135. Jahrgang (2018), Heft 4, S. 283–296

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

The role of native species of *Quercus brantii* and *Crataegus aronia* in soil reinforcement in Zagros forests

Die Rolle der einheimischen Baumarten *Quercus brantii* und *Crataegus aronia* bei der Bodenverstärkung in den Wäldern von Zagros

Tahereh Heidarian [1], Farhad Ghasemi Aghbash [1*], Iman Pazhouhan [2]

Keywords: *Biotechnical Soil Reinforcement, Root Tensile Strength, Wu Model*

Schlüsselbegriffe: *Biologisch-technische Bodenverstärkung, Wurzelzugfestigkeit, Wu Modell*

Abstract

In this study, biotechnical characteristics of the root system of *Quercus brantii* and *Crataegus aronia*, were studied in Zagros forests, the west of Iran. For each species, a number of eight individual trees were selected and 73 root samples were tested for measuring tensile strength using Instron Universal Testing Machine. Results showed a negative relationship between the diameter and tensile strength. The minimum and maximum tensile strength values in the diameter range of 0.13-2.93 for *Q. brantii* were 15.01 and 116.08 MPa and in the diameter range of 0.32-2.97 cm for *C. aronia* were 12.98 and 83.10 MPa, respectively. The parameters for soil cohesion and angle of internal friction of soil particles for soil samples of each individual trees were

[1] Natural Resource & Environment Faculty, Malayer University, Malayer, Iran
*Corresponding author: Farhad Ghasemi Aghbash (f.ghasemi@malayeru.ac.ir) und Tel: +989122379717
[2] Department of Forestry, Faculty of Natural Resource, Tarbiat Modares University, Noor,.Iran

measured using direct shear test apparatus after transporting samples to the laboratory. Calculation of soil reinforcement of the two species is based on a modified Mohr-Coulomb concept (Wu model) and on measured data of tensile strength and root area ratio (RAR). The maximum values of soil shear strength, considering the root cohesion effect of *Q. brantii* and *C. aronia*, have been estimated with 100.40 MPa and 98.28 MPa respectively. The results showed that the soil shear strength of *Q. brantii* is higher than *C. aronia*. The results confirm the effect of forest on slope stability and the findings of our study can be used in reinforced soils and lower the risk of landslides.

Zusammenfassung

In dieser Studie wurden die biotechnologischen Charakteristika des Wurzelsystems von *Quercus brantii* und *Crataegus aronia* im Zagros Wald im Westen Irans untersucht. Für jede Spezies wurde eine Anzahl von 8 individuellen Bäumen ausgewählt und es wurden 73 Wurzelproben untersucht um die Zugfestigkeit mit der Instron Universal Testing Maschine zu messen. Die Ergebnisse zeigen einen negativen Zusammenhang zwischen dem Wurzelfurchmesser und der Zugfestigkeit. Bei *Q. brantii* Wurzeln mit einem Durchmesser zwischen 0.13 und 2.93 cm wurden Minimal- und Maximalwerte der Zugfestigkeit von 15.01 und 116.08 MPa ermittelt. Bei *C. aronia* und einer Durchmesserspanne von 0.32 bis 2.97 cm wurden Zugfestigkeit zwischen 12.98 und 83.10 MPa ermittelt. Die Parameter für die Bodenkohäsion und den internen Reibungswinkel der Bodenproben von jedem einzelnen Baum wurden mit dem Direkten-Scherversuch-Apparat im Labor gemessen. Die Berechnung der Bodenverdichtung der beiden Spezies basiert auf einem veränderten Mohr-Coulomb Konzept (Wu Model) und auf den gemessenen Daten der Bruchkraft und Wurzelspannung. Die Maximalwerte der Boden-Scherkraft, welche den Kohäsionseffekt der Wurzeln von *Quercus brantii* and *Crataegus aronia* berücksichtigt, wurde mit jeweils 100.40 MPa und 98.28 MPa ermittelt. Die Ergebnisse zeigen, dass die Boden Scherkraft von *Q. brantii* höher ist als die der *C. aronia*. Die Ergebnisse bestätigen den Einfluss des Waldes auf die Hangstabilität. Die hier erzielten Ergebnisse können bei verdichteten Böden angewandt werden um das Risiko von Hangrutschungen zu minimieren.

1. Introduction

Soil erosion, a serious environmental problem, has intensified recently as result of human activities. Long-term sustainability of forest ecosystems depends on maintaining the soil quality. Bio-technical methods have been highly regarded because of considering environmental and economic issues. Bio-engineering strategies became a part of hydraulic and geotechnical engineering and have used bridge the gap between classical engineering disciplines, land use management, architecture and biological sciences. Bio-engineering is defined as applying the plants for controlling erosion and stabilizing slopes (Forbes and Broadhead, 2011) and identifying the reinforcement of riparian vegetation (Pollen, 2007). Vegetation plays a major role in increased slope stability and improving hydrological conditions of the soil.

Soils covered with vegetation are less exposed to the risk of water erosion and mass movements (Greenway, 1987). Many authors have stated the role of plant roots in stabilizing slopes and preventing erosion, quickly protect the soil, by means of their covering action, from surface erosion and degradation (Norris et al., 2005; Genet et al., 2008), increasing the shear strength of the soil and thus increasing the stability of the coasts (Simon and Collison, 2002; Hosseini et al., 2013). Reinforcement by roots improves mechanical and hydrology stability of slope. Soil is strong in compression, but weak in tension. Roots are weak in compression, but strong in tension (Pollen, 2007; Schwarz et al., 2015). Therefore, the soil-root matrix produces a kind of reinforced earth, which is much stronger than the soil or the roots separately. Thus, roots reinforce the soil (Nilaweera and Nutalaya, 1999, Abdi et al., 2011). Genet et al. (2005) suggest that there is a significant relationship between the root diameter and tensile strength, which depends on plant species so that tensile strength increases in thinner roots. In other words, changes in tensile strength can be well demonstrated by the root diameter (Nyambane and Mwea, 2011). Abdi et al. (2010), and Hosseini et al. (2013) demonstrated a negative relationship between root diameter and tensile strength.

Zagros area serves as one of the most important and valuable regions in the west of Iran in terms of biodiversity as well as soil protection and water resources which plays a major role in the national economy and is considered as among the most important sources for water (Maleknia et al., 2013). Yet there are few studies on tree roots from Zagros forest on soil strength.

Several studies have been carried out to investigate root reinforcement of soil in forest ecosystems (Naghdi et al., 2013). Given the importance of these forests and the role of the root system in stabilizing and controlling erosion, evaluating the effects of native species roots for the purposes of bio-engineering will be useful. But few researches have been done to find out the influence of Zagros plant roots on soil stability. This study aims to evaluate the soil reinforcement capacity of two species of *Quercus brantii* and *Craetegus aronia* because each species will produce a different rooting pattern and different amounts of above ground biomass. *Quercus brantii* is the most abundant tree species in the study area that intermixed with other species such as *Crataegus aronia* in this area.

2. Materials and methods

2.1 Study area

This study was carried out in Chahar-Zabar forests, located in the southwest part of Kermanshah province in Zagros Mountains forests, with an area of about 300 ha (Fig. 1). These forests can be considered as a starting point where arid and semi-arid regions are dominated by Persian oak (*Q. brantii*) forests. Chahar-Zabar region belongs to Mahidasht county, Kermanshah province located at about 46°41'1" E, and 34°13'50"

N. Elevation above sea level varies between 1400 and 1800 m in this region. The slope ranges between 35 to 60 percent. The average annual temperature is 16° C. The climate of the study area according to Demarton's classification is Mediterranean with average annual precipitation about 460 mm.

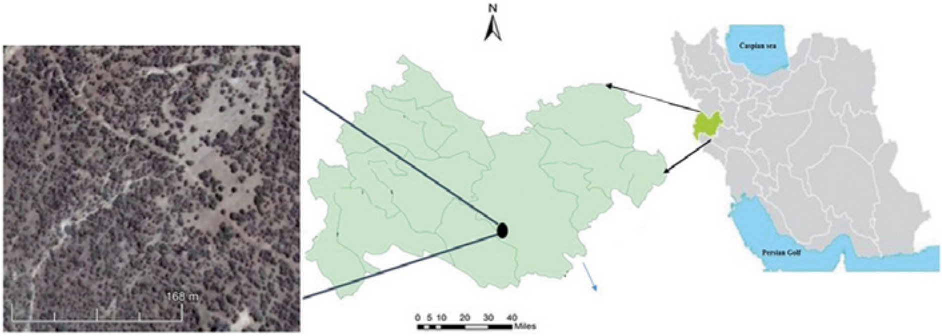

Fig. 1: The situations of the study area in west of Iran (Zagros Mountains forest)

Abbildung 1: Lage des Untersuchungsgebietes im westlichen Iran (Zagros Gebirgswald)

2.2 Root tensile strength test

Roots of eight trees of two species *Q. brantii* and *C. aronia* were selected randomly in the area. Around each sample tree at a distance of 0.5 m, the profiles were excavated to a depth of about 20 cm. Tensile strength tests were carried out on 40 root samples of *Q. brantii* in the diameter range of 0.13-2.93 cm and 33 root samples of *C. aronia* in the diameter range of 0.32-2.97 cm. Root samples were collected from surrounding areas of the tree at the top and bottom profiles. The collected samples were placed in plastic bags containing 15% alcohol solution (Mattia et al., 2005). Then, the appropriate roots for the experiment (10 cm long roots) were selected. The number (Normaniza et al., 2008) and diameter (Sun et al., 2008) of roots were measured in both sides by counting. The diameters of roots intersecting the soil profile was measured with a Vernier caliper (Sun et al., 2008). Roots were classified based on their diameters and the contribution to the RAR values in percent at each depth were calculated. The RAR distribution with soil depth for all sized roots and roots smaller than 10 mm were then determined.

Root tensile strength was measured using Standard Instron (Santam STM-5) at a speed of 10 mm per minute (Bischetti et al., 2005). The tensile strength of each sample was determined by dividing root breaking force by the root cross section.

2.3 Soil shear strength

Soil shear strength parameters were obtained through direct shear tests. The Dimensions of specimen box were set by 20 × 60 × 60 mm, accuracy of cutting ring gauge as 0.002 mm and strain ring gauge as 0.01 mm, ring factor as 0.167, device speed as 1 mm per minute and by performing three replications with normal stresses of 20, 40 and 60 kPa, the shear stress was determined and the Mohr-Coulomb resistance line was drawn using the obtained coordinates.

2.4 Root reinforcement

The common model for estimating the effect of root reinforcement was introduced by Wu (1976) and Waldron (1977). Wu (1976, 1979) and Waldron (1977) developed the perpendicular root model that assumed all roots would reach their maximum tensile strength and break at the same moment (Wu et al., 1979). However, the roots in a root-soil composite would break successively because of the various lastingness of every single root, and some large roots did not break, but rather be pulled out of the soil. Wu and Waldron's model therefore overestimates the roots' ability to stabilize soil (Pollen, 2007).

$$S = C + C_r + \sigma tan\varphi \qquad (1)$$

Where S is soil shearing resistance (kPa), is soil cohesion (kPa), C_r is the shearing strength caused by the roots (kPa), σ is the normal stress on the shear plane (kPa), φ refers to the internal friction angle of the soil (degrees) (Wu et al., 1979) which depends upon soil particle size distribution, soil dry density, soil surface texture, shape of particles, and soil moisture content (Jain et al., 2010).

C_r can be represented by:

$$Cr = k * t_R \qquad (2)$$

Where t_R the mobilized root tensile strength per soil unit area is, k is a factor taking into account the random 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:

$$k = sin\theta + cos\theta + tan\varphi \qquad (3)$$

Where *Θ* is the angle of shear distortion in the shear zone, and *φ* is the soil internal friction angle (°). The mobilized root tensile strength per soil unit area (t_R) can be written as:

$$t_R = T_r a_r \qquad (4)$$

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

3. Results

The soil texture is generally sandy clay loam and the soil origin is calcareous. Liquid and plastic limits for *Q. brantii* ranged from 42.12 – 55.75 and 23.72% - 37.70 % respectively. Also, liquid and plastic limits for *C. aronia* ranged from 25.45 – 42.17 and 15.44% - 36.23 % respectively. Some physical and mechanical properties of soil for both species are given in Tables 1 and 2.

Table 1: Physical and mechanical properties of soil at the root site sampling of Quercus brantii

Tabelle 1: Physikalische und mechanische Eigenschaften der Bodenproben von Quercus brantii

sample	Optimum moisture(%)	γd max (gr/cm^3)
Q1	15	1.48
Q2	16.50	1.55
Q3	17	1.44
Q4	13.31	1.38
Q5	14.32	1.40
Q6	15.52	1.33
Q7	12.5	1.32
Q8	17.25	1.6

*γd max = maximum dry density,

Table 2: Physical and mechanical properties of soil at the root site sampling site of Crataegus aronia

Tabelle 2: Physikalische und mechanische Eigenschaften der Bodenproben von Crataegus aronia

sample	Optimum moisture(%)	γd max (gr/cm^3)
C1	22.5	1.58
C2	16.94	1.48
C3	20.93	1.62
C4	18	1.5
C5	20.58	1.59
C6	23	1.6
C7	1.6	20.84
C8	1.62	21

3.1 Root tensile strength

The minimum and maximum tensile strength (: eq.4) values were 15.01 and 116.08 MPa for *Q. brantii*, and 12.98 and 83.10 MPa for *C. aronia*, respectively. The relationship between the root diameter and tensile strength for *Q. brantii* and *C. aronia* are following a negative power law with the exponent *β* and intercept *α*. Here, *β* describes the rate of strength decay with diameter, while *α* is defined as a specific scale factor.

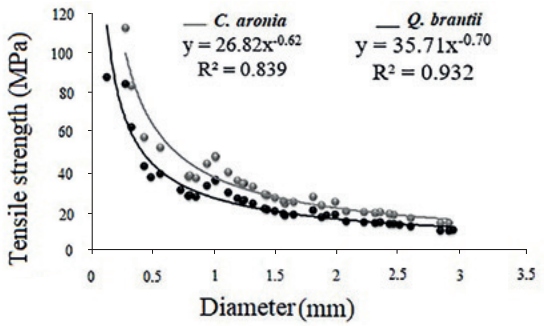

Fig. 2: The relationship between the diameter and tensile strength. The curves reveal a negative relationship between the diameter and tensile strength following power law.

Abbildung 2: Der Zusammenhang zwischen Wurzeldurchmesser und Zugfestigkeit. Die Ergebnisse zeigen einen negativen Zusammenhang zwischen dem Durchmesser und der Festigkeit

3.2 Soil shear strength test

Soil shear strength without roots include the two parameters of cohesion and angle of internal friction (*C* and *φ*) which can change by the quality of plant root systems. As a result, soil disintegration and erosion decreases and stability increase by increasing shear strength. The curves related to soil shear strength of sample number 1 for *Q. brantii* and *C. aronia* are shown in Figure 3. The parameters obtained from direct shear tests to determine shear strength are shown in Table 3.

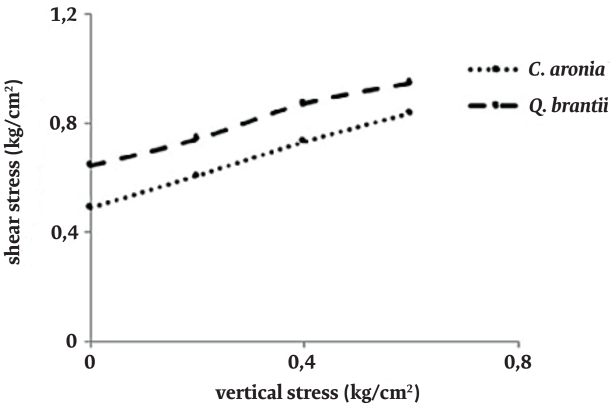

Fig. 3: Mohr-Coulomb resistance line relating to the number one example of Quercus brantii and Craetagus aronia

Abbildung 3: Mohr-Coulomb Widerstandslinie für jeweils eine Probe von Quercus brantii und Craetagus aronia

Table 3: The parameters of the shear strength of soil sample. C is the cohesion and φ is the angle of internal friction

Tabelle 3: Die Parameter der Schubkraft der Bodenproben. C ist die Kohäsion and φ ist der innere Reibungswinkel

sample	*Quercus brantii*		*Craetagus aronia*	
	φ (^{0})	C (kg/cm^2)	φ (^{0})	C(kg/cm^2)
1	30	61.78	28	59.82
2	26	72.56	30	54.91
3	31	68.64	31	49.03
4	30	63.74	30	55.89
5	28	67	28	58.83
6	29	69.62	27	57.85
7	28	66.68	26	60.80
8	25	75.51	25	62.76

3.3 Soil reinforcement

Using data of tensile strength and root area ratio (RAR) and by applying the Wu model (eq. 1), we can estimate the adhesion added to the soil through the presence of roots (Reinforcement). This model allows quick and simple calculation of the effect of soil reinforcement using data from root distribution and tensile strength. Our finding show that RAR values generally tend to decrease with depth below the surface. Also, the rein¬forcement effect (C_r) according to eq. 1 decreases with depth. The highest reinforcement value obtained by *Q. brantii* and *C. aronia* were 100.40 and 98.28 kPa, respectively.

4. Discussion and Conclusion

Vegetation can increase slope stability and improve soil hydrological conditions. Each species will produce a different rooting pattern and different amounts of above ground biomass depending on site conditions and climate. The role of vegetation in reinforcing and anchoring the soil contributes to its stability but is dependent on factors such as root system morphology, root strength, distribution, and root-soil interaction (Reubens et al., 2007).

A decrease in root diameter from 5 to 2 mm can result in a doubling or even tripling of tensile strength. This phenomenon has been attributed to differences in root structure, with thinner roots possessing more cellulose than thicker roots, cellulose being more resistant than lignin in tension (Genet et al., 2005). It is not yet known if cellulose content is greater in young roots (which are usually thinner), but initial studies suggest that in conifers, tensile strength is greater in roots from older trees (Genet et al., 2006). Root tensile strength is obtained from the force required for breaking the root divided by its cross section. The less diameter to be, the less breaking force and higher tensile strength will be. In fact, the higher amount of cellulose in thin roots has been suggested to be the main reason for their greater strength (Genet et al., 2005; Norris, 2005; Baets et al., 2008). In this study, the relationship between the diameter and tensile strength of root was found as a negative power function, confirming the results obtained by Makarova et al., 1998; Nilaweera and Nutalaya, 1999; Simon and Collison, 2002; Watson and Marden, 2004; Bischetti et al., 2005; Genet et al., 2005; Mattia et al., 2005 and Norris, 2005.

In case of the negative power function, *Q. brantii* had larger α, while *C. aronia* had smaller *β*. Given the magnitude of the factor *α* in *Q. brantii*, it was generally found that tensile strength of *Q. brantii* was higher than that of *C. aronia* in a constant diameter. Nilaweera (1994) suggested values of *α* and *β* for hardwood root, ranging from 26.1 to 87.0 and -0.8 to -0.4, respectively. Accordingly, a low scale factor (*α*) and a high exponent (*β*) mean a less resistant species (Abdi et al. 2014). In case of some species *β* value did not fall in the above mentioned range (Bischetti et al. 2005; Abdi et al. 2010), which may indicate that the range needs to be revised based on the results of new studies or classified based on forest area or environmental conditions.

On the basis of the Wu (1976) and Waldron (1977) model, the extent of root reinforcement depends on tensile strength, density and depth of roots, which vary significantly depending on species, local environmental characteristics and spatial variability of vegetation properties (density, age, fire events, erosion, trees health, etc.).

The Wu model was able to determine soil shear strength due to the presence of root, which has been used in several studies worldwide (Abernethy and Rutherfurd, 2001; Bischetti et al., 2005; Tosi, 2007; Baets et al., 2008; Mattia et al., 2005; Cazzuffi et al., 2006; Simon and Collison, 2002) and in Iran (Abdi et al. 2010, Abdi et al. 2011, Maleki et al. 2014). This model estimates the adhesion added to the soil due to the presence of root based on tensile strength and root area ratio (Abdi et al., 2010; Schmidt et al., 2001). In this model, there is disagreement about the diameter range. O'Loghlin (1984) suggested that roots with the diameter ranging from 1- 20mm have the highest impact on soil shear strength. Reubens et al. (2007) showed that roots smaller than 3mm are effective in soil reinforcement. But some authors believe that in this model there is no limitation or restriction for the diameter (Greenwood, 2006). Operstein and Frydman (2000) suggested an effective diameter of 2 cm because of limitations for higher diameters in tensile strength tests. Bischetti (2009) stated that the maximum 1 cm diameter for soil reinforcement which has been confirmed by many researchers. According to the diameter size range in this study (up to 3 mm), the highest reinforcement was found for diameter class 1 (roots smaller than 1 mm).

The results of this study can help us understanding the biotechnical characteristics of root systems of *Q. brantii* and *C. aronia*. However, these results cannot be generalized to all regions since to apply bio-engineering methods, we must consider the site conditions and climate at the first step. Furthermore, our results indicate that root strength decreases with diameter following a power law equation. This finding indicated soil reinforcement due to species are significant and the highest values are related to *Q. brantii*.

References

Abdi E., Majnounian B., Rahimi H., Zobeiri M., Habibi Bibalani Gh. (2011): Intraspecies variations of tree root tensile strength as Eco-Engineering materials in local scale (Case study: Kheyrud Forest). Journal of Natural Environment, 64: 137-144. (In Persian).

Abdi E., Majnounian B., Rahimi H., Zobeiri M., Habibi Bibalani, Gh. (2010): Investigation of Biotechnical Properties of *Parottia persica* in Order to Use in Bioengineering (Case Study: Patom district of Kheyrud Forest). Journal of Natural Environment, 63: 53-62 (In Persian).

Abdi, E., Azhdari, F., Abdulkhani, A. and Mariv, H.S. (2014): Tensile strength and cellulose content of Persian ironwood (*Parrotia persica*) roots as bioengineering material. Journal of Forest Science, 60: 425-430.

Abernethy B., Rutherfurd I.D., (2001): The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrol. Process, 15: 63–79.

Baets S. De., Poesen J., Reubens K., Baerdemaeker J. De. Muys B. (2008): Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant Soil, 305: 207–226.

Bischetti G.B., Chiaradia E.A., Epis T., Morlotti E.)2009(: Root cohesion of forest species in the Italian Alps. Plant Soil, 324: 71–89.

Bischetti G.B., Chiaradia E.A., Simonato T., Speziali B., Vitali B., Vullo P., Zocco A., (2005): Root strength and root area ratio of forest species in Lombardy (Northern Italy). Plant and Soil, 278:11–22.

Cazzuffi D., Coreneo A., and Cripra E.)2006(: Slope stabilization by perennial "gramineae" in Southern Italy: plant growth and temporal performance. Geotechnical and Geological Engineering, 24: 429–447.

Forbes K., Broadhead J. (2011): Forest and landslides. The role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia. FAO; RAP Publication 19/2011.

Genet M., Kokutse N., Stokes A., Fourcaud T., Cai X., Ji J., Mickovski S.B.)2008(: Root reinforcement in plantations of *Cryptomeria japonica* D. Don: effect of tree age and stand structure on slope stability. Forest Ecology and Management, 256: 1517–1526.

Genet M., Stokes A., Salin F., Mickovski S.B., Fourcaud T., Dumail J.F., VanBeek R. (2005):

The influence of cellulose content on tensile strength in tree roots. Plant Soil, 258: 1–9.

Genet M., Stokes A., Fourcaud T., Hu X., Lu Y. (2006): Soil fixation by tree roots: changes in root reinforcement parameters with age in Cryptomeria japonica D. Don. Plantations. In Interpraevent (pp. 25-27).

Greenway D.R. (1987): Vegetation and slope stability. In: Anderson, M.G., Richards, K.S. (Eds.), Slope Stability. J. Wiley and Sons, Ltd., New York, 187–230.

Greenwood J.)2006(: SLIP4EX – A program for routine slope stability analysis to include the effects of vegetation, reinforcement and hydrological changes. Geotechnical and Geological Engineering, 24: 449–465.

Hosseini A.R., shafai M., Musavi S.H., Rahimi H. (2013): Investigation of Root Tensile Strength of Trees (POPULOUS species) on the Riverbanks. Iranian Journal of Irrigation & Drainage. 6:432–440 (In Persian).

Jain R., Jain P.K., Bhadauria S.S. (2010). Computational approach to predict soil shear strength. International Journal of Engineering Science and Technology, 2(8): 3874-3885.

Makarova O.V., cofie P., Koolen A.J. (1998(: Axial stress–strain relationships of fine roots of Beech and Larch in loading to failure and in cyclic loading. Soil & Tillage Research, 45: 175–187.

Maleki S., Naghdi R., Abdi E., Nikooy M. (2014): Investigating the amount of reinforcement of Alnus subcordata root in order to use in bioengineering. Iranian Journal of Forest, 6: 49–58 (In Persian).

Maleknia R., Amiraslany A., Razi J. M. (2013): An ecological capability evaluation model for recreation, conservation and protection functions of Irans Zagros forests: Javanrood region. African Journal of Agricultural Research, 8: 1629-1635.

Mattia C., Bischetti G.B., Gentile F. (2005): Biotechnical characteristics of root system of typical Mediterranean species. Journal of Plant Soil, 278: 23–32.

Nilaweera N.S., Nutalaya P. (1999): Role of tree roots in slope stabilization. Bulletin of Engineering Geology and the Environment. 57: 337–342.

Nilaweera N.S. (1994): Effects of tree roots on slope stability: the case of Khao Luang Mountain area, So Thailand. Dissert. No. Gt-93-2.

Normaniza O., Faisal H.A., Barakbah S.S. (2008): Engineering properties of Leucaena leucocephala for prevention of slope failure. Ecological engineering. 32, 215–221.

Norris J.) 2005(: Root reinforcement by *Crataegus aronia* and *Quercus brantii* roots on a highway cut-slope in Southern England. Plant and Soil, 278:43–53.

Nyambane O.S., S.K. Mwea. (2011): Root tensile strength of three typical plant species and their contribution to soil shear strength; a case study, Sasumua Backslope, Nyandarua District, Kenya, Journal of Civil Engineering Research and Practice, 8: 57-73.

O'Loghlin C.L. (1984): Effective of introduced forest vegetation for protecting against Landslides and erosion in New Zealand steep lands, paper presented to Symposium on effects of forest land use on erosion and slope stability, Honolulu, Hawaii.

Operstein V., Frydman, S. (2000): The influence of vegetation on soil strength. Proceedings of the Institution of Civil Engineers-Ground Improvement, 4(2), 81-89.

Pollen N. (2007): Temporal and spatial variability in root reinforcement of stream banks: accounting for soil shear strength and moisture. Catena, 69: 197–205.

Reubens B., Poeson J., Geudens G., Muys B. (2007): The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. Plant Soil, 21: 385–402.

Schmidt K M., Roering J J., Stock J D., Dietrich W E., Montgomery D R., Schaub T. (2001): The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal, 38: 995–1024.

Schwarz M., Rist A., Cohen D., Giadrossich F., Egorov P., Buttner D., Stolz M., Thormann J.J. (2015): Root reinforcement of soils under compression. Journal of Geophysical Research, Earth Surface. 120 (10), 2103–2120.

Simon A., Collison A.J.C. (2002): Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms, 27: 527–546.

Sun H.L., Li S.C., Xiong W.L., Yang Z.R., Cui B.S., Yang T. (2008): Influence of slope on root system anchorage of *Pinus yunnanensis*. Ecological engineering. 32, 60–67.

Tosi M. (2007(: Root tensile strength relationships and their slope stability implications of three shrub species in the Northern Apennines (Italy). Geomorphology, 87: 268–283.

Waldron L.J. (1977): The shear resistance of root-permeated homogeneous, stratified soil. Soil Science Society of America Journal. 41 (3), 843–849.

Watson A.J., Marden M. (2004): Live root-wood tensile strengths of some common New Zealand indigenous and plantation tree species. New Zealand Journal of Forestry Science, 34: 344–353.

Wu T.H., McKinell W.P., Swanston D.N. (1979): Strength of tree roots, landslides on Prince of Wales Island, Alaska. Canadian Geotechnical Journal, 16: 19–33.

Wu T.H. (1976): Investigation of landslides on prince of Wales Island, Alaska. Ohio State University.