the superficial layers of the slopes, in many cases less than 1 m deep, and extend into the bedrock, where vegetation can have a beneficial effect on stability through the reinforcing action of lateral root.

The study site is located at latitude of 36°29′ N, and longitude of 50°33′ E, on a west-facing slope at 350–550 m altitude. The climate is humid and mild, with a relatively limited range of temperature fluctuations. The average yearly precipitation at the site is 1200 mm, falling mostly as rain and including a cover of snow in winters. The mean summer and winter temperatures are estimated to be 22.5 and 10 °C, respectively. The soil type is MH based on the UCSC1 method (Das, 2005) and the strength parameters of the soil based on direct shear tests are as: $C = 8$ kPa, and $\phi = 25^\circ$ (Abdi, 2009). Eight seed-origin trees were randomly chosen for the root distribution assessment. The 7- to 15-m high deciduous trees are low-branched, 7- to 12-m wide. The range of their DBH2 and heights were 20.00–37.30 cm and 7.50–11.00 m, respectively.

2.2. Estimation of root area ratio (RAR)

Variation of root distribution can be assessed using the concept of root area ratio (RAR), which has been defined as the ratio of the sum of the root areas to the area of soil profile they intersect (Gray and Leiser, 1982; Wu et al., 1979). Root area ratio (RAR) or root biomass concentration as a function of soil depth is required in order to estimate root contribution to soil strength (De Baets et al., 2008).

In order to obtain RAR values, a profile trenching method was employed (Abernethy and Rutherfurd, 2000; Bischetti et al., 2005; Burke and Raynal, 1994; Greenwood et al., 2006; Schmid and Kazda, 2001; Simon and Collison, 2002; Sun et al., 2008). Two trenches were excavated around each sample tree by hand, one in the downhill and the other in the uphill sides at a distance of 1 m from the stump, down to the maximum rooting depth (Abernethy and Rutherfurd, 2001).

Trenches were excavated to expose a fresh profile of the rooted soil. The horizontal dimensions of the profiles were approximately 100 by 50 cm. Layers of 10 cm thick were marked on the vertical profile walls using pins and string. The number (Normaniza et al., 2008), diameter (Sun et al., 2008) and maximum depth of roots were measured in both uphill and downhill trenches by counting. RAR values were obtained at depth increments of 0.1 m of all roots with a diameter larger than 0.1 mm (Bischetti et al., 2009). Roots of diameter less than 0.1 mm were too difficult to recognize. The diameters of roots intersecting the soil profile were measured with a Vernier caliper (Sun et al., 2008). Roots were classified based on their diameters into four classes (Abdi et al., 2009) (<2, 2–4, 4–10 and >10 mm) and the contribution to the RAR values in percent at each depth were calculated (Table 1). The RAR distribution with soil depth for all sized roots and roots smaller than 10 mm were then determined (Figs. 2 and 3).

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1 Unified Soil Classification System.
2 Diameter at breast height.
were thoroughly inspected for possible breakage and peeling. Root hairs were carefully dismembered. Suitable root samples of lengths of about 150 mm were cut (Cofie and Koolen, 2001). Before conducting the test, the average root diameter was found by measuring at about five different positions along the length of the root.

Tensile strength tests were carried out using a computer controlled Instron Universal Testing Machine (SANTAM co./SMT-5), equipped with a 500 kg maximum-capacity load cell. By visual inspection, the root samples were positioned as vertical as possible with its axis coinciding with the load cell axis. The root ends were clamped and a strain rate of 10 mm/min (Bischetti et al., 2005, 2009; Mattia et al., 2005; Pollen, 2007) was applied until rupture occurred. As many authors have stated (e.g. Bischetti et al., 2005; Cofie and Koolen, 2001; Mattia et al., 2005; De Baets et al., 2008), the most critical problem in tensile tests is that the grips damage the root structure and results in rupture at clamping position. In order to decrease this effect, at the beginning a number of trial experiments were carried out to develop appropriate clamping force empirically. Tensile strength was calculated by dividing the applied force required to break the root by the cross-sectional area of the root at its rupture point. Tests subject to slippage, or those roots that broke due to crushing at the jaw faces, were discarded (Bischetti et al., 2005; Cofie and Koolen, 2001; Mattia et al., 2005).

Table 1

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Downhill root classes</th>
<th>Uphill root classes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;2 mm</td>
<td>2–4 mm</td>
</tr>
<tr>
<td>10</td>
<td>5.20 ± 2.42</td>
<td>7.45 ± 1.90</td>
</tr>
<tr>
<td>20</td>
<td>8.72 ± 2.92</td>
<td>19.08 ± 10.29</td>
</tr>
<tr>
<td>50</td>
<td>5.55 ± 2.11</td>
<td>9.41 ± 2.87</td>
</tr>
<tr>
<td>60</td>
<td>10.40 ± 3.99</td>
<td>11.28 ± 3.79</td>
</tr>
<tr>
<td>70</td>
<td>19.97 ± 4.82</td>
<td>51.89 ± 12.33</td>
</tr>
</tbody>
</table>

Fig. 2. Average RAR values for downhill (○) and uphill (●) considering all roots (data are mean ± SE, n = 8. For each depth, means with same letter are not significantly different (p > 0.05).

Fig. 3. Average RAR values for downhill (○) and uphill (●) considering roots smaller than 10 mm (data are mean ± SE, n = 8. For each depth, means with same letter are not significantly different (p > 0.05).

2.3. Tensile strength tests

The sample roots for experiments were collected from forest stand in May 2008. Live roots were collected randomly from soil by excavating pits or trenches on uphill and downhill of four trees at a depth of about 30 cm below the soil surface (Cofie and Koolen, 2001). In order to prevent any pre-stress effects, none of the roots were pulled; instead they were cut with sharp scissors, placed in plastic bags and loosely sealed (see Bischetti et al., 2005). The sample roots were preserved for a few days using a 15% alcohol solution (Bischetti et al., 2005), which has no effects on the measured parameters (Bischetti et al., 2009).

The tensile tests were carried out on fresh roots within 1 week from sampling (Bischetti et al., 2005). In the laboratory, the roots

\[ \Delta RAR = \frac{1}{n} \sum_{i=1}^{n} (R_{i} - \bar{R}) \]

were thoroughly inspected for possible breakage and peeling. Root hairs were carefully dismembered. Suitable root samples of lengths of about 150 mm were cut (Cofie and Koolen, 2001). Before conducting the test, the average root diameter was found by measuring at about five different positions along the length of the root.

Tensile strength tests were carried out using a computer controlled Instron Universal Testing Machine (SANTAM co./SMT-5), equipped with a 500 kg maximum-capacity load cell. By visual inspection, the root samples were positioned as vertical as possible with its axis coinciding with the load cell axis. The root ends were clamped and a strain rate of 10 mm/min (Bischetti et al., 2005, 2009; Mattia et al., 2005; Pollen, 2007) was applied until rupture occurred. As many authors have stated (e.g. Bischetti et al., 2005; Cofie and Koolen, 2001; Mattia et al., 2005; De Baets et al., 2008), the most critical problem in tensile tests is that the grips damage the root structure and results in rupture at clamping position. In order to decrease this effect, at the beginning a number of trial experiments were carried out to develop appropriate clamping force empirically. Tensile strength was calculated by dividing the applied force required to break the root by the cross-sectional area of the root at its rupture point. Tests subject to slippage, or those roots that broke due to crushing at the jaw faces, were discarded (Bischetti et al., 2005; Cofie and Koolen, 2001; Mattia et al., 2005).

2.4. Soil reinforcement

The Wu/Waldron model was used to estimate the increase in soil shear strength due to the presence of roots, as the model allows for simple and quick calculation of soil reinforcement effect using tensile strength and root distribution information (De Baets et al., 2007). By combining the strength–diameter relationships and the RAR distributions calculated for the considered species, the potential reinforcement effect due to vegetation was determined using Eq. (7). The size of the roots which can be introduced into the Wu/Waldron model is still a controversial issue (Bischetti, 2008, personal communication). Bischetti (2008) stated that “It is (not only) our opinion that in terms of root cohesion coarser root (larger than 1 cm) can’t mobilize all their tensile strength. When, in fact, the root tensile strength exceeds the soil–root friction resistance, the roots tend to slip out instead to break” (Bischetti, 2008, personal communication). Therefore, in the present study 10 mm diameter was considered as upper limit for root diameter (Bischetti et al., 2009). Wu et al. (1979) considered a factor K for taking into account randomly orientation of the roots with respect to the failure plane. This factor may take values ranging between 1.0 and 1.3. In most previous studies this factor is set to an average value of 1.2 (Gray and Sotir, 1996; Abernethy and Rutherfurd, 2001; Genet et al., 2008; De Baets et al., 2007).

From the results of various shear tests conducted by Waldron (1977) on various root-permeated soils, the angle of shear distortion varied between 40° and 50°. The roots in the present study area are located within a relatively thin soil layer overlaying a firm
bedrock and therefore, likely to fail in tension in a constrained shear zone, and are of a similar size to Waldron’s. The angle of shear distortion is therefore assumed to be equal to 45° (De Baets et al., 2007) and the friction angle of the site soil equals to 25° (Abdi, 2009), then, K in Eq. (4) is taken as 1.04.

2.5. Data analysis

The gathered data were analyzed using the SPSS15.0 statistical software. Spearman correlation test was used to investigate correlation between RAR and \( c_r \). Curve estimation was used to explore mathematical function that exists between RAR and depth and also RAR and \( c_r \). Paired Samples T tests were used to compare uphill and downhill RAR values and also rooting depth of the trenches. Then ANCOVA employed to compare RAR values, number of roots and increased shear strength due to roots (\( c_r \)) between uphill and downhill with regard to the depth as the covariate.

Analysis of covariance (ANCOVA) was used to investigate differences in “root diameter” and “live root tensile strength” between uphill and downhill sides. As the roots were collected from four trees, the intraspecies variations of tensile strength can also be assessed. To determine whether there were any differences in root strength in four Persian Ironwood trees, the test results were subjected to analysis of covariance (Abernethy and Rutherfurd, 2001; Genet et al., 2005) and the root diameter as the covariate. A Kolmogorov–Smirnov test was used to check the normality of the data before proceeding with analysis and where this assumption was violated (normality); data were transformed to ensure homogeneous residual variance and normality.

3. Results

3.1. Root area ratio

Values of RAR show great variability with depth and uphill or downhill directions. In uphill trenches RAR values generally decrease with depth. In the downhill trenches there was a greater variability in RAR values when compared with those of the uphill. In most of the cases the maximum RAR values are located in the upper 0.1 m layer. The minimum and maximum values along the profiles are 0.001% and 1.33% for uphill and 0.004% and 1.39% for downhill sides, respectively (considering only roots smaller than 10 mm). The decrease in RAR values with depth was tested by some mathematical functions, where the exponential obtained not only the highest \( R^2 \) between uphill and downhill. The exponentials were plotted and then the power law was fitted. The values of power law parameters \( a \) and \( b \) were 33.05 and 5.00 mm; the mean tensile strength value was 31.34 ± 1.55 MPa and the maximum and minimum recorded values were 13.20 and 65.00 MPa, respectively. The diameter of uphill roots varied between 0.30 and 5.00 mm; the mean tensile strength value was 25.20 ± 1.19 MPa and the maximum and minimum recorded values were 11.61 and 57.40 MPa, respectively.

The tensile strengths (\( T_r \); MPa) versus root diameter (\( d \); mm) were plotted and then the power law was fitted. The values of power law parameters \( a \) and \( b \) were 33.05 and −0.37 for downhill and 26.84 and −0.37 for uphill, respectively. The corresponding fitting curve and related data are shown in (Fig. 5). The results of ANCOVA revealed that downhill roots had a significantly higher tensile strength than uphill (\( F_{1,91} = 23.24, p = 0.01 \)). Also, the mean root tensile strength was significantly different between sample trees (\( F_{3,58} = 5.537, p = 0.000 \)) with regard to the root diameter (\( F_{1,58} = 15.560, p = 0.000 \)) for downhill specimens, but the differences were not significant for uphill (\( p > 0.05 \)).

3.2. Tensile strength tests

In tensile tests, the tensile force (TF) increases with increasing diameter (\( D \)) as shown in Fig. 4. This relationship can be described well by a power regression curve. In general, 59 root specimens were tested for downhill and 62 for uphill tensile strength. The diameter of the downhill roots varied between 0.30 and 5.00 mm; the mean tensile strength value was 31.34 ± 1.55 MPa and the maximum and minimum recorded values were 13.20 and 65.00 MPa, respectively. The diameter of uphill roots varied between 0.30 and 4.40 mm; the mean tensile strength value was 25.20 ± 1.19 MPa and the maximum and minimum recorded values were 11.61 and 57.40 MPa, respectively.

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3.3. Soil reinforcement

Similar to the RAR distribution, reinforcement effect decreases with depth. The reinforcement effect exerted by uphill roots shows a shear strength increase of 46.0 kPa in upper layers and 0.1 kPa at 65 cm, where only a small number of roots are present. While, in the downhill the roots increase the shear strength by 44.0 kPa in the upper layer and 3.0 kPa at 65 cm (Fig. 6). These values were calculated for similar cross-sectional areas of the soil. The results of Paired Samples T tests showed that difference in root cohesion

![Fig. 4. Tensile force at failure versus root diameter. Lines show power regression curves fitted to the experimental data. (C) downhill. (●) uphill. (\( y = 24.38x^{1.68} \), \( R^2 = 0.92 \)).](image)

<table>
<thead>
<tr>
<th>Model</th>
<th>R square</th>
<th>Adjusted R square</th>
<th>Std. error of the estimation</th>
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<td>0.276</td>
<td>15.031</td>
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<tr>
<td>Logarithmic</td>
<td>0.267</td>
<td>0.259</td>
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</tbody>
</table>
values between uphill and downhill layers were not significant except in 5th and 6th layers where it is higher for downhill side (Fig. 6). Also ANCOVA revealed that not only the effect of covariate (depth) is significant \((F_{1,112} = 103.16, p = 0.00)\) but also there were significant differences between uphill and downhill root cohesion values \((F_{1,112} = 66.25, p = 0.01)\) for all depths. The overall mean for uphill and downhill are 15.46 ± 2.14 kPa and 21.35 ± 2.11 kPa, respectively. The results of Spearman test showed that there was significant correlation between RAR and \(c_r\) (correlation coefficient = 0.700, \(p = 0.00)\). The relation between RAR and \(c_r\) was tested by some mathematical functions, where the power obtained not only the highest \(R^2\) (\(p < 0.05)\) but also a low standard error of estimation (0.786) (see Table 3).

### 4. Discussion

The RAR values are strongly influenced by both genetics and local soil and climate characteristics (Bischetti et al., 2005). However, generally RAR decreases with depth due to a decrease in nutrients and aeration, and also the presence of more compacted soil layers and bedrock (Bischetti et al., 2005). In the present study, a similar RAR pattern was observed. The maximum observed RAR values were located in the upper 0.1 m of soil, and all samples had average RAR values with depth, satisfactorily approximated by an exponential function. The RAR values obtained in this study were consistent with those reported in other studies related to tree species in different environments dominated by hardwood forests (Greenway, 1987; Morgan and Rickson, 1995; Schmidt et al., 2001). In general, the decline of root density with depth is documented by several authors (Greenway, 1987; Nilaweera, 1994; Schmid and Kazda, 2001; Shields and Gray, 1993; Zhou et al., 1998).

The results of the present study showed that RAR values are significantly different in uphill and downhill sides with higher RAR values in the latter. Chiatante et al. (2003) state that asymmetry of the cross-sectional area in uphill and downhill is a sign that the mechanical function of the root system is different in these parts. Di Iorio et al. (2005) also stated that the larger cross-sectional area of the roots can only be due to the greater mechanical stresses. Thus, the results may support the hypothesis that regarding the trees under investigation, mechanical stresses in downhill are higher and therefore, the higher RAR value in downhill is a kind of adaptability in response to the environment. The capability of plants to adapt themselves in reaction to the environmental conditions is called “morphoplasticity” (Marler and Disecik, 1997) or “phenotypic plasticity” Ganatsas and Sponos (2005) and the asymmetry in the study area, means that the tree root system is susceptible to site stresses Ganatsas and Sponos (2005). As the root numbers in uphill and downhill had no significant differences, this may imply that the plant reacts to the stresses by thickening their roots instead of increasing their number.

The deeper downhill rooting is consistent with the bilateral fan-shape disposition suggested by Chiatante et al. (2003). The field observations in the present study of overturned trees also confirms of the “fan-shape” pattern. On the downhill side of a slope, there is evidence to suggest that the roots can grow out of the soil to avoid death due to desiccation; they are obliged to change the growth direction, bending their apex back into the deeper soil layers or beneath the soil surface Chiatante et al. (2003). A similar pattern was also observed by Di Iorio et al. (2005). During slope failure, the tree roots anchor the sliding mass to the stable side and prevent further movement (Stokes, 2002). As downhill rooting is deeper, then they may cross deeper cracks or critical failure planes compared with uphill. Thus, the down slope roots of the trees that are located on cut slopes and beyond it may have the highest impact on reinforcement and stability of cut slopes considering their deeper penetration.

Tensile strength data presented in this paper were compared with those for tree species (Greenway, 1987). Tensile strength of Persian Ironwood (31.34 ± 1.55 MPa for downhill and 25.20 ± 1.19 for uphill) is comparable to some hardwood species (mean values in MPa) including Ficus microcarpa 24 MPa, Fraxinus excelsa 26 MPa, Acer platanoides 27 MPa, Alnus incana 30 MPa, Quercus robur 32 MPa and Berula pendula 38 MPa (After Stokes, 2002). The root strength is strongly influenced by its diameter (Abe and Lawamoto, 1986; Burroughs and Thomas, 1977; Genet et al., 2005; Gray and Sotir,

### Table 3

Model summery for mathematical functions were tested to derive the relationship between RAR and \(c_r\).

<table>
<thead>
<tr>
<th>Model</th>
<th>(R^2)</th>
<th>Adjusted (R^2)</th>
<th>Std. error of the estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>0.351</td>
<td>0.344</td>
<td>16.076</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>0.436</td>
<td>0.429</td>
<td>14.995</td>
</tr>
<tr>
<td>Inverse</td>
<td>0.111</td>
<td>0.101</td>
<td>18.817</td>
</tr>
<tr>
<td>Quadratic</td>
<td>0.369</td>
<td>0.382</td>
<td>15.602</td>
</tr>
<tr>
<td>Cubic</td>
<td>0.415</td>
<td>0.395</td>
<td>15.438</td>
</tr>
<tr>
<td>Compound</td>
<td>0.239</td>
<td>0.231</td>
<td>0.945</td>
</tr>
<tr>
<td>Power</td>
<td>0.474</td>
<td>0.468</td>
<td>0.786</td>
</tr>
<tr>
<td>Growth</td>
<td>0.241</td>
<td>0.232</td>
<td>0.944</td>
</tr>
<tr>
<td>Exponential</td>
<td>0.239</td>
<td>0.231</td>
<td>0.945</td>
</tr>
</tbody>
</table>
that “Wu/Waldron’s model overestimated calculated in soil shear strength”. However, overestimation was corrected. Wu/Waldron’s model will result in maximum possible increase of tensile strength of the soil. Whether by an increase in apparent cohesion or an anchoring mechanism, the amount of increase is dependent on the quantity of root material expressed as the root area ratio (RAR) at the shear plane (Docker and Hubble, 2008). In forest engineering, it is generally accepted that the tree crowns prevent the roads surface from drying and if they are cut, the period of exposure to the sun is increased and the aeration of the surface is improved. The larger the clearing of the forest, the better is the air circulation (Sessions, 2007). Thus, in constructing a forest road a clearing width (right of way) is determined and all trees are clear cut. Traditionally, the clearing width in Iran is 15–20 m based on forest road type with no concession for stability considerations. This forms a gap strip inside the root network and if shallow landslides occur in the gap (Schmidt et al., 2001), clear-cuts cause greater possibility for landslides to occur. Furthermore, if landslides in clear-cuts tend to have larger initial source volumes (Schmidt et al., 2001), they may trigger long run-out debris flows. This highlights the importance of well-established vegetation in the right of way of forest roads to provide a spatially continuous root mat. According to Schmidt et al. (2001), the underlying root cohesion governs the landslide susceptibility. Ziener (1981) showed that it may take 15 to more than 25 years for a regenerating clear-cut lodgepole pine forest in California to restore 50% of its original root strength and in such a time period, significant increase in the rate of landsliding may occur. Therefore, in such periods, forest road’s cut and fill slopes are more susceptible to landslides as it happened in study area (e.g. Poplar switchback failure and the case in Fig. 1).

5. Conclusions

Root cohesion data of the type presented here can help to identify specific landslide hazards. Root distribution and tensile strength measurements can be used with soil geotechnical data to analyze the stability of road cut and fill with and without root reinforcement before clearing the right of way. The high ability of Ironwood to sprouting can be used to reinforce bare soils and lower the risk of shallow landslides.

In conclusion, we present a data set of root distribution, tensile strength and root cohesion for Persian Ironwood in Iran. The results revealed significant differences between RAR, rooting depth, tensile strength and cohesion values between uphill and downhill trenches and in all cases higher values were obtained for downhill side. Also validity of the power law in expressing the correlation between tensile strength and root diameter was confirmed.

Acknowledgements

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References


1996; Nilaweera and Nutralaya, 1999). The results of the present study show that root tensile strength decreases with diameter (Fig. 5), as found by many other authors, following a power law function (Bischetti et al., 2005, 2009; Burroughs and Thomas, 1977; Gray and Sotir, 1996; Nilaweera, 1994; Genet et al., 2005, 2008). The power law relationship observed between root tensile strength and its diameter is similar to that found in previous studies (Gray and Sotir, 1996; Nilaweera and Nutralaya, 1999; Operstein and Frydman, 2000; Bischetti et al., 2005; Genet et al., 2005). This trend could be due to a difference in cellulose content between smaller and larger roots (Hathaway and Penny, 1975; Genet et al., 2005; Hales et al., 2009). The values of the power law parameters $\alpha$ and $\beta$, obtained for the considered species, do not fall in the range already suggested for hardwood roots (between 29.1 and 87.0 for $\alpha$ and between $-0.8$ and $-0.4$ for $\beta$; Nilaweera, 1994) except for $\alpha$ of downhill which is in the range. Such discrepancies were also observed in some other studies (Bischetti et al., 2005; De Beats et al., 2008; Mattia et al., 2005) and which is indicative of need for further investigation.

Bischetti et al. (2005) suggested that the exponent of the power law equation ($\beta$) controls the rate of strength decay with diameter, whereas $\alpha$ can be considered as a scale factor. The results of the present study also recognize the same value of $\beta$ for uphill and downhill (Fig. 5), suggesting a similar strength decay.

Stokes (2002) stated that depending on the mechanical role of a root in the system, wood strength would change to resist better the acting forces; for example, in trees growing on slopes, tensile strength is greater in uphill roots than in downhill. Contrary to Schiechtl (1980) and Stokes (2002), in the present study it was found that the downhill roots are stronger than uphill ones. The differences show different roles of uphill and downhill roots in stability of the trees which may be due to the wind action as Stokes (2002) showed the leeward roots are normally stronger than the windward roots.

Genet et al. (2005) and Hales et al. (2009) believed there is a possibility that the local environment also influences the root cellulose content. Thus, they suggested further studies on variations of root tensile strength of different species from the same site to be carried out. The results of the present study showed significant intraspecies differences in root tensile strength for downhill specimens.

To evaluate the effects of the roots on the reinforcement of the soil in uphill and downhill sides, Eq. (7) was employed. Based on the obtained results, the increase in strength varies with depth from 46.0 kPa in the upper soil layers to 3.0 kPa at 60 cm (Fig. 6). The reduction of soil reinforcement with depth follows an exponential law according to RAR distribution which is consistent with the results of other authors (Abernethy and Rutherford, 2001; Mattia et al., 2005; De Baets et al., 2008).

The differences between RAR values and tensile strengths in uphill and downhill sides indicate that the root cohesion is also significantly different in with higher values in downhill side. Also validity of the power law in expressing the correlation between root tensile strength and cohesion values between uphill and downhill trenches and in all cases higher values were obtained for downhill side. Also validity of the power law in expressing the correlation between tensile strength and root diameter was confirmed.

4.1. Implications of the results

The presence of tree roots across a shear plane increases the shear strength of the soil. Whether by an increase in apparent cohesion or an anchoring mechanism, the amount of increase is dependent on the quantity of root material expressed as the root area ratio (RAR) at the shear plane (Docker and Hubble, 2008). In forest engineering, it is generally accepted that the tree crowns prevent the roads surface from drying and if they are cut, the period of exposure to the sun is increased and the aeration of the surface is improved. The larger the clearing of the forest, the better is the air circulation (Sessions, 2007). Thus, in constructing a forest road a clearing width (right of way) is determined and all trees are clear cut. Traditionally, the clearing width in Iran is 15–20 m based on forest road type with no concession for stability considerations. This forms a gap strip inside the root network and if shallow landslides occur in the gap (Schmidt et al., 2001), clear-cuts cause greater possibility for landslides to occur. Furthermore, if landslides in clear-cuts tend to have larger initial source volumes (Schmidt et al., 2001), they may trigger long run-out debris flows. This highlights the importance of well-established vegetation in the right of way of forest roads to provide a spatially continuous root mat. According to Schmidt et al. (2001), the underlying root cohesion governs the landslide susceptibility. Ziener (1981) showed that it may take 15 to more than 25 years for a regenerating clear-cut lodgepole pine forest in California to restore 50% of its original root strength and in such a time period, significant increase in the rate of landsliding may occur. Therefore, in such periods, forest road’s cut and fill slopes are more susceptible to landslides as it happened in study area (e.g. Poplar switchback failure and the case in Fig. 1).

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